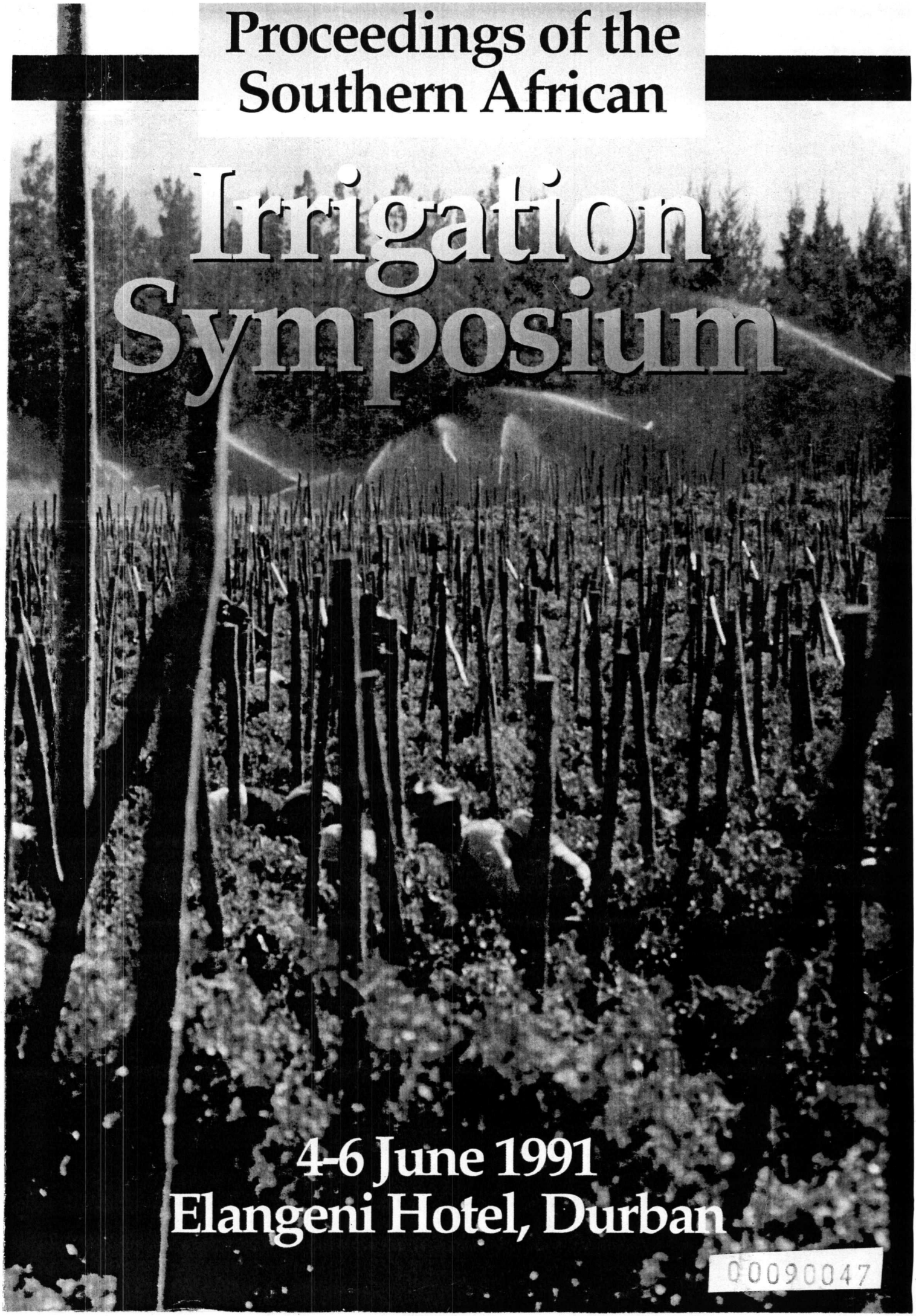
Proceedings of the Southern African

Irrigation Symposium



4-6 June 1991
Elangeni Hotel, Durban

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PROCEEDINGS

OF THE

SOUTHERN AFRICAN IRRIGATION SYMPOSIUM

Elangeni Hotel, Durban

4 - 6 June 1991

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The Proceedings of a symposium constitutes not only a permanent record of the papers and addresses presented at the symposium, but also reflects the level at which discussions took place and the extent to which the theme of the symposium was covered during the various sessions. As such it is therefore also a measure of the success of the symposium. The use of the Proceedings subsequent to the symposium as a source of information to elevate operational activities to a higher level of efficiency, and to provide guidance for further research, represents the "final chapter" of the symposium.

In this regard the Proceedings of the Second National Irrigation Symposium held in 1991 in Durban is no exception. The Organising Committee of this symposium wishes to use this opportunity to acknowledge the contributions of presenters of papers at the symposium, and especially the contributions of those authors who submitted their presentations for inclusion in these proceedings.

In addition to the above, the role played by the Editorial Committee, consisting of the following members, needs to be acknowledged:

* Dr GR Backeberg
* Dr GC Green
* Dr JP Green
* Prof JJ Human
* Prof LK Oosthuizen
* Mr FB Reinders
* Dr DM Scotney

Several editorial subcommittees, each under the convenorship of a member of the Editorial Committee, guided the process of reviewing papers within the various disciplines. Sincere thanks are due to all members of subcommittees and reviewers of individual papers for their valuable contributions to the preparations of these proceedings. A special word of thanks to Dr GC Green, in his capacity as Editor-in-Chief of the proceedings, who meticulously attended to the final editing thereby ensuring that this publication will meet the needs of the irrigation community of South Africa. The able assistance provided by Mmes Elaine Huyser and Gerda Kruger is also gratefully acknowledged.

It also needs to be mentioned that it would not have been possible to publish these proceedings in this format without the financial contribution of the Department of Agriculture of the South African Government. Through this contribution the Department clearly emphasized the importance of irrigated agriculture in the South African context and indirectly acknowledged the role of the irrigation research community.

In conclusion: Organising, presenting and concluding a symposium of the extent and standard of the Second National Irrigation Symposium, is a mammoth task beyond the capabilities of an individual. The Organising Committee of this symposium attended to this task with great enthusiasm and efficiency, thereby ensuring that this symposium was indeed a milestone along the road of irrigation in South Africa. I acknowledge the inputs of the Organising Committee, consisting of the following members, with great appreciation:

* Dr GR Backeberg
* Mrs E Esterhuyse
* Mr IL Forrest
* Dr GC Green
* Prof JJ Human
* Dr J Piaget
* Dr PCM Reid
* Dr DM Scotney

Signed: _____

DS VAN DER MERWE
Chairman, Organising Committee

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OPENING ADDRESS

Dr. A.I. van Niekerk
Minister of Agriculture and Agricultural Development, Republic of South Africa

"Of all occupations from which gain is secured, there is none better than agriculture; nothing more productive, nothing sweeter, nothing more worthy of a free man". These were the wise words of Cicero in days of yore. Whether he also had irrigation farming in mind with all the intricacies involved, will never be known. Today, however, irrigation is part and parcel of modern-day agriculture and it seems to be only appropriate to have a symposium with the theme: Irrigation research and development in southern Africa: past progress, present standing and future challenges.

All our attention is directed to the future. The past is history from which important lessons can be learnt. From the 66 papers and 28 poster papers to be presented over the next 3 days, we will hear of such lessons, of current affairs and of future needs and expectations. I honestly believe that at the end of the day we will agree with Shakespeare that "strong reasons make strong actions" and perhaps a move towards a well-defined irrigation strategy for southern Africa will result from this symposium.

Irrigation is defined as the artificial application of water to soil for the benefit of growing crops. Only when we analyse this definition, do we realise how comprehensive this single word is. Irrigation represents a highly complex practice involving the all-important soil-plant-water-atmosphere continuum. Furthermore, irrigation relies on sound engineering and economic principles which include important technological and sociological considerations. Finally, the manager - the farmer - is the key factor influencing the success or otherwise of an irrigation project. With the march of time it has become clear that three factors, namely *water*, *soil* and *human* resources are of vital concern to the future success of irrigation development in southern Africa.

We are honoured to have representatives from 7 different countries. A special word of welcome to Mr John Hennessy, president of the International Commission on Irrigation and Drainage. To all our visitors from abroad I wish to say that I trust that the rest of your stay in South Africa will be most enjoyable and rewarding and that you will not find us lacking in hospitality. May this visit be the forerunner of many more to come. We hope to lean strongly on your expertise to help us overcome problems like soil sodicity and waterlogging already encountered on 10% of our irrigated areas, and to promote water use efficiency. I am also convinced that your horizons will be broadened by what you see and hear of our experience in irrigation development.

In presenting data for southern Africa I specifically refer to the Republic of South Africa, the six self-governing states Lebowa, Kwazulu, Gazankulu, Kangwane, Kwandebele and QwaQwa and the Republics of Transkei, Bophuthatswana, Venda and Ciskei, collectively known as the Economic Community of Southern Africa or *Ecosa*. The *Ecosa* region covers about 122 million hectares or 4% of the African continent with an estimated population of 37 million or some 5% of the total population.

The region shares boundaries with neighbouring countries and as river systems and associated catchments generally disregard political boundaries, close co-operation and mutual support between all countries involved are essential. Far greater attention will need to be given to expanding current co-operative actions to ensure, above all, equitable distribution of water supplies and the protection of the water and soil resources for the benefit of all. It augurs well for the future that so many scientists and interested persons from all parts of southern Africa have gathered at this symposium to discuss important issues concerning irrigation.

You will agree with me that there is need for vertical expansion of agricultural production in southern Africa and that irrigation can make an important contribution towards achieving this. But irrigation farming, important as it may be, can maintain its rightful place in the economy of a country only when it is based on sound economic principles. When these principles are employed to utilise resources, it results in a significant contribution to national welfare, higher standards of living and general progress. It is, however, evident from experimental data that even top farmers can still improve on production by employing improved irrigation management. In this regard experts like you will have to decide whether your methods of technology transfer are effective and whether your experimental results can indeed be duplicated on the farm.

A review of natural resources and land utilisation of the *Ecosa* region reveals several important features. The region is characterised by great diversity and has limited potential for intensive agriculture. Arable land is restricted to between 11 and 15% within the region and water supplies are limited and already over-taxed in some catchments. The region also faces the consequences of an exponential population growth which will require a major effort in environmental management.

Deteriorating water quality resulting from urbanisation, industrialisation and other developments is, for instance, a matter of much concern to agri-

culture, especially in terms of the adverse impacts on valuable and scarce land suitable for irrigation. Deterioration of water quality through mineralisation, salinisation and pollution is regarded as a particularly important problem. With water a critical resource in southern Africa, every effort is needed to use supplies efficiently and to retain quality at the highest possible level.

Southern Africa's agricultural production is associated with several serious limitations. For instance, an estimated 65% of the *Ecosa* region receives rainfall of less that 500 millimetres per annum. There is also considerable variation in the intensity and distribution of rainfall. The vulnerability of agriculture with its important role in the national economy, as a result of its dependence on nature, is very evident. Periodic droughts cause catastrophic losses to agriculture in all parts of the region. Carefully planned and well-managed irrigation projects can be the major component in stabilising agricultural production even though this intensive enterprise is also seriously affected by severe droughts. Today, irrigation farming accounts for about 30% of the total crop production of the *Ecosa* region.

In the Republic of South Africa irrigated crop and pasture production are practised on close to 1 million of the 4 million hectare of high-potential arable land. Of this area 78% is permanently irrigated, 13% receives supplementary irrigation and 9% irrigated occasionally. The dominant method of irrigation is by sprinkler which accounts for 55%, followed by flood (33%) and micro-irrigation (12%). Irrigation farming meets the local demand for irrigation production and also provides for the export market.

Agriculture in South Africa is by far the largest user of available water and consumes some 50% of the total. Demands by other sectors such as industry, power generation and domestic uses will no doubt increase, but irrigation is likely to remain the major consumer for the foreseeable future. Domestic use and industry, as primary consumers, are of course favoured during times of shortage. Even under normal conditions, their expected demand for water will increase from 20% in 1990 to 27% in the year 2010. It must be borne in mind that in economic terms the yield achieved by agriculture per unit water does not compare favourably with that of industry. It is also alarming that up to 20% of the water used in irrigation systems at farm level, never reaches its destiny and that 10 to 15% of the water is wasted because of over-irrigation. Maximum crop yield per unit of water should therefore be the target. For this reason it is imperative that a symposium of this nature should strive to enhance water use efficiency, especially at farm level. The exploitation of scarce water and the energy required to deliver it, is important to every designer and irrigator.

To the best of my knowledge, the first ever irrigation congress in this country was held in 1909. It is therefore appropriate to again take stock of where irrigation science and technology currently stand and to assess outstanding research and development requirements in the light of the ever-increasing demands for limited water resources in a rapidly changing southern Africa.

A southern African irrigation strategy is necessary and it should be a united effort as the subcontinent has a very limited irrigation potential and an ever-increasing population to feed. I doubt that any of you do not believe in co-operation, but if you don't, consider what happens to a wagon that loses a wheel. Equally important, all involved with irrigation research, development and technology transfer should be committed to the highest possible standard of scientific excellence.

This symposium was organised by the South African Irrigation Institute in collaboration with the South African Society of Crop Production, the South African Institute of Agricultural Engineers, the Soil Science Society of South Africa, the Agricultural Economic Association of Southern Africa and the Water Research Commission. This reflects to what extent irrigation has a bearing on various other disciplines and that the solving of problems and the development of new techniques and systems needs a co-ordinated approach by all the parties involved.

We know that there still are many problems to be solved and much development that has to take place in the field of irrigation. Along with the technical there are also the policy aspects in terms of politics, socio-economics, conservation and other national aims that need to be addressed. Moreover there is the important aspect of technology transfer and specialist extension services to promote efficient irrigation that warrants particular attention. I am sure that this symposium will contribute much to clear the way along which irrigation will have to develop to meet the pressing current needs and those of the future for the benefit of the whole of southern Africa.

In conclusion I would like to thank the organisers of this symposium and again compliment them on a task well done. Many thanks also go to the various sponsors who have generously supported the venture. A special word of thanks goes to those who will chair the different sessions, and to those who are committed to formal presentations. My very best wishes to each and everyone of you for a most successful symposium.

SPOTLIGHT ON IRRIGATION DEVELOPMENT IN THE RSA: THE PAST, PRESENT AND FUTURE

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Abstract

The RSA has an annual average rainfall of 475 mm, with 60 percent of the country getting less than 500 mm. Therefore, irrigation has always been in the spotlight. Approximately 1.2 million ha are under irrigation, but no large scale expansion seems likely, as the country is expected to run out of surplus surface water by the year 2020.

The early irrigation history is vague. There is some speculation as to the possibility of Van Riebeeck having irrigated the first vegetable garden. However, definite reference is made to small scale irrigation development along the Olifants River during 1797. By the end of the 18th century, irrigation in the Eastern Cape had been described by travellers. The formation of a Hydraulic Section in the Cape Colony during 1875 and the first Irrigation and Water Conservation Act promulgated during 1912, endeavoured to solve the problem of earlier unco-ordinated development. Large scale development took place during the early part of the period from 1912 to the present. Reference to lower than expected runoff, droughts and farmers unable to repay development debts, are found as early as 1923. The depression of the 1930's, the system of share-cropping and the second world war, resulted in large scale unemployment. During this period irrigation schemes, such as Boegoeberg, Vaalharts and Rietrivier were developed for short term employment during construction, and long term employment through settlement. The plots were small, but natural consolidation took place during later years. From the 1960's onwards, irrigation development was co-ordinated by the inception of inter-departmental liaison committees. Irrigation research results indicate a relatively low irrigation efficiency in certain areas, with waterlogging and salinisation occurring on 11 percent of the total area irrigated. Crop production levels are disappointingly low. With regard to the future, the expected shortage of water could lead to rationing between sectors of the economy. With a gross geographical product of one-sixtieth that of mining, a strategy for future irrigation development will have to concentrate on a higher production per unit of water. One of the biggest challenges to face irrigation farming in the future, will be the production of food at affordable levels, while still remaining economically viable. A strategic plan for irrigation development is strongly suggested and should *inter alia* include projections of availability of water at economic cost, upgrading of existing schemes versus the building of new schemes, strategies for dealing with uneconomically small farms, policy on dealing with schemes where regular water shortages occur and the future training of prospective irrigation farmers as well as pro-active technology transfer.

Introduction

The RSA is relatively dry, with an average rainfall of 475 $mm.a^{-1}$ (Du Pisani, A.L., S.A. Weather Bureau, Pretoria. Personal communication, 1990.) with 60 percent of the area receiving less than 500 $mm.a^{-1}$ (Scotney, Volschenk & Van Heerden, 1990). For this reason, full scale and supplementary irrigation has always been in the spotlight as a means of increasing food and fibre production for both humans and animals.

To provide a perspective on irrigation development in this country, this paper reviews irrigation development from the time of the founding of the country by Jan van Riebeeck in 1652, when a garden, presumably irrigated, was laid out for the production of fresh fruit and vegetables, to the present, with more than 1.2 million ha now being irrigated (Anon., 1989; Scotney, *et. al*, 1990). The paper also suggests a basis for strategic planning of future irrigation development, bearing in mind that the RSA is expected to have exploited all surplus usable fresh surface water by the year 2020 (Anon., 1986).

Early history

The early history of commercial irrigation development during the period 1652 to 1912, when the first Irrigation and Water Conservation Act was promulgated, is vague. Irrigation along the Olifants River in the western Cape Province is a typical example of such development. The first farm in that area was given to a certain Pieter van Zyl in 1732, and by 1797 travellers described small scale irrigation in the area. By 1862, the first surveys were made with the aim of irrigation development along the river and by 1911 an irrigation district was proclaimed.

Construction of a weir and canals started during 1913 and these were completed by approximately 1923. The construction of the present dam at Clanwilliam took place between 1932 and 1935. Within 20 years of completion of the dam, a shortage of water was experienced. This State Water Scheme is presently one of the big six in the country, with a scheduled area of 9 300 ha, subdivided into 1 022 properties. By 1962 the Olifants River valley was inhabited by approximately 13 000 people (Nieuwoudt, 1962).
References to irrigation development and good wheat crops under irrigation in the eastern Cape Province can be found in journals of travellers from as early as the end of the seventeenth century, a good example of which is found in the journal of Paravincini di Capelli, *aide de camp* of Governor De Mist, written in 1803

(Van Heerden & De Kock, 1980).

References to irrigation development by missionary societies for indigenous people are also found, a case being the development of irrigation at Cambria on one of the tributaries of the Gamtoos River in the Eastern Cape, which first took place between 1827 and 1840 (Malan, 1970).

This early period is mainly characterised by uncoordinated private irrigation development. The formation of a Hydraulic Section during 1875 under the Commission of Public Works in the Cape Colony, led to more orderly irrigation development (Anon., 1986).

Instances of large private irrigation development at the end of the last century and the beginning of this century have been found. For example the farm Riverton (Saltpansdrift) of H.J. Collett in the Cradock district, was scheduled for 857 ha of irrigation during the first quarter of the present century. During the same period, Golden Valley Estates in the Somerset East district was scheduled for 2 056 ha, and Houghamdale Estates in Golden Valley was scheduled for 1 143 ha. In certain existing irrigation board areas, for example those of Halesowen and Gannavlakte, the canals currently in use were built during 1875 and 1862 respectively, and apart from some upgrading, are as they were originally constructed. All these properties and irrigation boards are to be found on the banks of the Great Fish River (Van Heerden & De Kock, 1980).

During this period some towns supplied water for irrigation to certain plots within the municipal boundaries. When the town of Cradock, for instance, was founded during 1814, fairly large plots with irrigation rights where laid out. These plots were supplied with water after completion of the town weir during 1816 (Van Heerden & De Kock, 1980). Some of the older towns in the country still have water furrows (canals) along streets, from which owners can divert water for irrigation onto their properties at certain times of the day or week.

1912 to present

From 1912 to 1930 : Early co-ordinated development

During this period, large scale irrigation development took place, which included the construction of such schemes as: Great Fish (Lake Arthur and Grassridge Dam), Clanwilliam (Clanwilliam Dam), Graaff-Reinet (Van Rhyneveldspas Dam), Lower Sundays River (Lake Mentz), Hartebeespoort (Hartebeespoort Dam). Most of these dams were constructed as Irrigation Board schemes, but as in the case of both Lake Arthur and Grassridge, the irrigators were unable to meet the repayments because of drought, lower than expected runoff, and the depressed economy of the 1930's. In most cases the State wrote off the outstanding amounts (Anon., 1986; Van Heerden & De Kock, 1980). Reference to the problem of farmers being unable to repay capital development costs can be found in reports of meetings as early as 1923, where specific reference was made to the Great Fish River Scheme (Reitz, 1923).

The history of water supply by some of the dams built during the beginning of the twentieth century, gives the impression that runoff calculations were over-optimistic. During the period 1945 to 1956 Lake Arthur and Grassridge Dam could, for example, only supply an average of 1 850 $m^3.ha^{-1}.a^{-1}$ and 1 690 $m^3.ha^{-1}.a^{-1}$ respectively. Compared to the present assured water allocation of 13 500 $m^3.ha^{-1}.a^{-1}$, this gives some idea of the extent of water shortage that was experienced under the Great Fish irrigation scheme before Orange River water was first supplied by the Orange-Fish River Project during 1977 (Van Heerden & De Kock, 1980).

An interesting feature of irrigation development during the early part of the present century was that resident engineers, under whose guidance the larger works were constructed by irrigation boards, were provided by the former Department of Irrigation (Van Heerden & De Kock, 1980).

The 1930's and 1940's : The great depression and second world war.

The drought and the depression of this period led to much misery amongst the white farming community of the country, because the main thrust of the South African economy was in the rural direction. Many farmers went bankrupt and had to be accommodated elsewhere. The "bywoner" (share-cropper) which appeared in the early part of the century, added to the problem of an over-supply of homeless and unemployed people who had to be accommodated in some way. This problem had already been identified some years previous to the depression (Reitz, 1923). The surfeit of white, mainly unskilled, labour in depressed economy gave rise to the so-called "poor-white" problem. As a possible means of alleviating this problem, the State developed irrigation schemes such as Vioolsdrift, Boegoeberg, Rietrivier, Pongola, Vaalharts and Boskop with the socio-economic aim of creating jobs during the developing period in the short term, and of settling some of the people out of the "poor-white" sector in the long term (Anon., 1986).

One also finds earlier references to the "poor-white" problem and the development of irrigation schemes as one of the possible solutions offered, with regard to Van Wyksvlei and at Kakamas. At Kakamas, the State undertook the building of an irrigation scheme, with a certain Reverend Schröder as the leading personality. Construction of this scheme started during 1898 (Marchand, 1909). The contractors used rifles, to which spirit levels were attached, as instruments for determining the levels of the canals.

The plots on these socio-economic schemes were small. In some cases, the guideline for determining the size was to double the area which could be cultivated

by a farmer with one span of draught animals. The reasoning behind this approach was that one half of the farm could be intensively cultivated and cropped, whilst the other half could be used as a fodder production unit for the animals. In some cases, houses were built, so that the prospective farmer could virtually move into his house one day and start cultivating the next, with the certainty that his family had a roof over their heads (Myburgh, J., Personal communication, 1988).

A good example of such a development is that of the Rietrivier Irrigation Scheme. The possibility of developing a scheme in the dry south western part of the Orange Free State was first mooted during 1862, when the Inspector-General of Public Works of the Free State Republic tabled a report on the construction of a dam in the Riet River. Planning and discussion took so long that the decision to construct was only taken during 1934. In 1940 it was decided to develop an irrigation scheme of 5 800 morgen (4 900 ha) in the Jacobsdal district on the banks of the Riet River. Houses on the plots were built by Italian prisoners-of-war. During 1946 the first 40 plots were given to South African ex-servicemen who fought in the second world war, with a further 40 ex-servicemen being settled during 1947. The scheme was extended to include 121 plots by 1965. During 1944, the water quota was fixed at 24 inches per morgen per annum (700 $mm.ha^{-1}.a^{-1}$) and this was increased to 44 inches (1 280 $mm.ha^{-1}.a^{-1}$) during 1951, with the possibility of buying an extra ten inches per morgen per annum (440 $mm.ha^{-1}.a^{-1}$) (Visser, 1965).

This scheme could not supply enough water to the farmers, with the result that over a large number of years, a chronic water shortage was experienced. This led, inter alia, to the Orange-Riet River Scheme (Sarel Hayward Canal), which was completed during 1987 and which takes water from the P.K. le Roux Dam in the Orange River to the Riet River Scheme (Anon., 1987).

From the 1950's to the 1990's : Recent development

Because of the multi-disciplinary nature of irrigation, and because all aspects relating to irrigation development were handled by four State departments, a need arose for the creation of a co-ordinating body. During the fifties the "Interdepartementele komitee vir besproeiing en besproeiingsbeplanning" (IKBOB) and the "Interdepartementele komitee vir dreinering" (IKD) were formed. These two committees acted in an advisory capacity to the Ministerial and Chief Executive committees (Nieuwoudt, 1978).

They were replaced by the "Ministeriële Landbou-Waterwese skakelkomitee" (MLSK) and the "Departementele Landbou-Waterwese skakelkomitee" (DLSK) on the policy and decision-making levels and by the "Landbou-Waterwese skakelkomitee" (LWSK) during 1988. All relevant State Departments are represented on the LWSK. During 1989 the "Besproeiingsondersoekkomitee" (BOK) was added to the LWSK as a technical and economic co-ordinating and advisory committee. All irrigation development and upgrading are co-ordinated by these committees.

In an effort to improve irrigation design to an acceptable level, the South African Irrigation Institute was founded during October 1976. Irrigation designers, advisors and merchants of irrigation equipment were encouraged to join the seven regional branches of the Institute and to subscribe to its minimum set of design and advisory standards. The present membership totals 700. The Institute holds annual congresses, where the latest research findings and applications are discussed. The proceedings of these congresses are distributed to members. Since September 1979, a bi-monthly magazine has been published and distributed free of charge to members, with non-members also able to subscribe. Other professional bodies that concern themselves in some way with raising the level of irrigation efficiency, are the South African Societies of Crop Production and Soil Science and the South African Institutes of Agricultural Engineers and Civil Engineers.

Extension surveys in irrigation areas proved that a generally low level of irrigation efficiency, from both a managerial and design point of view, prevail. It was found by Van Heerden (1988) that the efficiency of irrigation in the Great Fish River irrigation area varied from 21 to 64 percent, with an average of 45 percent. This inefficiency leads to a wastage of irrigation water and suppression of crop yields and tends to increase input costs unnecessarily. Irrigation farmers tend to over-irrigate in winter and under-irrigate in summer. Coetzee (1967), in his study on irrigation farming along the Crocodile River, found that the average age of irrigation farmers was relatively high, educational level relatively low, and that they lacked ambition. These factors could be barriers to change and could be partly responsible for the existence of badly designed systems and a low level of irrigation management. On the other hand, a high level of ambition, a relative youthful age and better educational level could enhance the acceptance of better irrigation practices (Van Zyl, 1965).

Irrigation efficiency of citrus, in the Sundays River Valley, was estimated at less than 50 percent, even though the system of irrigation had a potential efficiency 90 percent (Shone, 1965). Streutker (1971) found that part of the waterlogging problem on the Vaalharts Irrigation Scheme could be ascribed to over-irrigation as a result of wrong irrigation practices.

The low level of irrigation efficiency found by Van Heerden (1988), combined with a relatively high age and relatively low educational level found by Coetzee (1967), could be some of the major reasons why Scotney, Le Roux, Van Heerden & Aucamp (1990) found disappointingly low average crop yields on irri-

gation schemes. Average wheat production varied from approximately 3.5 to approximately 5.5 $t.ha^{-1}$, that of maize varied from approximately 3 to 9 $t.ha^{-1}$ and cotton varied from approximately 2 000 to 2 500 $kg.ha^{-1}$.

Further problems encountered, especially on the older schemes, were that farms were laid out as neat rectangles or squares which looked good on a map, but did not take soil boundaries into consideration. On most of these schemes, virtually no provision had been made for surface water drainage. This resulted in excess water from irrigation or rain not being able to drain away and consequently increased waterlogging. Certain of these schemes were also planned to use flood irrigation systems, and over-irrigation took place to such an extent that salinity problems due to waterlogging were commonly found on all such schemes. Scotney *et al.* (1990) found, mainly on older irrigation schemes, that out of a total of approximately 665 000 ha under irrigation, 21 000 ha were subject to severe waterlogging and salinity problems, whilst less severe problems occurred on 50 000 ha.

As the construction of newer schemes progressed, further problems were experienced on some of the older schemes because plots were too small to form viable economic units and, in certain cases there was just not enough water available. To some extent, as was experienced along the Riet River and on the Vaalharts irrigation scheme, a natural tendency to consolidate land developed, with farmers enlarging their holdings by buying out other irrigation farmers in the vicinity.

During this period, the Republic's two major dams, namely the Verwoerd Dam (5 673 million m^3) and the P.K. le Roux Dam (3 236 million m^3), were built on the Orange River with part of their water storage capacity being allocated to the supply of irrigation water (Anon., 1986).

Inter-basin transfer of water and the upgrading of schemes, with the aim of ensuring a permanent water supply and of satisfying peak demand, also took place, for instance the further development of the Orange River Project, the Orange-Riet River Canal system and upgrading of the canals of the Vaalharts irrigation scheme (Anon., 1986).

In certain cases where the development of future State irrigation schemes was a good probability, the State stepped in and bought out so-called uneconomic farming units. During the early 1960's, approximately one-third of the area under irrigation along the Great Fish River was purchased in this way. After achieving an assured water supply via the Orange-Fish River tunnel (part of the Orange River Project), these farms were consolidated into economic units, ranging from 45 to 80 ha in size, and sold to new irrigation farmers during the late 1970's (Van Heerden & De Kock, 1980).

In launching new State irrigation schemes, a policy was followed whereby new, mainly young farmers were settled. Instead of the more usual practice of auctioning new farms, applications to purchase were invited. A board of adjudicators then selected the most promising of the applicants on the grounds of education, managerial ability, available capital and age, to become the new irrigation farmers. As a rule, the purchase price of new farms was very low, being, in many cases, only about one-quarter that of the market value of the properties (Myburgh, J., Personal communication, 1988).

Progress made since the National Irrigation Symposium (NIS), 1967

In the Proceedings of the NIS various important aspects regarding irrigation were identified which needed to be addressed. Certain remarks in this connection by Dr. S.J. du Plessis, at the time Policy Advisor to the Minister of Agriculture, are discussed in the following paragraphs (i to iv).

(i) Water requirements of crops

"While water consumption by irrigation plays such an important role in the water housekeeping of the Republic and the advantageous use of water in agriculture is so important, it is of the utmost importance that dependable, fundamental data regarding water consumption by plants be made available as soon as possible" (Du Plessis 1967). Today, 24 years later, water consumption data for most of the important crops have been obtained. These data, published as "Estimated Irrigation Requirements of Crops in South Africa" by the Department of Agricultural Technical Services and the Department of Water Affairs in 1973 and "Crop water requirements, deficits and water yield for irrigation planning in Southern Africa" by Dent, Schulze & Angus (1988) are, in general, very useful for the irrigation *planner*. For the irrigation *practitioner*, however, these data are guidelines only, requiring adjustments for micro-climatic conditions.

To help the irrigation practitioner, irrigation scheduling aids have also become available, often in the form of computer programs which estimate water consumption of crops using growth models and weather data. A large number of programs are available, each of which needs to be adapted to suit local conditions.

More investigations need to be done to identify *suitable* computer programs for *specific* applications and *guidelines* must be provided to help practitioners to successfully implement these scheduling aids. The conclusion is that significant advances have been made over the last 24 years, but further progress is needed.

(ii) Crop Selection

"It should be considered whether it is justifiable to produce crops like maize under irrigation when it is already produced in profusion under rainfed condi-

tions. Priority should be given to the production of commodities which are not produced in sufficient quantities or for which profitable markets can be found in the Republic or overseas" (Du Plessis, 1967).

This statement is as true to day as it was 24 years ago. However, there has been a shift towards more intensive crops and orchards in many areas. Good progress has been made.

(iii) Irrigation methods

"Sprinkler irrigation has been propagated by experts on many occasions as a method which can facilitate judicious irrigation. This method of irrigation, however, seems too slow in gaining acceptance on many of our irrigation projects" (Du Plessis, 1967).

It is true to say that about 33 percent of all irrigated land in the Republic is today still flood-irrigated, mostly on the heavier soils. Although centre pivots, specifically, enjoyed much acceptance by farmers on the lighter soils, present economic realities of high interest rates and low commodity prices have curtailed this popularity. The situation in this country is therefore much as it was 24 years ago, with flood irrigation still very much in the foreground.

(iv) Labour and mechanisation

"The position today is that many small irrigation farms are each separately equipped with a truck, tractor, and cultivation and harvesting implements of great diversity. This equipment now costs so much in terms of interest, redemption, maintenance and fuel that, converted to capital investment, it adds up to thousands of Rand per hectare" (Du Plessis, 1967).

The plea was for irrigation farmers to resort to contractors for their mechanisation services. Apart from the use of contractors for harvesting wheat or cotton, the only other contractors used by farmers on irrigation schemes are installers of sub-surface drain pipes. Very little, thus, has changed!

Irrigation schemes

At present three types of irrigation exist, namely State water schemes, Irrigation Board schemes and private schemes.

State water schemes

On these schemes the State is solely responsible for the development of the scheme and is the controlling body for water distribution, upkeep of the infrastructure and for new construction. The land, however, is privately owned. On most of these schemes rates payable by irrigators do not cover the administration costs of the schemes, and are also inadequate for capital redemption and interest. It has been calculated that the average water rates vary between 0.5 and 1.2 percent of the gross yields of plots, whereas the operating and maintenance costs, excluding interest on capital, vary from 1.5 to 2.5 percent of gross yield. On average, water rates currently cover on the average about 30 percent of the annual operating costs and make no provision for interest and redemption of capital.

These schemes comprise approximately 19 percent of total area under irrigation.

Irrigation Board schemes

On these schemes irrigation boards, consisting of irrigation farmers within the irrigation district, are in control of construction, upkeep and the day to day running of schemes. The irrigation boards qualify for a subsidy on the construction of new irrigation schemes and in some cases on the upgrading of their infrastructure. Because of the high cost of upkeep and new construction, it is often found that the infrastructure on these schemes are substandard and canal losses are in excess of 30 percent (K.O. Bang, Personal communication, 1987).

These schemes comprise approximately 22 percent of total area under irrigation.

Private irrigation farmers (schemes)

These vary from very small (< 10 ha) on-farm schemes to fairly large (> 2 000 ha) privately owned or communal schemes. The owner or owners of the scheme are responsible for construction, upkeep and control on the schemes. As private owners, they can qualify for a limited subsidy on construction expenses. These schemes comprise approximately 59 percent of total area under irrigation. Scotney *et al.* (1990) found the following relative importance in respect of different methods of irrigation:

Systems	Percentage of area
Flood and related systems	33%
Sprinkler systems	55%
Micro- and drip systems	12%
Type	
Permanent irrigation	78%
Supplementary irrigation	14%
Opportunistic irrigation	8%

Permanent irrigation is used where crop production is completely dependent on irrigation, *supplementary irrigation* where crops can normally be grown under rainfed conditions but would respond well to additional water, and *opportunistic irrigation* where sufficient surface runoff water can only be stored on an irregular basis. The latter situation is normally found in the dry western parts of the country.

The optimal use of water is of great importance in the RSA because the country is prone to regular droughts and suffers from prolonged water shortages. The Department of Water Affairs has the following to say on this subject: "The key to optimising the use of water resources of the Republic of South Africa often lies in identifying and improving our understanding of

the increasingly complex dynamic factors and inter-relationships involved. Water research has made great progress in the RSA during the last decade and is co-ordinated by the Water Research Commission (WRC). The organisations most active in this field of research are various institutes of the Council for Scientific and Industrial Research (CSIR), the Department of Water Affairs and the universities" (Anon., 1986). The WRC was established as an autonomous statutory body in terms of the Water Research Act, 1971 (Act 34 of 1971) for the advancement, co-ordination and funding of research in connection with water matters in the RSA and for promoting the dissemination and application of research findings. Research topics funded by the WRC and which could be related to agriculture in general and irrigation in particular, include: surface water hydrology, ground water, hydrometereology, irrigation and salinisation.

Apart from research being funded by the WRC and undertaken by the various abovementioned bodies, the Department of Agricultural Development funds its own irrigation research. During 1988, 113 personnel were involved in 70 research projects, at an estimated annual cost of R5 000 000 (Van Zyl, Backeberg, Beukes, Nel & Nortje, 1989). Research subjects include:

* crop water requirements	43 %
* soil-crop-atmosphere water relations	28 %
* soil	10 %
* engineering and water distribution systems	7 %
* irrigation economics	6 %
* development and monitoring of irrigation schemes	3 %
* drainage	1 %
* saline/alkaline soils	1 %
* irrigation efficiency (management)	1 %

A multi-disciplinary co-ordinating committee of the WRC, the Co-ordinating Committee for Irrigation Research (CCIR), annually reviews all research relating to irrigation on a national level with the aim of co-ordinating irrigation related research between different institutions and disciplines.

As stated earlier, the water resources of this country are very limited, and coupled with that is the fact that the cost of developing large State irrigation schemes has increased to a 1986 estimate of R10 000 to R15 000 per ha (Anon., 1986). The number of new State irrigation schemes being developed is thus rapidly decreasing. It seems likely that the only State schemes that will be developed in future, will be schemes where aims other than economic, such as political or socio-economic needs, will be satisfied. It also seems likely that this will only happen where the other considerations far outweigh the problems of creating a "subeconomic" irrigation community or of an assured water supply.

Because of the limited availability of water and high estimated cost of new irrigation development (R10 000 to R15 000 per ha), current development is and should be confined mainly to the maintenance and upgrading of existing schemes. In the case of Vaalharts and Taung irrigation schemes, the cost of the upgrading the main canal which is presently under way, is estimated as R2 500 per scheduled ha, which is obviously far lower than the cost of new development (Badenhorst, M.J., Department of Water Affairs, Pretoria. Personal communication, 1990).

The present demand for water exceeds the supply in all areas of the country, except the Orange River and rivers along the eastern and southern seaboard of the country. An interesting feature is that the expected excess of water in the Orange River will be more or less equal to the expected demand for extra water out of the Vaal River basin by 2020 (Anon., 1986).

Because of the nature of agricultural production under irrigation, water use is very high per unit of income and therefore irrigation farming as an industry compares unfavourably with other sectors of the economy. For example it was found for the Vaal River area that the gross geographic product (GGP) per cubic meter of water was only R1.23 per m^3 of water, compared to R22.03 for electricity, gas and water supply, R47.72 for manufacturing and R70.92 for mining (Anon., 1986).

Figure 1 shows the relative GGP in terms of R/m^3 water between agriculture and some of the other sectors of the economy.

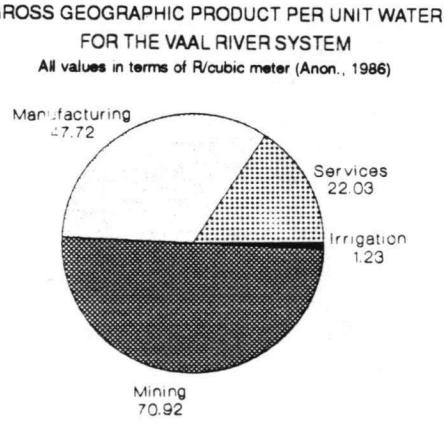


Figure 1 The relative geographic gross product for the Vaal River area of irrigation compared to services and manufacturing.

The future

The trend of estimated future water use compared to the availability of water in terms of usable surface water is depicted in Figure 2 (Anon,. 1986).

This is a graphic representation of the estimated available usable water for the period 1980 to 2010, compared to the estimated water requirement of different sectors of the economy for the same period.

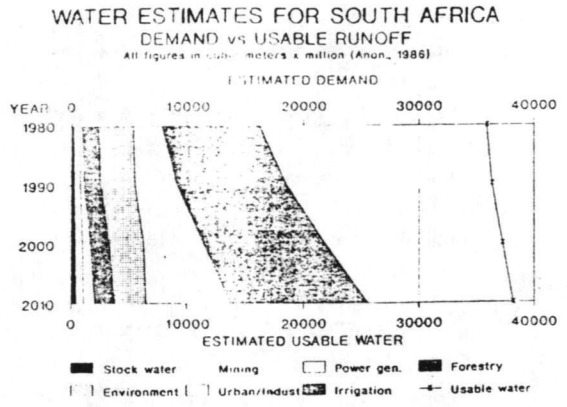


Figure 2 Estimated usable water (runoff) compared to the estimated water demand for different sectors of the economy for the period 1980 to 2010.

The estimated total demand for water increases rapidly from 1980 to 2010, while the quantity of usable water increases very slowly. The fast decreasing gap over time between usable surface water and total demand indicates that the country is fast running out of excess usable water, and it could be foreseen that a time will come when water will have to be rationed between the different sectors of the economy. The urban sectors and industry have the highest growth rate in usage, while the water usage by irrigation will increase from 24 percent of total usable water during 1980, to an estimated 31 percent during 2010 (Anon., 1986).

To determine ways of alleviating the problem of water shortages in some areas, the major thrust of present hydrological studies and evaluations of future scenarios by the Department of Water Affairs concern the inter-basin redistribution of water as a way of balancing supply and demand (Anon., 1986).

Looking into the future, one can expect irrigation to compete for water with all other sectors requiring water, and that the relative importance of irrigation on an economic, political, social and even strategic level will determine what percentage of the "water pool" can be allocated to irrigation.

From the agricultural point of view, it has become imperative that a *strategic plan for future irrigation development* should be developed as soon as possible. This strategy should concentrate on a future scenario in which water supply to the agricultural sector might not be as freely available as during the past. The strategic plan should take cognizance of the fact that food should always be affordable to the population at large without the necessity of large scale subsidisation of production and that, individually, each new scheme should be economically viable. Such a strategic irrigation development plan should take full account of at least the following:

* Future availability of water for irrigation and at what cost.
* A drastic policy change to the effect that existing irrigation schemes should be upgraded before any major new irrigation schemes are considered and a strong recommendation that large scale capital investment in new irrigation schemes should be discouraged.
* A meaningful water plan for dealing with the regular water shortage on some irrigation schemes, a historic phenomenon which is being repeated on many modern irrigation schemes.
* A plan for dealing with the problem of uneconomic units still found on many of the older irrigation schemes, possibly by adopting alternative cropping patterns based on well-adapted, high income crops.
* A definite plan for dealing with non-viable irrigation schemes that constantly look to the State for aid to keep them going.
* A plan for achieving a higher agricultural production per unit of water, whilst at the same time ensuring "economically viable" production levels for the farmer. The emphasis of agricultural research and extension should shift to *strategic irrigation and water conservation methods* instead of the present approach where virtually all research, extension and design is based on the assumption that enough water for irrigation will always be available.
* The recently drawn up report concerning the development of a strategy for food supply and food production for the RSA and in which the extent and condition of the natural resources as well as the present and potential production levels of agricultural crops under irrigation in different areas are fully described, *should form the basis for any future planning of irrigation development.*
* Any future irrigation policy should go hand-in-hand with a strategy for the training of future irrigation farmers as well as pro-active technology transfer to existing and new irrigation farmers.

Conclusion

South Africa is a land with a history of water shortages, and a prognosis of future spells of water shortages. Irrigation has always played an important role and it can be expected to go on being important. Economic factors will play an increasingly important role in providing significant signals as to *where*, *what* and *how* much agricultural products (food) should be produced under irrigation.

Let it never be said:
We did not plan to fail
We just failed to plan

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WATER RIGHTS AND THE MARKET FOR WATER: THE WESTERN USA EXPERIENCE

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Abstract
Recent fiscal and environmental pressures have brought pressure for change in USA water policy. Indeed, unusual coalitions between fiscal conservatives and environmentalists have halted federal water projects and encouraged increased use of water markets. The result is that western water law in the USA is rapidly moving in the direction of free water markets. This form of "free market environmentalism" is encouraging more efficient allocation of water for off-stream and instream uses and promises to improve water quality. Lessons from this experience in the American West are valuable for water policy around the world.

Introduction

Institutions governing water use throughout the world evolved during an era when diversion for agriculture was dominant. In semi-arid environments where it was necessary to take the water to the land, diversion or extraction from a water course marked the main form of beneficial use. In the western U.S., for example, 80 to 90 percent of all water consumed is consumed in the agricultural sector. Even in California with a burgeoning metropolitan population, agriculture still consumes 85% of the total.

Only in recent years have instream uses of water began to compete with traditional extractive uses. Early demands for instream use were for navigation, but these were often confined to coastal regions or large rivers where water scarcity was unlikely to create a binding constraint on other users. Flows to generate power with water wheels became one of the first instream uses recognized by the law. In industrial areas like the northeastern U.S., water law allowed precedence for mill owners who stored water, sometimes diverting it short distances to their mills. Eventually, such power generation demand increased and hydroelectric power generation took its place along the agricultural, municipal, and industrial users. Though rights to use streams as conveyors of effluents were not explicitly recognized like other instream uses, this use of instream flows has expanded as environmentalists have asserted that instream flows produce biological, recreational, ecological and aesthetic benefits. With growing incomes, people have more time to enjoy recreational and aesthetic opportunities associated with water. Since these values are tentatively new to the scene, the process whereby they will be integrated into the overall allocation of water among competing uses is only beginning to evolve. Some legal settings have been flexible enough to find a place for instream uses, while others, especially those where water is more scarce and where extraction is the lifeblood of the community, have not.

At the same time the demand for instream flows has been growing, water allocation among traditional uses has been increasingly determined by market forces. In the western U.S. where urban demands are placing the most pressure on water supplies, dominant agricultural users are being offered large sums for their resource. The highly acclaimed exchange between the Municipal Water District (MWD) of southern California and the Imperial Irrigation District (IID) has shown that conflict over who gets the water can be replaced with cooperation as competing users gain from trade. Water farming in Arizona where municipalities purchase farms and retire the land or at least switch it to less water intensive agriculture provides another example of water markets at work.

There are basically three reasons why water marketing has become a more acceptable method of allocating this scarce resource. First, growing demands, especially from urban centres, have increased the scarcity of water and brought pressure for reallocation from traditional agricultural uses to municipal and industrial uses. Second, expanding supplies to meet these growing demands is no longer a viable alternative. In the past, national governments have formed complex and cumbersome bureaucracies around the storage and delivery of water, especially to agriculture. Fiscal constraints, however, have put a cap on this approach. In addition, the subsidized storage and delivery of water in the past has led to some of the worst environmental disasters. Reservoirs are silting in, dams are being found unsafe, drainage waters are killing wildlife, and regulated river flows have threatened or eliminated fish populations. Hence any new schemes to increase water supplies with concrete and steel meet substantial opposition from the environmental movement. If the days of expanding supplies are gone and new demands are being expressed, we have no alternative but to reallocate water among the competing uses, and markets provide one instrument for doing this.

To understand the policy options for accomplishing this reallocation, this paper will provide a framework for considering the peculiar problems of water allocation in a hypothetical water basin. The analysis will begin with a simple case where uses compete for water consumed and where good hydrological information allows identification of potential third-party impairment. From this relatively simple case, we will move to more complex issues of instream flows

and less complete information. Within the context of the analytical framework, various legal instruments for allocating scarce water between offstream and instream uses in the western U.S. will be reviewed. Alternative arrangements for establishing legitimate claims will be examined, regulatory controls for guarding third party impairment will be considered, and the limits of water marketing will be discussed. The paper will close with a summary of the necessary conditions for water marketing and with some suggestions for how government can facilitate voluntary transfers.

An analytical framework

Any consideration of alternative water institutions must begin with an understanding that optimizing water use depends on comparing its marginal or incremental value in different uses. Marginal value is the change in the total value of output resulting from a small change in the amount of water used in the production of that output. For example, if a small quantity is taken from hydroelectric production, the marginal value of water will be the value of the electricity production given up. Similarly, if a small amount of water is taken from agricultural use, its marginal value will be a function of the value of agricultural produce foregone. The marginal concept is no less applicable to the enhancement of instream flows, but because there is no market for these flows, determining the marginal value is more difficult.

Understanding the importance of marginal value helps avoid fallacious reasoning regarding what will happen if one use values water more highly than another. Suppose that municipal users are willing to pay $500 for a unit of water while agricultural users are willing to pay only $50[1]. Agricultural users fear that such differential values suggest that reallocating w r to its highest valued alternative would result in no water for agriculture. Marginal thinking shows why this is incorrect. As more water is moved from agricultural uses to municipal uses, the marginal value of the agricultural use rises and the marginal value of the municipal use declines. This results because of what economists call diminishing returns. The net result is that marginal values converge long before all water is reallocated from one use to the other. Even in instream flows there is a hierarchy of values which creates diminishing returns. For example, if only a little water were available for instream flows, it might be used for preservation of endangered species habitat or spawning beds in small streams. But if more water became available, it might be used to provide recreational or aesthetic benefits.

With the concept of marginal value in mind, we can develop a framework for considering various institutions for optimizing water use. Begin by assuming that the only water uses are those where water is extracted from the system and that once it is consumed, it is no longer available for other uses. As shown elsewhere (Anderson & Johnson, 1986), optimization for such extractive uses requires that the net marginal value product of consumptive uses be equal across all uses. If the additional value of water consumed in any use along the stream exceeds that in another, reallocation of the water to the higher valued use will increase the overall value of the resource.

The problem is complicated once the possibility of non-consumptive uses are introduced. For example, consider the value of instream flows like hydroelectric production. Unlike water consumed by a crop, water run through a turbine can be used and reused for this purpose along the stream's course. Hence the incremental value of water in hydroelectric production is additive[2].

A similar case can be made for recreational, environmental, or aesthetic instream values. When a stream has both extractive and instream uses, optimization requires that the marginal value of an extractive use where the water is consumed and not available for other uses be equal to the summation of the marginal values for all instream uses. In this case additional consumption not only impacts flows immediately below the point of consumption but at all downstream points. Hence with the introduction of instream flow values, optimization would call for less consumption at the head of the water course and more at the bottom.

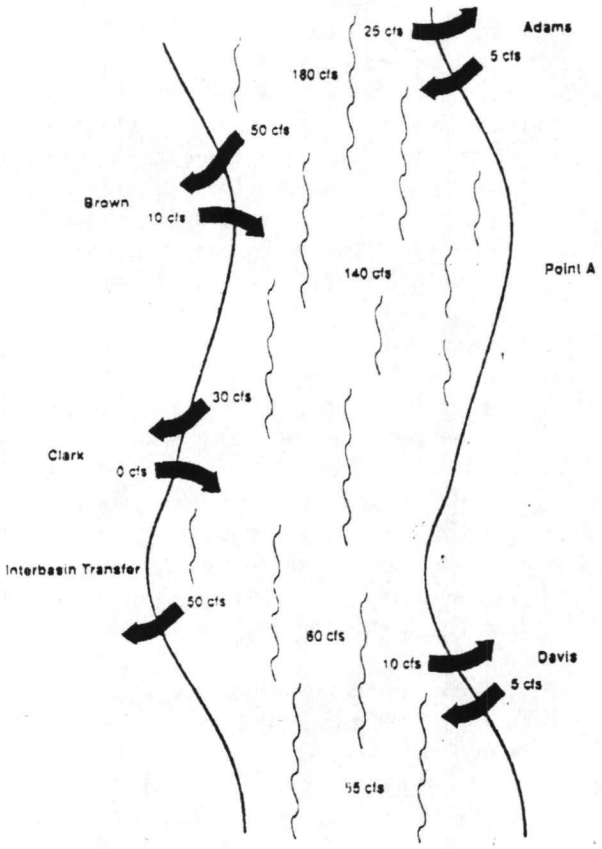
Consider the implications for the hypothetic stream shown in Figure 1. Suppose that Adams values water at $10 per cfs (cubic feet per second) while Clark values it at $20. In this case reallocating water from Adams to Clark would increase the total value of water in the basin. Now suppose that an additional cfs would generate $15 worth of electricity flowing at both Point A and at the bottom of the stream. The marginal value of this water would be $30. The total value of water could be increased by reallocating water from consumptive uses at the upper end of the basin to hydroelectric production. Since consumptive uses below the lower point of electricity production would not compete with the non-consumptive use, marginal values of consumption could be less than $30 below that point.

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[1] Figures in this order of magnitude are approximately correct for an acre foot of water in California. 1 acre foot = 1 234 m^3.

[2] Such uses are referred to as "public goods" because one use does not preclude another. Being a public good in the sense that values are additive rather than competitive does not necessarily mean that the good must be provided by the public sector. For example, once a movie is shown at a theatre, it can be enjoyed by many viewers; their individual values are therefore additive, not competitive. Nonetheless, the movie can be provided by the private sector.

Figure 1 Surface water basin: 200 cubic feet per second (cfs).



Potential for market allocation

With the context of this simple optimization framework, we can examine the institutional arrangements necessary for achieving optimal water use. Of utmost importance is how water values will be determined. Markets have proven their efficacy for determining values through bargaining between willing buyers and willing sellers of well-specified ownership claims. Relying on information that is time and place specific to their situation, sellers evaluate the marginal value of water relative to offers from buyers.

Consider the potential for allocating water for extraction via markets. Since extraction especially for agriculture requires diverting more water than is consumed, extractive rights must specify both the quantity diverted and the quantity consumed. The reason for this specification is that the difference between diversion and consumption is a return flow that can be used by downstream users. In Figure 1 all points of extraction reflect these diversions and return flows. With these specified it is possible for any user to sell to another when marginal consumptive values diverge. Obviously, the first institutional constraint on a well functioning water market is the ability to specify and enforce these rights. Such specification requires knowing stream flows, diversion requirements, consumption coefficients, return flow patterns, and other complicated hydrological information. In short, specifying rights places an important burden on governmental agencies responsible for such specification.

To the extent that good information is lacking on the hydrology of a water basin, it will be more difficult to specify rights. However, as individuals make claims to water, information is generated. Extracted water with return flows moves through the ground at a variety of rates. Only when extraction has occurred can specific information be generated. If one claimant alters his place and amount of extraction, it will behove others who are potentially impaired to prove what impact this has. Similarly, information on flows comes from long histories of basins. Often it is the claimants in the basin, rather than the hydrology experts, who have this type of information because it is they who must be prepared for uncertainties associated with variations in flows. The short of this is that hydrologic information necessary for specifying water rights is not necessarily something that is the domain of a centralized agency; time and place information from water claimants may be invaluable in the specification of rights.

Another problem with establishing water rights is what has been referred to as "the race for the pumphouse". Recognizing that water may have value in the future even if it does not today, potential users may put water to use prematurely in an effort to establish legitimate rights in the future[3]. Since premature water use can have significant implications for investment and for stream hydrology[4], developing institutions that discourage the race to the pumphouse is important. Unfortunately, as long as there are future values that are "up for grabs", it is worth it for water users to invest in premature use or to lobby government to establish their claim. In either claim expensive "rent seeking" can occur[5].

Assuming that rights can be specified without significant rent-seeking costs, there is still the problem of guarding against third-party impairment. If all of the water in a stream is claimed and if an individual attempts to sell more than his consumptive right, he will be, in effect, stealing from other owners. The process must provide a way for guarding such impairment.

Another source of impairment exists if there is binding flow constraint on the stream. Referring to

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[3] For a complete discussion of "the race for property rights", see Anderson & Hill (1990).

[4] It should be noted that the problem may even be worse for groundwater use. See Anderson, Burt, & Fractor (1983).

[5] For a simple discussion of rent seeking see *The Economist*, "Dear Landlord", February 9, 1991, pp. 75-76.

Figure 1, assume that diversion and consumption rights are specified as shown and that another user establishes a consumptive claim to the remaining 55 cfs at the bottom of the basin. If the owner of the 55 cfs were to move his point of extraction and consumption upstream from Davis, the total flow would be reduced to 5 cfs, not enough to meet Davis' extractive right. Davis would have a legitimate claim that he is impaired. Again before such a transfer of water would be allowed, legal mechanisms would determine whether there would be impairment.

A binding flow constraint would also result if an instream flow claim for 140 cfs was established at Point A. In this case any increase in consumption above Point A would impair the instream claimant and reduce the flexibility in transferring extractive rights.

There are factors, however, which reduce the problems stemming from the binding flow constraint caused by instream flow claims. Claims to instream flows in the upper reaches of a river would create fewer problems because diversions could take place at fewer upstream points. Likewise, claims to instream flows near the mouth of a river would have little impact because they would be subject to upstream consumptive rights. Finally, the problems would be mitigated if consumption rights could be transferred without impairing instream claims. For example, suppose that Adams wanted to increase his consumption of water and could purchase a consumption right from Clark or Brown. If he purchases it from Brown, there will be no impairment.

Therefore, if many users hold consumption rights between the desired point of increased consumption and the instream flow claim, there would be little reason to acquire the rights to flows at lower points and transfer them upstream.

Nonetheless, given this potential for impairment created by instream flow claims, it is easy to understand why extractive users and courts have traditionally opposed simple claiming of water for instream values except hydroelectric production[6]. Most water uses require some investment to establish use. For example, farmers must divert water and apply it to their crops; hydroelectric producers must build storage facilities and divert their water through turbines. However, claiming unappropriated water for recreational, environmental, or aesthetic purposes would require no investment, making it possible for instream flow appropriators to opportunistically claim water and to significantly reduce the flexibility of reallocation. While there is good reason for restricting the simple claiming of water for instream uses by either private or public entities, there is less reason not to allow willing buyers to purchase or lease existing consumptive rights for instream uses. Since such transactions would require would-be instream flow demanders to do more than simply claim water, there would be some test of whether it is really worth reallocating water from extractive uses to instream uses. To be sure, such transactions would be complex because of the enormous potential for impairment. If consumption rights are clearly specified, only those rights could be converted to instream uses. However, since there will always be some question of how much is actually consumed, how much water can be sold will always be in question. Moreover, if diverters act collectively in their diversion and application of water, any action by a single owner may affect the others. For example, suppose that a certain amount of diverted water must flow through an irrigation canal to provide a sufficient head of water to supply all users along the canal. If individual diverters sell their consumptive rights and stop sending them through the canal system, other users along the canal may be impaired. Any institution allowing for water marketing for any purpose must guard against these types of impairment.

Before reviewing institutions for allocating water, the use of streams for waste disposal must be introduced. Instream flows provide a medium for discharge and are able to assimilate wastes. If stream flows can be augmented, this assimilative capacity increases. In recent years, public policy has been aimed at specifying levels of pollution and regulating discharge. In an effort to reduce the cost of meeting pollution standards, however, governmental agenc have been looking for market mechanisms such as tradeable discharge permits (see Anderson & Leal, 1991). Once acceptable levels of pollution are determined and discharge permits are distributed, markets can allocate the permits. New sources of pollution can purchase permits from existing polluters, paying them to reduce their pollution or paying for pollution control equipment. Even environmental groups can enter the market, bidding for and retiring pollution permits.

As with other water marketing, regulatory mechanisms must guard against impairment caused by pollution permit transactions. Suppose that an individual is granted a discharge permit along a stream course and that all of the other water in the stream been appropriated for extraction or instream flows. Any effort to move the discharge permit upstream will reduce water quality between the old and new points of discharge thus harming existing water users. Any attempt to move diversion rights upstream will also have third-party effects because a decrease in the flow of water at the point of discharge will reduce water quality.

None of this is to say that discharge permits cannot

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[6] For a complete discussion of the problems of allowing private appropriation of instream flows and of examples of how courts in the U.S. have responded to this see Anderson & Johnson (1986).

contribute to market allocation. With discharge rights clearly specified, those desiring less pollution can purchase and retire existing permits so as to reduce the level of discharge. If a discharge permit is moved upstream, it will be clear who is creating the harm and it will be possible for the polluter to compensate those who are harmed[7]. Similarly, if a diverter wishes to move his point of diversion above the discharge permit, he can pay the polluter to reduce discharge or compensate the downstream rights holder who are harmed. The important institutional requirement is a legal hearing process wherein those who may be harmed by the transfer can demonstrate harm and be awarded compensation or injunctions. Common law precedent provides the model for how this can work. Like other instream flow institutions, however, markets are only beginning to evolve making institutional experimentation necessary.

It should be noted that well-specified rights for offstream or instream uses also can help solve pollution problems because owners of these rights have an incentive to monitor water quality and attempt to collect damages where they occur. This is illustrated nicely in Great Britain where fishing rights are privately owned by individuals and groups. The Anglers' Cooperative Association which represents a multitude of owners, has pursued more than 1 500 cases involving pollution and successfully obtained injunctions to stop pollution or received damage awards for pollution resulting from warm water discharge, sewage, and siltation (Anderson & Leal, 1991, 124). The point to be recognized is that with rights well specified, the owner becomes an effective monitor.

The Evolution of water marketing in the Western U.S.

Because extractive uses of water have a long history in the western United States and because each state has experimented with different institutions, a brief survey of these institutions is instructive. Building on an early Spanish tradition, miners and irrigators on the semi-arid western frontier devised a system of prior appropriation wherein rights were established by use and given priority on a first-in-time, first-in-right basis (see Anderson, 1983). These customary rights which could be traded separately from the land on which they were used provided for efficient allocation of the precious resource.

Two aspects of the evolution of the prior appropriation doctrine should be stressed. First, the system began taking shape without formal governmental institutions. It was individual claimants who diverted water from the stream's course who made their claims known. When conflicts occurred, disputes were settled through local, usually private courts, which settled them on the historical basis of prior use. If stream flows were insufficient to allow all diverters the quantities they claimed, it was the junior users who cut back first. Second, the initial role for government under this doctrine was to codify that which was evolving privately. As state governments caught up with the frontier, the customary rights were recorded and codified and institutions were established to guard against impairment[8]. Most states therefore require that water transfers go through a water bureau responsible for notifying other users of proposed changes and determining if impairment will occur[9]. It was only as the twentieth century progressed that this role expanded to include a multitude of restrictions on who could claim and transfer water, and markets were replaced with bureaucratic allocation.

In 1902 with the Newlands Reclamation Act, the federal government entered the water scene by providing massive subsidies to storage and delivery of water to agricultural and municipal users (Rucker & Fishback, 1983). Such subsidies virtually eliminated the need to worry about reallocation of water among competing uses because additional water could always be counted on from federal projects. The combination of federal projects with water dedicated to agriculture and state regulations on appropriation and transfer virtually eliminated any possibility for water marketing until recent years.

Today fiscal and environmental constraints are forcing westerners to recognize that the days of solving water problems with concrete and steel are over. Former Colorado Governor Richard D. Lamm described the change:

"When I was elected governor in 1974, the West had a well-established water system ... Bureau (of Reclamation) officials and local irrigation districts selected reservoir sites and determined water availability. With members of the western congressional delegation, they obtained project authorization and funding. Governors supported proposals, appearing before congressional committees to request new projects, and we participated in dam completion ceremonies.

In 1986, the picture is quite different. The boom in

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[7] This important point was recognized by Coase (1960) in his seminal article on "The Problem of Social Cost". For an excellent summary of Coase's point regarding how the legal system can internalize pollution externalities see *The Economist*, "Of Bees and Lighthouses", February 23, 1991, pp. 72-73.

[8] Unfortunately, some of these institutions went beyond this simple safeguard and began restricting water transfers. See Anderson (1983).

[9] For a thorough discussion of how state agencies deal with third-party impairment see Johnson, Gisser & Werner (1981).

western resource development has fizzled ... Congress .... has to worry about how to cut spending, not which (water) projects to fund .... Farmers are trying to stay in business and are recognizing that their water is often worth more than their crops. Policy-makers recognize that the natural environment must be protected because it is a major economic asset in the region" (quoted in Driver, 1986, ii).

This political, social, and economic climate ushered in a new era in managing water resources in the West. In the face of efforts to curtail government spending and protect the environment, the customary and legal institutions that govern water allocation have had to change in order to foster conservation and efficient allocation of existing supplies and take water's growing recreational and environmental value into account. Hence water marketing has become a coalescing theme among environmentalists and fiscal conservatives who oppose water projects that are both uneconomical and environmentally destructive.

Political coalitions have been pressing for relaxation of restrictions on water marketing especially within agriculture and between agricultural and municipal users. The Bureau of Reclamation has been encouraged to make the transition "from an agency whose workload has been constructing large water projects to an agency that assists the West to make better use of the waters the Bureau already provides. It can facilitate this transition by providing support for voluntary transfers of Bureau-provided water" (Driver, 1986, xi).

State legislatures are also being pressed to take "significant steps towards the encouragement of water use efficiency ... in terms of meeting in-state demands for water at the least cost, with due regard for community and environmental values in water ... (and) consider implementing a comprehensive program, going beyond water pricing reform, to encourage conservation and salvage of water through markets (Driver, 1986, viii-ix).

States are moving in that direction. New Mexico, Colorado, Utah, and California have made it legal for a person or an agency to temporarily transfer surface-water rights to another and reclaim those rights in the future. California's legislature also encourages voluntary water conservation by allowing water rights owners to retain their right to water saved rather than applying the "use it or lose it principle"[10]. Such changes provide an encouraging indication that the water law regarding existing rights especially for extractive uses is responding to increasing scarcity by more clearly specifying rights and by reducing restrictions on transfers.

Most states have also moved in the direction of clarifying water rights so that disputes will be reduced, and Montana is typical of states that have moved in the direction. It has established a central recording system with the state Department of Natural Resources and Conservation. Would-be claimants or persons desiring to change their amount or place of use can contact this department and obtain reliable information on the potential that others will be impaired.

Since 1973, Montana has allowed new claims under a permitting system which specified quantities and priority dates. While these may be somewhat less secure than older water rights, they still have all the protection of private property and can be traded within the limits of state legislation. Finally, Montana has gone beyond other states by requiring that all water basins be adjudicated through a state water court. The purpose of this adjudication is to eliminate uncertainties of title to early water rights where records are less clear and therefore to eliminate potential disputes. While the net benefits of this costly process can be disputed, it is a step in the direction of solidifying private water rights and thus facilitating water marketing.

But dealing with prior rights for extraction or establishing new ones is much easier than allocating claims for future use or accommodating new demands for instream flows. Montana again is one state that has dealt with future use by allowing water reservations[11].

Under the reservation system, political subdivisions of the state including municipalities, counties, state departments, and irrigation districts can request that water be set aside for them for future use. Such reservations require a long legal process wherein potential reservants have an opportunity to defend their requests and existing rights holders have an opportunity to object. In granting reservations, the Board of Natural Resources and Conservation must determine whether the reservant has provided convincing evidence that a legitimate demand for water will exist. At this point, the process encourages rent seeking as potential reservants compete in the political arena to obtain their water. Moreover, a "race for the pumphouse" may also be encouraged when the reservations must be periodically reviewed to determine whether they are being put to beneficial use. If they are not, the reservations can be revoked or reallocated, so reservants have an incentive to put their water to use.

Though this process is still evolving in Montana, it does provide a model for allocating rights for future

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[10] It should be noted that during the recent drought in California, the legislature has seemed more willing to rely on command and control rather than water marketing. The current problem is exacerbated by the lack of water and subsidized water prices. See Anderson & Leal (1991).

[11] See Montana Code Ann., Sec. 85-2-316 for the details.

water use. The costly hearing in advance of actual reservations guards against impairment andforces potential reservants to invest in their claim. On the other hand, application of water may still encourage "the race for the pumphouse" and force reservants to "use it or lose it". Moreover, the inability of reservants to sell their reservations makes efficient reallocation more difficult because any reallocation of reservations by the state is a zero-sum game in which the existing reservant loses and the new one gains. Nevertheless, because it is virtually impossible to prevent rent seeking and opportunistic claiming, this reservation process seems to provide a way of recognizing future demands that warrants more attention.

Accommodating instream flow demand: Three approaches

As values change, pressures to allocate water for instream uses are growing. Since this is a relatively new phenomenon, the necessary institutional mechanisms to accommodate these demands are still in their infancy. States in the western U.S. are moving in the direction of recognizing instream flows as a beneficial use and of encouraging water marketing as a means of meeting these flows. The spectrum of alternatives covers judicial, political, and market approaches for addressing instream flows demands[12].

Judicial

In 1983 a long-standing common law doctrine known as the "public trust doctrine" was applied in the Mono Lake decision (*National Audubon Society v. Superior Court of Alpine County*, 658 P. 2d, 709 (1983)). Historically this doctrine held that the government holds certain aspects of beds, banks, and beaches of lakes, rivers, and oceans in trust for fishing, navigation, and commerce, and therefore that it cannot grant exclusive rights to these resources to individuals. This "public trust" was expanded in Mono Lake to include environmental and recreational values associated with water. At issue was the dewatering of Mono Lake by the city of Los Angeles which had a permit to divert 99 % of the average annual inflow into the lake. As the water in the lake declined aquatic and bird populations were adversely affected, prompting environmental interests to file suit to stop the diversions. In an effort to avert a collision course between the prior appropriation doctrine and the public trust doctrine, the court ordered the state of California to review the diversion permit and to balance environmental and recreational uses against Los Angeles' claim. In the final analysis, the city had to reduce its diversions. Some would say that it had its rights taken without compensation; other would say that it never had such rights in the first place.

In either case battle lines were drawn in a zero-sum game where the environmentalists won and appropriators lost. Armed with this victory, environmentalists marched forward. Applying the doctrine to stream access in Montana[13], they argued that access could not be denied by riparian landowners because the state constitution clearly specifies that water belongs to the people of Montana with appropriators having a *usufructuary right*. After the smoke cleared from long judicial and legislative battles, recreational access was granted (though with some legal restrictions), but again the public trust doctrine had created much acrimony between environmentalists and land and water owners.

Political

Given the acrimony created by the zero-sum nature of the public trust doctrine, some states have sought to assure instream flows by mandating minimum stream flows or allowing state agencies to "appropriate" water for fish, wildlife, aesthetic, and water quality purposes. Washington and Oregon, two states with important salmon fisheries, were the first to require "that a flow of water sufficient to support game fish and food fish populations be maintained at all times in the streams of this state" (Washington Rev. Code, Sec. 75.20.050). It should be noted, however, that the Pacific Northwest is blessed with abundant rainfall making it less likely that this requirement will significantly affect other appropriators.

Many other western states (Alaska (Alaska Rev. Stat., Sec 46.15.145), Arizona (Ariz. Rev. Stat., Sec. 45-151-A), Colorado (Colo. Rev. Stat., Sec. 73-92-102-3), Idaho (Idaho Code, Sec. 42-1501 and 1505), Montana (Mont. Code Ann., Sec. 85-2-102, 223, and 311), Nevada (Nev. Rev. Stat., Sec. 533.030), and Wyoming (Wyo. Stat., Sec. 41-1-1001-1014)) have revised their statutes to designate instream flows as a beneficial use and allowed state agencies to appropriate water under the appropriation doctrine[14]. Such appropriations grant wildlife or health agencies water permits specifying a flow quantity over a specified stream reach. Like minimum flow requirements in the Pacific Northwest, this approach to appropriation has received opposition from existing appropriators as Wahl (1990, 201) notes:

"They fear that allowing individuals and public interest groups to file for instream flow rights would clog state agencies with applications; that it would be difficult to rule on the validity of such requests compared with quantifying consumptive sues; that

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[12] Two excellent review articles survey the multitude of options practised in the U.S.: Lamb & Doerksen (1987) and Wahl (1991).

[13] See Dana (1986).

[14] For additional details see Wahl (1990).

such rights, if granted, would forestall other more beneficial uses of water: and that private interests could file for instream rights and hold them for speculative purposes, later selling them for a substantial profit".

Alaska is one of two states that allows private individuals to apply for instream flow rights, requiring that a successful claimant not restrict public access. To guard against opportunistic claiming, Alaska requires that applicants complete hydrological and environmental studies before receiving a priority date for their rights. Arizona also allows private instream flow claims, and has granted small appropriations to The Nature Conservancy on at least two streams. Its Department of Water Resources has many requests for instream appropriations which it is processing (Dishlip, 1989).

Markets

In cases where additional water is not available for instream appropriation, where stream flows are inadequate to meet recreational, environmental, and aesthetic demands, and where existing appropriators have successfully thwarted new appropriations for instream flows, policy makers are experimenting with the use of markets. Colorado, Utah, Arizona, and Montana, for example, have legislation that enables private and public entities to acquire existing consumptive rights and retain them to augment instream flows. One of the first examples of such a conversion occurred on Boulder Creek in Colorado where the Colorado Division of Wildlife worked with The Nature Conservancy and a private appropriator to acquire one cfs (cubic feet per second) of flow in 1977.

Since then, The Nature Conservancy has been diligently bargaining to obtain 300 cfs from the Pittsburgh and Midway Coal Company to help preserve the endangered humpback chub on the Gunnison River in Colorado. If they are successful, the right will have to be donated to the state because Colorado law still does not recognize private instream flow claims. They will, however, have some say in how the instream flow will be managed. In Utah it has been the state Division of Wildlife Resources that has purchased irrigation rights to maintain instream flows (Wahl, 1990, 201). Despite these successes, Wahl (1990, 201) summarizes some of the fears of existing appropriators.

Following the stream access controversy and a summer of drought, some conservation groups in Montana sought a mechanism for ensuring instream flows that promotes cooperation rather than conflict. Legislation was introduced in 1989 to allow private or public organizations to purchase or lease water from appropriators on a "willing buyer, willing seller basis". Ultimately this was considered too radical a change, and an alternative version passed allowing the Department of Fish, Wildlife, and Parks (DFWP) to experiment with leasing (not purchasing) on five stream reaches approved by the Board of Natural Resources and Conservation. Negotiations are underway on 3 of these reaches though no final agreements have been consummated. Under this experiment, DFWP can receive contributions from private organisations, and Trout Unlimited has raised funds toward this end.

In the mean time, other groups, namely the Montana Wildlife Federation, has grown impatient with the process and reintroduced legislation opening the leasing process to private entities. Such efforts have been consistently opposed by farmers. In some cases, their opposition stems from unfounded fears that all of their water will be bought up by well-financed environmental groups. In other cases, legitimate concerns over binding flow constraints, third-party impairment especially related to return flows, and rising water prices during low-flow years due to new buyers in the market have been expressed. On the other side, a few conservationists and environmentalists contend that this process is flawed because instream flow buyers will be underfunded. With tight budgets, state agencies will not have large coffers to use for purchasing water, and private financing will be faced with the proverbial "free rider" problem constraining them from collecting as much as the water is really worth for instream proposes. All of these fears reflect a market process that is in its infancy and therefore filled with uncertainties. If nothing else, however, "relying on purchases and donations to enhance instream flow has the benefit of subjecting public uses of water to something of a market test" (Wahl, 1990, 200). Moreover, these experiments represent an evolution of water institutions that is demonstrating increasing success with market allocation.

Summarizing the requirements for water marketing

From the analytical framework and institutic examples presented above, it is possible to summarize the necessary conditions for water marketing, to point out potential problems, and to suggest ways in which government can facilitate market transactions to promote water use efficiency.

Well-specified and transferable water rights

1. Like all markets, water marketing requires that rights be well specified and transferable. In the case of diversion, rights must be specified in terms of quantities diverted and quantities consumed. Since there are variations in flows, rights must also specify the priority when flows are insufficient to meet all demands. The prior appropriation doctrine give higher priority to the earlier users. But other priorities may be used. The important thing is to make the priority clear and to allow those with the

highest priority to sell their water to lower priority users during low flows.

2. Instream flow rights must specify quantity of the flow and the reach of the stream over which the right applies. Again priority must be assigned in the event of insufficient flows.
3. Pollution discharge rights are similar to instream flow rights but they must be specified in terms of water quality variables such as types of discharge per volume of water. Priority must be established and transferability allowed.
4. Willing buyer, willing seller trades should be allowed to determine beneficial use as long as third-party impairment does not result.

Potential problems for water marketing.

1. Impairment must be guarded against in any transaction. Impairment may result from reduced flows or reduced quality or both. This problem is more complicated where good hydrological data are not available. Return flow quantities and usage are especially difficult to determine, making transfers from consumptive uses to instream uses more problematic.
2. Appropriation of unclaimed water for future use or for instream use may result in opportunistic claiming that creates binding flow constraints, especially for instream flows.
3. Discharge rights also create binding flow constraints and create a potential for impairment, especially when several forms of discharge are mixing in the stream.
4. Instream flow values may be subject to a free-ride problem. If the free-rider problem exists, there may be under-provision of this good in the voluntary market process.
5. The efficiency of market transactions takes the distribution of income as given and therefore may under-represent those with low incomes. This problem is not unique to water marketing and can be dealt with best through social-welfare programs.

Reducing transaction costs

1. Centralized recordation of water rights can reduce the potential for impairment by informing buyers and sellers who might be harmed.
2. A formal hearings process gives third parties an opportunity to present their case and provides a forum for ruling on impairment.
3. Public agencies using revenues from taxation can work through the market to provide goods where the free-rider problem may result in underfunding by private organizations. It should be noted, however, that public funding generates a different type of free-rider problem in that special interest groups desiring recreational or environmental amenities can get these at the expense of the general taxpayer. Moreover, without market prices it is difficult to know what level of instream flows should be provided[15].
4. If the initial distribution of wealth, including the initial distribution of water rights, is perceived to be a problem, unassigned water can be appropriated for the groups perceived to have less wealth. For example, new appropriations could be given to environmental groups if they are at the lower end of the wealth distribution. Two points need to be emphasized, however, First, once appropriations are made, the rights should be made transferable so the value of water can be maximized. If it is deemed that the initial appropriation should only be used to enhance recreational or environmental values, the appropriation might be put into the hands of a private trust charged with such enhancement. They could then sell their water as long as the proceeds would work toward this end. Second, though it is often alleged that environmental interests are not wealthy, the facts may not support this. Fishermen, for example, are not likely to be below median income. The top ten environmental groups in the U.S. have annual revenues of nearly a half-billion dollars and often receive large contributions from major corporations. Indeed the income profile of members of these groups suggests they are above the median. If recreational and environmental interests are above median income and wealth, the case for redistribution is much weaker.

Under these conditions there may still be cases where markets will not achieve optimal allocation. But the alternative is political allocation which has tended to subsidize water use, contributing to misallocation, scarcity, and environmental degradation. Though water marketing is in its infancy, it is proving to be superior to politics for improving allocation, alleviating scarcity, and improving environmental quality. Mark Twain said, "Whisky is for drinkin', water is for fightin'". With application of markets to this precious resource, fightin' can be replaced with cooperation, inefficiency with efficiency, and environmental destruction with good resource stewardship, and all of this with less cost to the public fisc. The time has come to "give markets a chance".

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[15] Some may argue that contingent valuation and benefit-cost analysis provide ways around this problem, but it is not clear that these techniques provide good information on values because consumers are not actually required to make trade-offs.

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IRRIGATION DEVELOPMENT ON SWAZI NATION LAND

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Background

Physical features

The Kingdom of Swaziland is one of the smallest countries in Africa covering 17 364 km^2. The country is landlocked in the south-eastern part of the African continent between latitudes 26° and 27° south and longitudes 31° and 32° east. It is almost entirely surrounded by the Republic of South Africa except for a common eastern border with Mozambique.

The country is divided into four distinct topographical and climatic regions namely the Highveld, Middleveld, Lowveld and Lubombo Plateau. The Highveld in the west covers 5 029 km^2 with an average altitude of 1 300 metres. This region is usually the wettest part of the country with a mean annual rainfall of 1 250 mm.

Immediately east of the Highveld lies the undulating Middleveld cover 4 597 km^2 with an average elevation of 700 m and annual rainfall of between 760 mm and 1 140 mm. The Lowveld, which is the driest of the four regions has an average altitude of 200 metres. This region covers 6416 km^2 with mean annual rainfall ranging between 500 mm and 889 mm. At present, the Lowveld has the largest irrigated area involving mainly estates of sugarcane, citrus and cotton. The Lubombo Plateau runs along the eastern border of Swaziland at an average altitude of 600 m with a climate closely resembling that of the Middleveld.

Land tenure and economic setting

As a result of land concessions given to non-Swazi farmers, traders and prospectors in the nineteenth century, the country can today be broadly classified into Title Deed Land TDL and Swazi Nation Land (SNL). On Swazi Nation Land every married Swazi male is by reason of clan, lineage or homestead, allocated rights to use a parcel of land to cultivate crops. Such rights are passed on to his offspring. Under Swazi Law and Custom such land is held in trust by the King for the Nation. Grazing land on the other hand falls under the same legal category but is normally used communally. Title Deed Land is based on the widely accepted and known system of freehold.

The difference between these two land tenure systems is reflected in the levels of agricultural production. Whilst accounting for about 40% of the total land area, TDL farms contribute almost 60% of the agricultural sector's overall contribution to GDP. On the other hand SNL farms which make up about 60% of total land area contribute less than 7% of GDP. This low level of productivity on SNL has led to a greater concentration of Government policy interventions in this sector since independence in 1968. Moreover this sector of SNL currently carries about 77% of the total population of the country which is presently estimated at 750 000 people. It is also for this reason that this paper will focus on SNL.

Evaluation of irrigation on Swazi Nation Land

Pre-independence period

The first of the smallholder schemes on Swazi Nation Land was Zakhe which was established in 1960 in the South-East of Swaziland. The scheme was initiated by a group of 8 farmers whose forefathers had left Swaziland for Zululand in the Republic of South Africa. They returned to Swaziland in the mid-1950's and were settled as Swazis. These farmers had gained agricultural experience after working in South Africa. They intended to utilize their acquired knowledge for commercial agriculture and followed the example of another Swazi Small farmer who was irrigating along the banks of the Ingwavuma River. Through the cooperation of the local traditional chief, assistance from the government and a loan from the Swaziland Credit and Savings Bank, they started an irrigation scheme which was later officially opened by the head of the government of the day. For a number of years, this scheme was considered the showpiece of irrigation projects.

Post-independence period

Shortly before Swaziland attained political independence, the British Colonial Government had initiated a Rural Development Area Programme (RDAP) on Swazi Nation Land. This programme was initiated to bring about better land-use practices among indigenous Swazis which, hopefully, would lead to increased crop and livestock production on SNL. The programme introduced soil conservation measures such as grass strips and broad-base terraces.

It also brought about localised agrarian reform measures by consolidating fragmented land parcels which were typical on SNL and provided basic infrastructure such as rural roads and fencing of grazing lands. Although this programme had a potential of accelerating agricultural development on SNL, it was largely resented by the general rural population as its implementation was identified with an occupying power. At independence in 1968, the new Government modified and intensified the RDAP by bringing in more elements of popular participation by the affected communities. Four Rural Development Areas (RDAs) were selected in the North, Central Southwest and South of Swaziland. These areas were chosen on the

basis of the better soils and the keen interest of the communities in participating in agricultural activities. It was during this period that a number of irrigation schemes were initiated with substantial government assistance in the form of technical advice, credit facilities for agricultural inputs and capital investment for irrigation layout and construction. Whilst this period witnessed an increase in the adoption of the relatively "new" technology of irrigation, it soon became evident that small scale irrigation farmers were assuming that Government would always provide substantial capital assistance. As a result, a number of RDA Schemes started experiencing a number of problems such as inefficient marketing, poor maintenance and organisation. The RDAP was largely financed from external sources such as the United Kingdom (UK), United States Agency for International Development (USAID), European Development Fund (EDF), African Development Bank (ADB) and the Government of Swaziland (GOS). Between 1977 and 1984 project costs were estimated at US$ 60.35 million (see Table 1).

Table 1 RDAP planned project costs (E1.00 = US$1.15).

Funding agency	US$.000	E.000
IBRD	4000	3478
ADP	5367	4667
EDF	3013	2620
USAID	16756	14371
UK	7335	6378
GOS	23878	29764
TOTAL	60349	52478

Source :- Ministry of Agriculture & Cooperatives 1983. Review of Rural Development Area Programme, Interim Report (Hunting Technical Services).

As pointed out earlier, the RDAP involved a number of components, including crop production, livestock production, infrastructural development, soil and water conservation, irrigation development, etc. An evaluation of the programme in 1983 concluded that while the programme did contribute significantly to the general living standard of the communities, it fell short of meeting economic targets. The subsequent suspension of direct donor funding to the RDAP meant that irrigation development on SNL also suffered since irrigation was an integral part of the programme.

After suspension of the RDAP, government support, which had been readily available during the RDAP era, was severely curtailed, leading to a slowing down in components of the former programme such as smallholder irrigation development. As if all this was not enough, a severe cyclone (Domoina) hit the country in 1984 which led to a complete disruption of most of the irrigation infrastructure that had been built since independence.

The Rationale for SNL smallholder irrigation development

It has been pointed out that almost 80% of the population of Swaziland resides in rural areas. This large rural population derives its livelihood from a variety of sources such as wage employment in the urban modern sector (private and public), agricultural estates on TDL and the mines in the Republic of South Africa. According to official statistics, paid employment rose by 7.7% in 1987 to 95 800 and by 5.5% in 1988 to 101 000. For 1989 it is estimated that paid employment increased by 4.6% to just under 106 000. This is all against a population growth rate which is estimated at 3.3% per annum. The Government has therefore realised that past direction of investment into large scale commercial estate operations on the TDL and into social and economic infrastructure on the SNL are no longer adequate. Large agro-industrial projects are local in social impact and being largely capital intensive cannot meet the needs of a growing labour force. It is now generally recognised that population growth will increasingly outstrip economic growth resulting in increasing unemployment and increasing food deficit. Consequently agriculture is expected to continue to be the mainstay of the economy and that surplus labour would have to be absorbed in the smallholder sector such as in SNL irrigation.

The Swaziland Government also realises that irrigated agriculture on SNL offers a potential for realisation of better economic returns that extensive and rainfed agriculture for traditional crops such as maize. Recent surveys on SNL rural households indicate that 38% of total income originates from agricultural activities compared to 60% from non-agricultural and off-farm activities. This suggests that agriculture has to be more economically rewarding to be attractive to rural households and irrigation development offers this opportunity.

As in many developing countries, better economic opportunities in urban areas of Swaziland lead to a large rate of rural-urban migration. Such migration overstretches the limited resources of these small urban centres thereby creating problems such as development of slums, crime and general socio-political instability. Productive and efficient use of irrigation water on SNL therefore provides a hope for reducing the drift to cities.

The general droughts and other weather and climatic changes hostile to an efficient agricultural system suggest that there is a need to develop a stable and dependable system of agriculture such as that offered

by irrigated agriculture on SNL.

The broad sectoral policy of the Governement of Swaziland continues to follow the objectives of achieving basic food self-sufficiency, improvement of nutritional levels, increasing agricultural exports and boosting rural incomes and employment. It is therefore suggested that irrigation development on SNL will help achieve these four objectives as briefly outlined above.

Characteristics of SNL smallholder irrigation schemes

There are presently no accurate statistics on the number and hectarage of irrigation schemes on Swazi Nation Land. Some estimates put the number of schemes on SNL at 25 covering about 600 hectares. An irrigation scheme, in this sense, refers to an area of two or more irrigated contiguous plots.

Types of irrigation schemes

There are several types of irrigation schemes. The largest number of schemes involve farmers associations. These have no legal status but have been encouraged by the Ministry of Agriculture and Cooperatives, through its extension service, on the basis that such schemes encourage group effort. Included in this category are those schemes which were initiated from within the community rather than by Government. Recent research by De Vletter indicates that out of a total of 22 operative schemes, about 70% were community initiated. Community initiated schemes may involve a group of farmers approaching the Chief and Government or the Chief himself. Farmer association schemes are characterised by several features. For instance, crops may be grown on individual plots where the choice of the crop is left to the discretion of each farmer. Marketing may be on an individual or group basis. Where there are common facilities such as dams, furrows, agricultural inputs sheds and tractors to be funded, the scheme committee will convene a meeting to raise collective contributions or use existing funds from previous contributions by members.

The other type of scheme now being officially encouraged by the Government is the cooperative. Such schemes have rules which are legally binding. Currently very few schemes operate as pure cooperatives whilst about eight operate partly as a cooperative and partly as an association.

Size and Membership

Generally speaking, irrigation schemes on SNL vary in size from 2 ha to 100 ha with an average plot size per farmer varying from one half to one hectare.

Most schemes on SNL come about after a certain piece of land has been identified and set aside for this purpose by traditional authorities (Chiefs and their committees). The Ministry of Agriculture and Cooperatives normally provides technical advice on the choice of land such as soils' capability for irrigation, type of crops that can be grown and water availability. Once the land has been identified, entrance into the scheme is voluntary on a first-come first-served basis. Land allocated for irrigation purposes is often in addition to some other land that belongs the the household for rainfed crops such as maize, sorghum, tobacco or cotton. This arrangement almost always brings about conflicts between rainfed and irrigated agriculture, particularly with respect to the allocation of labour and time. The membership per scheme ranges from 6 to 60 whilst the mean number of participants is 25 for most of the schemes.

Vuvulane Irrigated Farms

A different type of smallholder irrigation was developed in 1962 with the inception of Vuvulane Irrigated Farms (VIF) on land that was previously owned by the Commonwealth Development Corporation (CDC). VIF was the first and remains the most important contract farming scheme in Swaziland. The scheme involves 263 smallholders with plots ranging from 5 to 7 ha. Individual farmers are supposed to sign a twenty year lease. The scheme was formally handed over to the Swazi Nation by CDC in 1983. The CDC however retained a management contract to run VIF. Over the years, the conditions of the lease have brought about considerable misunderstanding between farmers and VIF management.

Crop and Technology

The major feature of cropping patterns on SNL schemes is their lack of diversity. Winter is usually the most important season for irrigated crops. During this period most of the schemes grow tomatoes and cabbages with a combination of other secondary vegetables. About 20% of the schemes are reported to be growing principal crops other than tomatoes and cabbages. Such principal crops include sugarcane and potatoes.

In summer, most farmers have to attend to their rainfed crops such as maize, tobacco and beans. As pointed out earlier, this practice diverts attention from irrigated crops. The other difficulty during summer is that the weather becomes very hot and humid in most parts of the country, thereby favouring a high incidence of horticultural pests and diseases. Except for those schemes concentrating on growing sugarcane, rice and cotton, most of the schemes grow maize which is normally planted early to take advantage of the attractive green mealie market and leaving unharvested maize to dry for domestic consumption. Four of the schemes are assisted by experts from the Republic of China (Taiwan) and these concentrate on growing rice in summer.

Most irrigation schemes on SNL employ surface gravity fed systems. In such schemes water is drawn

from rivers or streams through simple diversion weirs and often stored in small overnight storage reservoirs. This type of technology is preferred, where possible, because of its simplicity in operation and maintenance. A few schemes, including those which are individually owned, use overhead or sprinkler systems. In areas where water is not readily accessible, a scheme may involve a pump system which may be powered by diesel or electricity. Pump systems on Swazi Nation Land have experienced difficulties, particularly with respect to obtaining collective contributions for operating and maintenance costs including payment for fuel or power.

Lessons from the smallholder experience on SNL

The development of smallholder irrigation schemes on Swazi Nation Land has brought about benefits to the participating farmers as well as to the Government. Such benefits include increase in incomes, expanded employment opportunities as well as improved nutrition in rural areas. On the other hand, irrigation development in this sector of agriculture has also brought to the surface certain issues which have serious implications for the future of smallholder agriculture in Swaziland. Some of these issues can be categorised as follows:

Marketing

Perhaps the greatest problem facing irrigation schemes on Swazi Nation Land is marketing. The few schemes that do not experience this problem are those growing sugarcane where markets are guaranteed through a sugar quota system which is negotiated with the Swaziland Sugar Quota Board.

The most important purchasers of fresh produce (fruits and vegetables) from small producers are itinerant traders from within Swaziland as well as from Durban in the Republic of South Africa. The visits of these traders are sporadic and depend entirely on when their stock has been depleted. Other traders include market women who travel by bus to the irrigation schemes and buy as much as they can carry.

The majority of small-scale irrigation farmers are located far from potential markets and are without transport. They are therefore dependant on the sporadic visits of traders and this, combined with the usually saturated market for tomatoes and cabbages, leads to a one-sided bargaining relationship where the sellers are often faced with the prospect of selling their produce at highly exploitative prices.

It was because of such problems that in 1986, the Swaziland Government in collaboration with the International Fund for Agricultural Development (IFAD), launched the Smallholder Credit and Marketing Project. One of the results of this project was the creation of the National Agricultural Marketing Board (NAMBOARD). This statutory organisation is charged, among other things, with the responsibility of regulating import and export of fresh vegetables and fruits as well as establishing and operating a new national fresh produce market. Both activities were designed to assist smallholder farmers on irrigation scheme by curbing excessive imports of fresh produce which dampen local production whilst at the same time providing a more secure market outlet.

The national fresh produce market is operated on a consignment basis i.e. private market agents are appointed by NAMBOARD to receive and sell fresh produce from and for farmers and they charge a commission for that service ranging from 5% to 7.5%. Experience from this market has demonstrated that small farmers prefer to operate on a cash basis than to consign their commodities to be sold later by somebody else. The other lesson that has been learnt from such a market is that because of the small and fragmented production areas, transport costs are very high. To minimise such costs farmers need to form strong marketing cooperatives.

Group Development

Smallholder irrigation schemes whether operated by an individual or a group require some level of group development. Individually operated irrigation schemes in Swaziland usually have run into problems of acquiring the necessary agricultural inputs (such as fertilizer, seed and chemicals) in a cost effective manner. The other problem relates to the disposal of fresh produce through competitive markets.

Communal schemes on the other hand also usually face input acquisition and marketing problems. In addition to such problems, communal schemes often experience organisational and management difficulties ranging from poor record keeping to poor water management. In an effort to address such problems, the Smallholder Credit and Marketing Project has included a group development component. This involves providing specialist services from both Government and non-Government Organisations (NGOs) for strengthening Farmer' Associations and Cooperatives such that the irrigation schemes are self-managed and self-financed. The process usually starts by assisting the group to identify its problems and then helping them develop a strategy for solving those problems. Rules of procedure or a constitution for the scheme are developed, followed by democratically electing an executive committee. The committee then appoints and pays a trained secretary/manager who keeps all records of the scheme including production schedules, input quantities and costs. The secretary/manager also designs water maintenance schedules and costs and also makes marketing arrangements for each irrigation scheme.

The group development approach has been initiated after realising that initial community enthusiasm in establishing irrigation schemes usually wanes with time unless effective structures are developed to maintain

and improve community participation in these schemes. It is still too early to assess the success of this approach but it is already evident in several schemes that it is the right direction. A conclusion can therefore be drawn to the effect that technical systems such as smallholder irrigation schemes usually have important parallel social systems which operate them. In other words in a communal system such as obtains in Swaziland, one has to take full account of sociological implications of technical programmes like irrigation development.

Land tenure

It should be noted that the land tenure situation that is found in Swaziland was not deliberately adopted but is a historical and colonial legacy. That legacy has brought about a situation where the largest proportion of the population is concentrated on very little land, thereby bringing about very small (about 3 ha) arable and rainfed fields per farm family. The situation is very similar on irrigation schemes where each farmer is allocated about 0.6 ha on average (Table 2). It is therefore yet to be demonstrated whether a family can make a meaningful living from such small parcels of land given the current level of technology and the sociological set-up.

Except for very few homestead specific schemes, land for irrigation is usually allocated separately and in addition to land that is traditionally allocate for rainfed crops such as maize. Each family therefore has to divide its resources, including labour, between these two land parcels.

Traditional rainfed crops on SNL usually require less labour concentration than irrigated plots which have to be tended throughout the year. One therefore finds that irrigated agriculture is usually intensively practised by smallholders and farmers during the dry winter months which is the slack period for rainfed dryland crops. This practice has brought about a number of problems including concentration of fresh produce production during August to November which depresses prices of commodities such as tomatoes and cabbages. The other problem related to this type of pattern is that it brings about low usage of irrigation land. In winter Hansen (1978) estimated that 60% to 70% of the irrigated land is utilised whilst only 25% is utilised in summer on small-holder schemes. The level of land utilisation can also be expressed by the coefficient of land utilisation (CLU) which is obtained by dividing the total area cropped in any one year by the total area available for cropping.

Table 2 Size of plots for selected irrigation schemes.

Scheme	Size per plot(ha)
Lomshiyo	1.1
Ndlalambi	0.6
Bhokweni	0.33
Ntshanini	2.0
Mgomfolweni	0.5
Mpatheni	0.475
Ntamakuphila	0.4
Makhondowane	0.8
Tikhuba	0.36

Table 3 Irrigated Land Utilisation for Selected Schemes (1981/82).

Scheme	Size (ha)	Area cropped (ha)	Coefficient of land utilisation (CLU)
Lomshiyo	2.2	4.4	2
Ndlalambi	22.8	19.24	0.84
Bhokweni	1.35	-	-
Ntshanini	2	3.075	1.54
Mfomfolweni	9	14.15	1.57
Mpatheni	23.78	18.76	0.79
Private garden (SRDA)	12.44	10.76	0.86
Ntamakuphila	13.6	16.71	1.23
Makhondowane	13.6	10.6	0.78
Tikhuba	3.6	8.07	2.24
Total Surveyed	103	105.77	1.03

Note: CLU = (total area cropped)/(total area available for cropping)
Source : Ministry of Agriculture & Cooperatives Irrigation Scheme Results (1981/82)

From Table 3 it can be seen that the CLU for Swaziland's smallholder irrigation schemes ranges from less than 1 to 2 which means that for some schemes there is less than one crop per year whilst others have up to two crops per year. Efforts are therefore being made to increase the national average CLU to between 1.5 to 2.

It is of course realised that whilst fresh produce prices are attractive in summer it is very difficult for small scale farmers to produce vegetables during this period because of high temperatures and high humidity which are very favourable conditions for the high incidence of pests and diseases. However research in this area is underway.

The government has realised that irrigation schemes offer distinct advantages over more homestead-specific innovations in irrigation development. Such schemes are usually jointly endorsed by the government and traditional authorities and therefore offer more security to individual farmers in the sense that arbitrary dismissal is either minimal or not possible. More

importantly, however, since schemes are based on communal initiative they involve pooling of resources such as land, manpower, capital and experience. This pooling of resources in turn allows for exploitation of economies of scale and the spreading of risks. Individual initiative, however, is maintained on individual plots, particularly with respect to production. Economies of scale and risk sharing are most evident with respect to acquisition of inputs, organisation and management as well as in marketing.

Under traditional Swazi custom, women and bachelors are not normally given access to land unless attached to their husbands or fathers. Allocation of land in irrigation schemes allows for the participation of these disadvantaged groups who may also be given access to group credit.

The division of the country into TDL and SNL has led to a situation where the two sectors have very little in common. In particular, the smallholder sector suffers from acute shortage of irrigation know-how despite very active support from Government. It is for this reason that current Government policy promotes better communication between the public and private sector (including NGOs) so as to exploit among other things, irrigation technological advantages of the private sector.

The qualifications for participating in an irrigation scheme are still not very well-defined. In most cases the selection process depends on a first-come first-served basis, nearness to the area to be irrigated as well as self-declared enthusiasm. Such criteria have proven to be inadequate

Experience in smallholder irrigation development is currently being assembled with a view to developing better criteria for selecting potentially good farmers.

Donor Participation

Over the years since independence, agricultural development in Swaziland has been the result of cooperation among the Swaziland Government, donor agencies and governments as well as the affected farmers. These donors have ranged from multilateral agencies such as the World Bank, EEC, ADB, FAO, and IFAD to individual friendly governments and national and international NGOs which are too numerous to mention individually. Some donors have offered general assistance to agriculture whilst others have been specific to certain sectors such as livestock, forestry and irrigation.

The experience of this tripartite arrangement has been generally positive but not always smooth going. Conflicts have often arisen in determining priorities concerning what is to be done, how it is to be done and when. Normally donor agency support comes in the form of projects, with specified periods during which funds are to be spent as well as technical assistance to carry out these projects. There have been many cases of different perceptions as to how such projects or programmes are to be implemented. Government has been caught between donor and farmer aspirations. There have been numerous cases where the donors are frustrated by the pace of development which is often measured by the rate of disbursement of donor funds. In the meantime, the Government would still be trying to solicit farmer involvement in an irrigation scheme, a process which may take longer than the specified project schedule of implementation. In view of shortages of local irrigation technical expertise the technical assistance which comes as a package from the donor may not be appropriate for the social and technological setting in communal irrigation schemes.

Such experiences suggest that the government has a role to play in making donors and local farmers conscious of each others aspirations. Ideally, the donor should then be able to assist the government in implementing clearly and locally articulated programme strategies in smallholder irrigation.

IRRIGATION RESEARCH IN AUSTRALIA - ACHIEVEMENT AND CHALLENGES

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Introduction

Irrigation in Australia is a 4.5 billion dollar industry (Banks & Wood, 1991). It has grown from humble beginnings as an insurance against the high frequency of drought, through the grand vision of making "the desert bloom", to a mature industry faced with the challenge of greatly increasing its productivity while avoiding long term resource degradation.

Irrigation is a complex of multidisciplinary science, politics, economics and a way of life. Any short overview of the effects of research and the challenges facing irrigation research will be incomplete and generally biased towards the most well known examples. Given this limitation, my aim is to pick out the major historical events which have shaped present Australian irrigation and to indicate successes and failures. I will attempt to highlight where the influence of research has improved irrigated productivity and to indicate the challenges now facing irrigation scientists. I will argue that while the challenge of improved understanding of system components is still needed, the major challenges are in system management, by applying what is known in a cost effective and environmentally sensitive manner.

Early irrigation development

The earliest irrigation developments were undertaken by individuals generally associated with the coastal settlements in New South Wales (around Sydney) and in Tasmania. In the mid-1800s pastoral development (primarily grazing of sheep) occurred on the large flat inland tracts of south central and south western New South Wales and northern Victoria (Figure 1). The development of this industry was put in jeopardy by the high frequency of drought. Agitation for insurance against the effects of drought through irrigation was in part responsible for the formation of the Deakin Royal Commission of Victoria in 1884. Deakin visited the USA, India and other irrigation areas and strongly recommended the development of large irrigation schemes in Victoria. He was impressed by irrigation which was occurring in California, a semi-arid climate not dissimilar to that of northern Victoria. The USA influence was also important in directing the control of water away from the problematic "laissez-faire" system in western USA towards state government control of water resources. This resulted in the Victorian Irrigation Act of 1886 which ensured all water rights rested with the Government and to a large extent committed them to carry out major works associated with water storage and regulation. Similar laws followed in other states.

Early attempts at forming private Irrigation Trusts were largely unsuccessful; returns from water sales were inadequate and returns from irrigated production were generally poor. As early as 1885 an engineer by the name of Gordon urged caution in assessing the costs and benefits of large irrigation schemes. However, his protestations were largely ignored as was his advice about the need for irrigation to be accompanied by adequate drainage.

The scene was thus set for irrigation to proceed, largely with Government control and backing and with a focus on support for the pastoral industry. A further significant event occurred with the Chaffey Brothers' developments at Renmark in South Australia and Mildura in Victoria. Both developments were instigated by the respective State Governments and both suffered similar fates. Within the space of 10 years the developments were transformed from the grand vision, to application, to failure; caused by such fundamental problems as the cost of lifting water from the river, seepage losses from unlined channels, poorly adapted crop varieties, lack of transport and poor on-farm management skills. However, both areas now exist as productive irrigated regions, largely as the result of persistence from individuals to overcome problems and Government willingness to inject capital into infrastructure, research and extension.



Figure 1 States and major rivers of Australia. The shaded area is the Murray-Darling Basin, the major catchment and drainage division of Australia.

These early developments set the framework for the irrigation industry in Australia. The area under irrigation continued to increase gradually during the period 1910 to 1940. Thereafter, a rapid increase,

especially in New South Wales and Victoria occurred until the mid-1970s. More comprehensive descriptions of early developments are given in Framji & Mahajan (1969) and Smith *et al.* (1983). Present day irrigation areas are shown in Figure 2. The major features of some of these areas will be discussed below.



Figure 2 Major drainage divisions of Australia indicating areas of irrigation development of less than 30 000 ha (○) and exceeding 30 000 ha (■).

Major irrigation areas (their features and responses to research)

Northern Victoria and Murray Riverlands

The irrigation areas of northern Victoria are located on the flat Riverine plain largely made up of duplex clay soils. These soils have been relatively easy to irrigate by surface flooding. Much of the irrigation area is used for pasture production (some 87%) which has relatively low economic return in the form of milk, milk products and meat (Smith *et al.*, 1983). There has been research input in the form of new pasture varieties and improved agronomy - much of it though has been through adaption of dryland agronomic experience. In recent times, an upsurge in land forming as the result of availability of laser controlled levelling machinery has transformed some of the poorly laid out border check systems. Where this land forming is done in conjunction with whole farm planning to improve water distribution and recycling, considerable long-term management advantages are possible. However, there is little evidence to suggest that landforming greatly improves crop productivity, in fact the reverse may be true in the short term where topsoil removal exposes low fertility subsoils. The advantages in landforming rest mainly with making irrigation easier for farm managers. Soils of this region are generally structurally unstable. Irrigated cropping has needed to carefully manage these soils if high production is to be obtained. Recent research on soil management has shown the principals (Tisdale & Adem, 1988) but wide application is still to come.

Current research in agronomic crops is concentrating on improving engineering aspects of surface irrigation, on the mechanics of water control and measurement, and on crop water use and soil management especially under high water table and developing salinity conditions (Department of Agriculture, Tatura, 1989).

There are some areas within northern Victoria where intensive horticulture is practised. Management has shifted from under tree basin irrigation to furrow and in some places under tree micro irrigation systems. Most change has come in cultural practices with variety selection, pruning and fertilisation becoming more refined. Very recent work on improved high density planting with controlled trellising and water control is being taken up in a few commercial orchards. The use of controlled water deficits to limit vegetative growth but retain reproductive fruit yield (Chalmers *et al.*, 1984) is setting a benchmark for future irrigation management. There are good indicators that greatly improved productivity is possible from many horticultural enterprises (Crockroft, *et al.*, 1985). However potential overseas markets are yet to be fully explored because of problems with transport and constancy of quality supply.

The ribbon development of irrigation along the Murray River in north western Victoria and eastern South Australia began with the Chaffey Brother. These areas are semi-arid, receiving winter rainfall (<300 mm annually) with sandy loam soils developed over limestone ("mallee soils"). These soils are highly variable in depth and profile, and are generally quite permeable, unlike the clay soils of the Riverine plain further to the east. The need for lined channels, and for adequate subsurface drainage was recognised early in development. A high proportion of the irrigation on the predominately horticultural crops is by pressurised systems. Much research has been invested in better design and management of these systems although the prevalence of poorly designed systems unable to cope with site to site variability in available soil water is still a major concern (Cole, 1985). A steady increase in salinity of the River Murray prompted research which has resulted in undertree sprinkler systems being used in recent years. All new developments, especially of grapevines, employ microjet or drip systems. The management of irrigation to reduce groundwater accessions and saline drainage disposal is a major concern of current research.

Water distribution costs in these areas have ensured a reasonable consciousness about water use efficiency. However many of the early developments now have major infrastructure in need of replacement (Anon, 1989a). Socio-economic and bio-physical research will

be needed to help decide the future of these areas where major restructuring of farm size, water delivery and system management will be needed.

Southern New South Wales

Following the NSW Water Act of 1896, irrigation in the large flat riverine areas bordering the Murrumbidgee and Murray Rivers proceeded in the early 1900s. The major development, the Murrumbidgee Irrigation Area, opened in 1913. However, the early promises of good returns from lucerne and dairying did not materialise. Small areas of horticulture gradually developed on the better, more freely draining soils. While some of the limitations to crop production may have been indicated by soil survey scientists, these tended to be swept away by political, economic, social and engineering aspirations.

A solid base for efficient water application, especially in horticultural crops was developed by researchers in the 1930s and 1940s. Unfortunately many of these lessons are still only partly applied. Poor water control in many horticultural areas resulted in high water tables in the late 1930s and 1940s. Death of citrus, deciduous fruit and grapevine plantings following several wet winters resulted in a flurry of activity on drainage design and installation. Engineering solutions were very successfully applied in the form of tile drainage which overcame the immediate problems (Anon, 1965).

The availability of water for irrigation in southern NSW has generally been high and established areas have rarely experienced shortage. Total water delivered to these areas was nearly 3 km^3 (3000 GL) in 1988/89. The large supplementation of supply produced by the Snowy Mountain Scheme in the 1950s led to pricing and development policies which encouraged water use. Only very recently has this attitude changed because of demands of downstream users for more water of adequate quality and as the value of water for uses other than irrigation, have been reassessed. This attitude change has been associated with the formation of the Murray Darling Basin Council in November of 1985. The Council has a charter which is to "promote and coordinate effective planning and management for the equitable, efficient and sustainable use of land, water and environmental resources of the Murray-Darling Basin". The formation of the Council, consisting of three state and federal government delegates, represents the most significant change in government control since 1914 when the three states agreed to reconcile navigation and irrigation developments in the River Murray Basin.

Irrigation development in southern NSW has been strongly driven by rice production. Experiments in the 1920s and 30s showed that it could be successfully grown and yields were generally good. Rice is grown under ponded conditions for more then 100 days. It has a high demand for water; the evaporative requirement being between 1 000 and 1 200 mm per season compared with maize of 600 to 800 mm per season. Water application on some rice crops has exceeded 2 500 mm where soils are permeable. These more permeable areas have been eliminated from rice growing over the years but the total area per farm sown to rice has increased to help farmers match the ever decreasing cost/return difference. The rice industry is well integrated and has provided the stable economic base for the region. Considerable inputs into rice breeding and agronomy have been made. In the last 6 years average yields have increased from 5-6 t ha^{-1} to over 8 t ha^{-1} as the result of both improved varieties and improved management. The improved management, embodied in a program called Ricecheck (NSW Agriculture and Fisheries, 1990) makes use of concepts introduced in a research program called SIRAGCROP (Stapper *et al.*, 1986). SIRAGCROP aimed to provide management of crops (other than rice) by combining irrigation scheduling advice tied to objective crop management. This program demonstrated that improved yields can be achieved if key production steps are followed and crop growth stages are quantified.

While rice has been the dominant and successful crop of this region, other crops have enjoyed less success. Many of these crops (such as wheat) have been grown opportunistically, production methods generally being little different from dryland methods. Many of these crops have yielded poorly (Smith *et al.*, 1983). The difficult soils of the region, quite suited to rice production, proved the undoing of a promising cotton industry. Early maturing varieties suitable for the area were bred but establishment problems and poor soil drainage discouraged the early commercial ventures. More recent research has shown that high yields of crops such as maize will only be possible on many soils where water management avoids periods of inundation exceeding 48 hours, where soil internal drainage is improved and where high levels of N fertilizer are carefully metered out through the season (Meyer *et al.*, 1987).

In common with many areas of northern Victoria, about 40% of the irrigated area of southern NSW is now underlain by shallow water tables (<2 m). The area of visibly salinized land is presently about 2% but this is expected to rise rapidly to 15-25% (Hallows, 1985). The estimated losses from attendant waterlogging and salinity are $AUS 65 million per year. While engineering solutions such as shallow aquifer pumping and evaporation basin storage of saline effluent are possible on a regional basis, the cost of these per unit area is now unacceptably high. There are now more widely based attempts to find solutions both at the cause and the effect end. Increased research is being done at a monitoring and investigation level while more strategic research, developing

"tools" to help assess combinations of both above ground and below ground management changes is underway.

Northern New South Wales

Irrigation has developed along selected areas of several rivers (Namoi, Gwydir, MacIntyre) which join into the Darling River. These areas are influenced by summer rainfall and warmer temperatures associated with the sub tropics. Many areas developed since the 1950s are located on the flat, grey vertisol soils in the eastern areas while to the west the grey and brown soils of heavy texture dominate. Irrigation in this area has generally been developed by private investment, mostly with direct diversion from the river. Unlike the major schemes in the south of the state, the supply of water has been severely limited in times of drought. This potential restriction has resulted in water availability having a high value. Farmers have been prepared to invest in large on-farm storages and to pursue high efficiency in water delivery and water reuse systems. There has also been considerable research work on water allocation arrangements and optimising water availability within a season (Anon, 1989b). The reality of limited available water has forced crop physiology, engineering and economic analysis to come together to decide how best to distribute water.

The major crop grown in this area is cotton, which in the last 20 years has been developed mainly by large corporate farms. This high value crop has been the subject of some very successful research in terms of new varieties and new management methods (CSIRO, 1986). The development of a computer based insect pest management system (SIRATAC) has expanded into most facets of cotton management (CSIRO, 1986). The focus on a single crop and its use by a few very large producers have helped its success. There is also an example of the successful introduction of irrigation management using neutron soil water probes in this industry. Again its success revolves around a well focused and profitable industry with a significant number of corporate farms, and, in this case a competent and committed marketing company (Cull, 1986).

Another initiative coming from this area has been a combined effort by an industry group (Irrigation Association of Australia) and government agencies to bring together the elements necessary for successful irrigated agriculture. This initiative, called "Waterforce" was driven by the reality that average field yields of many irrigated crops are less than half yields achieved by better farmers, and that comparable overseas competitors produce two to ten times the gross value of production per megalitre (Anthony, 1989). The realisation developed from earlier work (Smith, 1983) which formed the rational basis for irrigation research within CSIRO. The "Waterforce" concept has been used to effectively focus the need for improved management in other states (Cornish *et al.*, 1990). It is not yet possible to assess the impact of such extension projects.

The development of irrigation on some of the soils in northern New South Wales has been accompanied by a marked decline in soil physical structure. Much research work has been devoted to identifying management practices which overcome and avoid the problems of compaction and poor surface soil structure. The fragility of the soils and thus the need to avoid cultivation when wet, the need to reduce ground traffic and the importance of "digging a hole" to actually look at soil profiles have all contributed to more informed management and improved yields.

Northern Australia

This grouping covers a hugh area where developments have been scattered and sporadic. Most developments have occurred in the semi-arid tropics where available water supplies are large but annual variability of rainfall is also large (Skerman, 1985). In Queensland, the most notable recent development has been associated with the Burdekin River. The irrigation of sugarcane, principally in the River delta has recently been followed by expanded areas of crops such as maize and rice. Research into crop adaptation and management has underpinned development into expanded areas. However research and monitoring have also identified the rapidly developing water tables associated with flood irrigation on some of the more permeable soil types.

Irrigation schemes in the Northern Territory have generally been characterised by their grandiose intent and their generally rapid demise. In short, failure has resulted from both crops and managers that were poorly adapted and from limited market opportunities within affordable reach.

In Western Australia, the building of the huge storage (Lake Argyle, approx 6 km^3 of water) on the Ord River from 1961 gave the possibility of irrigating more than 75 000 ha of land. Research into possible commercial crops has continued for more than 40 years. Cotton was the main crop grown until 1974 - its cost of production, the cost of transport and the removal of government subsidies led to its demise. Although development of the area held great promise from a political, strategic and water and land resource point of view the reality is that it struggled to remain economically viable. Agronomic research was able to develop management systems which were productive but costs and market availability have severely limited continued development. Today the strength of agricultural development lies in its diversity. A market niche for out-of-season-fruit and vegetables has proved to be viable while markets for maize and sorghum now exist locally and in countries to the north of Australia (McGhie, 1990).

Challenges for irrigation research

There are a number of ways of compiling a list of research needs for irrigated agriculture. These can be broadly categorised into lists by discipline, research areas or problems. A good listing by discipline, which represents a fairly conventional reductionist scientist view is given by Clothier (1989). His list contains crop meteorology (stomata, local advection and areal evapotranspiration), soil physics (variability, redistribution and solute transport) and plant physiology (roots and plant water status). An alternative listing by research area is given by Von Mengersen *et al.* (1987). They had four main categories (1) physical processes (climate effects, crop water use, water and salt distribution and associated salinity and waterlogging), (2) crop agronomy (soil management, crop selection, input scheduling, water and energy use efficiency), (3) irrigation system and equipment design (soil characteristics, economic design, standards) and (4) community impact of irrigation (history of irrigation, economic impact, institutional structures, risk assessment, technology transfer). A more recent listing compiled after extensive consultation is given by Banks & Wood (1990). Their list pulled together eight national priority issues: sustainability, irrigated crop management systems, water use efficiency, drainage, pollution, salinity, technology transfer and education.

To some extent the listing and thinking about research needs reflects a need to satisfy administrative convenience. An alternative listing uses a problem solving approach. This approach requires the formulating and prioritising of researchable questions about the system of concern. This approach will require multidisciplinary teams in which there is a well defined goal, clear leadership and a subjugation of individual dominance for the benefit of the whole. This grouping is administratively difficult and runs counter to much of our scientific training and many of our scientific institutions.

To me, the problems of Australian irrigated agriculture are system problems. These problems really revolve around the central issue of increasing irrigation productivity so that it is economically viable while at the same time avoiding long term resource degradation.

The challenge for research therefore is to use a problem solving approach to ensure that irrigated agriculture remains viable. This challenge is common to all irrigated regions; the component problems will vary between regions. For example, in southern New South Wales the key questions needing resolution are "what intensity of rice production can we sustain on the landscape" and "how can we manage soils and water to optimise production from areas with shallow watertables". Further more specific questions which flow from the above are:

* what are the values of the limiting soil hydraulic properties concerned with infiltration, ponding and runoff and subsequent redistribution *at field scale?*
* how does root distribution change in response to soil conditions and what is the effect of root "clumping" on plant available water?
* how do shallow watertables interact with capillary rise and rates of salinization for different soils, crops and irrigation management?
* how can we optimise crop and groundwater management in space and time, to achieve salt and water balance in an irrigated region?
* how can we best work with irrigators to bring about beneficial changes in land, water and crop management?
* what form of "knowledge packages" (which influence on-farm management) will be best accepted?

By posing such questions we can see that a range of discipline inputs will be needed. Importantly they include not only agronomy, soil science, and crop physiology but also groundwater hydrology, systems science, rural sociology and economics. To help focus the efforts of these people a sound modelling framework is needed. Functional models of the crops, water distribution and groundwaters will be needed to form the basis for biophysical and economic assessment of possible management options. This does not negate the need for sound field experimentation and survey data, in fact, it will very likely enhance experimentation by more clearly focusing on the most important, least known aspects of the system.

Summary and conclusion

In Australian irrigation, much of our early engineering knowledge came directly from overseas. There has been a general adaptation of this knowledge, which when coupled with the early work on water infiltration and movement, crop evaporation and crop physiology led to irrigation practices with little emphasis on water use efficiency. Much of the initial work by engineers and soil survey scientists was thorough and in many cases highlighted potential limitations to long term irrigation development. These warnings were not generally heeded and many older irrigation areas are now contending with the problems of high water tables and increasing salinisation.

Much of the impact of Australian research in irrigated areas is only now being realised. Examples are cotton productivity in northern New South Wales, viable crops in the Ord River, improved rice yields and intensive horticultural systems using dense plantings and controlled water applications. Other potential tools such as irrigation scheduling advice, objective crop management and increased use of real time weather data for strategic decisions are yet to be widely adopted. In one sense, irrigation science may be regarded as a mature science. However in the sense of application of existing knowledge there are huge

opportunities.

The challenge before irrigation scientists is to improve productivity while avoiding resource degradation. To address this problem we need a systems approach to bring together engineers, agronomists, soil scientists, rural sociologists and economists. These people will need to work within a modelling framework made up of biophysical inventories, crop models, water distribution descriptions and optimisation systems. Integral to support this is an education system which produces thinkers rather than regurgitators.

Finally, the challenge before the Australian irrigation industry as a whole is to increase its input into the national research and development effort. Presently the direct input represents only 0.3% of the gross value of production. A value of 4% would be more appropriate for the size of the capital investment. To help achieve this there is a need for a change in attitude where irrigation is seen as a collection of disciplines. Rather it needs to be viewed as a system in its own right which produces a constant supply of high value products from the well managed use of land and water resources.

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IRRIGATION RESEARCH INITIATIVES IN CALIFORNIA

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Introduction

The San Joaquin Valley (SJV) of California (2.1 Mha irrigated) is one of the most agriculturally productive valleys in the world. The northern half of the SJV drains naturally into the San Francisco Bay through the San Joaquin River and its tributaries, but the southern half of the SJV has no natural drainage outlet. Much of the SJV floor is underlain by a thick clay layer (Corcoran Clay) which separates the aquifer into a semi-confined aquifer (top) and a confined aquifer (bottom).

Following the development and availability of high quality imported surface water, pumping of groundwater decreased, excessive irrigation increased and caused a recharge of the semi-confined aquifer and a rise of the "perched" saline water table. Although a drainage canal was started, its outlet was never completed and salinity developed on the west side of the valley. Subsurface tile drainage systems were installed in 50 kha of the most affected areas and drainage water was allowed to accumulate in Kesterson Reservoir, a natural wildlife refuge. In 1984 death and deformities of migratory birds were associated with selenium toxicity (Presser & Barnes, 1989) and led to the closure of Kesterson Reservoir and plugging of the drainage system.

Although water shortages are recurrent and increasing they have recently been overshadowed in priority by the water quality problems associated with deep percolation, salinity, and drainage effluents because of th perceived environmental health hazard. In 1984 the San Joaquin Valley Drainage Program (SJVDP) was created with a five year mandate to study the problem and suggest potential solutions to the rising drainage problem. Several major technical options were proposed and studied which if implemented could contribute to the long term solution of the agricultural drainage problem and the reduction of water shortages; of these, the source control option must first be achieved in order for the options to be viable.

First, "We must understand that, on the time-scale of human life, the soil is a non-renewable resource; so is a mature forest, a river, a lake, or an aquifer. They belong not only to those who are the titled owners at this moment, but to future generations as well" (Hillel, 1991). Hence it is imperative to implement long term sustainable solutions; from this standpoint, it is usually better to address the source of the problem (irrigation) rather than to treat the results (drainage). Since 1978 the USDA-ARS Water Management Research Laboratory (WMRL) has conducted irrigation research to minimize deep percolation and maximize water use efficiency (WUE) and to reuse saline drainage water for irrigating crops; more recently, research has also included the selecting and growing of plant species capable of removing toxic elements from soil and drainage water. The objectives of this paper are to discuss the major results of some of these projects and to demonstrate how the developed methods can help solve the problems of recurring water shortages and drainage in the SJV. These projects were conducted in cooperation with the U.S. Salinity Laboratory in Riverside, CA, the University of California (UC), other State and Federal agencies, irrigation industry and farm cooperators.

Management options

High irrigation efficiencies which assume that deep percolation to groundwater and irrigation return flows do not represent partial losses is flawed, because every time water is recycled through the soil, its quality is inevitably degraded by energy losses and leaching of soluble salts and pesticides. The real efficiency of an irrigation system ought to be evaluated by how well it conforms to design specifications (Rawitz *et al.*, 1991). Source control minimizes runoff and deep percolation and is the primary component of any solution to return flow, toxic solutes in the drainage water, and a high saline water table.

Source control options were outlined by The San Joaquin Valley Drainage Program, Draft of Final Report (1990) (SJVDP-DFR) as: (a) Water Conservation; (b) Drainage Management; (c) Crop Management; and (d) Alternative Land Use. "Crop management" and "alternative land use" involved converting intensively irrigated land to a different use by: (1) replacing salt-sensitive crops with salt-tolerant ones and irrigating them with reused drainage water and (2) retiring of intensively irrigated land and transforming it to wildlife habitat, evaporation ponds, or even urban development. In both cases, such land would cease being a recipient of imported water (Rawitz *et al.*, 1991). These two options will not be addressed.

Water conservation

Presently most of the large west side field crop acreage is furrow irrigated. Orchards and vineyards are irrigated either by narrow border checks or by furrows, except for new acreage which is often irrigated by drip. Crops such as alfalfa and wheat are irrigated by border checks or by portable hand-move

sprinkler systems. Hand-move sprinkler systems are also used quite extensively to irrigate for pre-plant or germination of field crops, subsequently irrigated by furrows. In view of the quality of land levelling achievable by laser technology, the delivery structure capacity and the water control achieved by available distribution systems (including surge irrigation) and further substantial improvement of water application efficiency and uniformity are nearly unlikely with presently well managed furrow or border check irrigation (Westlands, 1989).

The sprinkler irrigation is the first alternative to gravity irrigation. Recent developments such as micro-sprinklers mounted on small-diameter plastic tubing or modified lateral move irrigation machine such as the low energy precision applicator (LEPA) (Lyles & Bordowsky, 1983) or the TTIS systems (Phene *et al.*, 1981 and 1985) have some of the advantages of drip systems. Sprinkler systems are well adapted to automation, and can apply accurately any desired amount of water to a field. Under proper conditions, sprinkler irrigation can achieve uniformity and application efficiency values between 80 and 90%. For the LEPA and TTIS systems, application efficiencies can exceed 90% (Howell & Phene, 1983, Phene *et al.*, 1985). Water losses are caused by wind drift, deep percolation due to non-uniform distribution, runoff, and evaporation.

Drip irrigation offers another alternative to gravity irrigation. Drip irrigation is so different from surface or sprinkler irrigation that it is an entirely new cropping system (Goldberg & Shmueli, 1970). With drip irrigation water and nutrients can be applied to the soil uniformly and exactly when and where they are needed.

Subsurface drip irrigation (SDI) maximizes the advantages of drip irrigation, especially in the area of water conservation. SDI offers the most promising and sustainable option to gravity irrigation. SDI is the oldest modern irrigation method. In the USA, E. B. House (1920) irrigated apples, alfalfa, and cereal crops with porous subsurface pipes.

Phene *et al.* (1987a) described the advantages of SDI beyond those of surface drip irrigation. From the aspects of water conservation and salinity, (1) the top 15-20 cm of soil remains dry; hence, evaporation of water from the soil surface will be limited to vapour diffusion because of the mulching effect of the dry soil and less salts will accumulate at the surface; (2) by using high frequency irrigation to apply the water lost by the evapotranspiration of the crop (Et_c), a constant wetted soil volume and a net upward hydraulic gradient can be maintained even in the presence of a shallow water table; (3) since water and nutrients are applied directly to the centre of the root zone, the roots will take up and use nutrients more efficiently provided that the irrigation and fertilization schedules are adequate; (4) any soil surface crusts which usually cause infiltration problems, ponding and runoff will be bypassed and infiltration variability will be minimized.

Reduced evaporation at the soil surface

The evaporation (E) of water from a bare clay loam soil, irrigated by high frequency subsurface drip (HFSSD), surface drip at two frequencies (HFSD and LFSD) and rainfall (or sprinkler) was measured by a weighing lysimeter system. Figure 1 indicates that the mean ratio of bare soil ET (ET_{BS}) to cool season grass ET (ET_o) for irrigation by the HFSSD system is only 0.06 (when ET_o was measured by a similar weighing lysimeter located 150 m south). The ratio ET_{BS}/ET_o for HFSSD is much less than that of surface systems. As the crop canopy develops, E decreases linearly to zero as the light intercepted by the canopy increases to above 90% (Phene *et al.*, 1985). The partial wetting of the total soil volume and the dry soil surface have the additional advantages of restraining weed growth and of permitting implement traffic while an irrigation is in progress (Phene *et al.*, 1987).

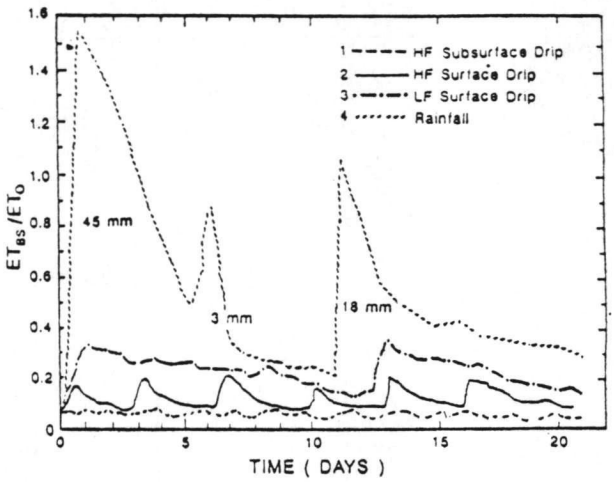


Figure 1 Bare soil evaporation from soil surface as affected by irrigation system and management. In the ratio ET_{BS}/ET_0, ET_{BS} is the bare soil evaporation and ET_o is the evapotranspiration of a short clipped, cool season grass.

Constant soil water and upward hydraulic gradient

In another experiment (Phene *et al.*, 1989), the soil matric potential (ψ_m) of a clay loam soil was measured hourly at depths of 15, 30, 45, 70, 100, 155, and 200 cm in a lysimeter irrigated by an HFSSD system with the drip line installed at 45-cm depth and a constant water table at a depth of 200 cm. The soil was irrigated one mm at a time to replace water lost from the lysimeter by ET_c. Figure 2 shows the mean daily ψ_m measured hourly for a period of 30 days in the crop lysimeter planted to a mature tomato crop. These data indicate that the HFSSD system maintained a constant ψ_m profile and hydraulic gradient ($\Delta H/\Delta Z$).

Figure 3 shows the ψ_m profile and the direction of

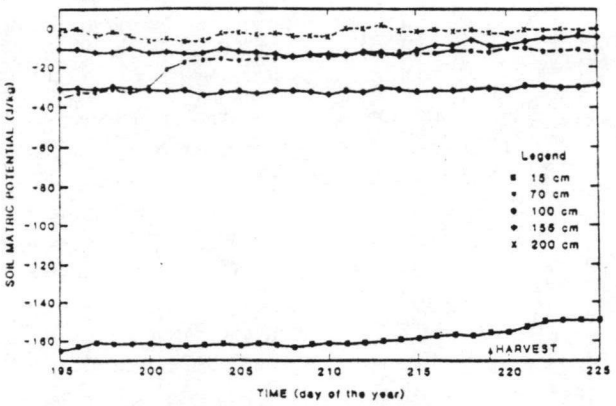


Figure 2 Mean daily soil matric potentials at 15, 70 100, 155, and 200 cm depths, from day 195 to day 225 of 1987 during the maturation phase of tomato crop in a lysimeter irrigated with a single drip line at 45-cm depth, in the presence of a water table deeper than 200-cm depth. (after Phene *et al.*, 1989).

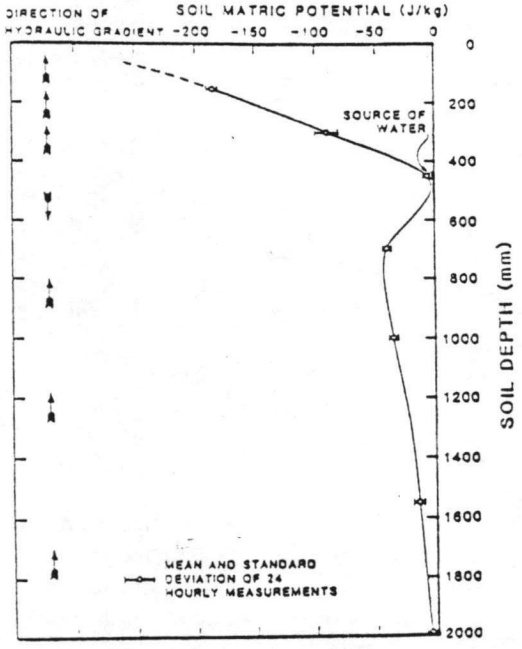


Figure 3 Soil matric potential and direction of the soil hydraulic gradient in the lysimeter, irrigated with a single drip line at 45-cm depth and in the presence of a water table deeper than 200 cm depth for day 195 and 1987 (after Phene *et al.*, 1989),

$\Delta H/\Delta Z$ for day 195 of 1987. These data indicate that except directly below the drip tube, between soil depths of 45 and 70 cm, $\Delta H/\Delta Z$ is upward everywhere else, and therefore the net flux of flux of water will be upward and deep percolation can be prevented or controlled.

Precise fertility and water use efficiency

Water use efficiency (WUE) has important implications when considering irrigation, soil and water conservation, productivity, and sustainability of irrigated agriculture. Water use efficiency is usually defined as the ratio of dry matter yield (Y) per unit of water evapotranspired (E+T) for a non-water stressed crop. Phene *et al.* (1988) have shown that processing tomato yields could be increased greatly with precise daily fertilizer injections of N, P, and K designed to match daily crop requirements without an associated increase in ETc. SDI also improves WUE since E of SDI systems is minimal, T is maximized and maximizing T increased stomatal opening and photosynthesis (Phene *et al.*, 1987).

Results are summarized in Table 1 for each year. (a) The irrigation efficiencies indicate that field systems were operated at a slight deficit and probably without deep percolation. Eventually some extra water will need to be applied to maintain the salt balance. However, if in the meanwhile the water table depth been lowered, then leaching can be possible without causing drainage outflow. (b) In 1985, when P was injected and 1987, when K and P were injected, all yields and WUE increased significantly but ETc's were not affected. The yield and WUE of the HFSSD tomato increased significantly over that of the HFSD and LFSD. (c) The WUE of the 1987 HFSSD (P = 67kg/ha treatment) increased by 93% over that of the 1984 LFSD treatment. These results indicate nearly twice as many tomatoes can be grown with the same amount of water when subsurface drip irrigation and fertigation are practised correctly as compared to conventional irrigation practices or with inadequately fertilized drip systems.

Demonstration project

Following the selenium toxicity problems generated by drainage flow into the Kesterson Reservoir, the California Department of Water Resources (DWR) and the State Water Resource Control Board (SWRCB) as advised by the UC Committee of Consultants (UCCC Report, 1988) funded several projects to demonstrate potential drainage reduction in the San Joaquin Valley of California. One of the demonstration projects is being conducted by Boyle Engineering, USDA-ARS Water Management Research Laboratory (WMRL) and the UC Cooperative Extension, Riverside, California (Phene *et al.*, 1989 and Smith *et al.*, 1991) and is based on the design and management concepts developed by Phene *et al.* (1987 and 1989).

A 65 ha field, provided by Harris Farm, Coaligna, California, has a shallow, saline water table, typical of the 600 000 ha drainage problem area of the west side of the San Joaquin Valley. This field was divided into four 17 ha blocks. Two of the blocks were furrow irrigated, one using existing furrow irrigation practices (Historic Furrow) and the other using improved irrigation scheduling practices (Improved Furrow).

Table 1 Irrigation efficiency (Ei = (ETc + LR) ÷ (ETc + DP + RO + L + S)], yield of large red tomatoes (Yr), and water use efficiency (Yr ÷ ETc = WUE) for tomatoes grown with drip irrigation at Five Points, California (from Phene *et al.*, 1990).

	1984 (N-only)			1985 (N+P)			1987 (N+P+K)				
								Yr (t/ha)			WUE
Irrigation Treatments	Ei	Yr t/ha	WUE g/kg	Ei	Yr t/ha	WUE g/kg	Ei	P=0	P=67	P=134	g/kg (P=67)
HFSSD	1.10	121a*	18a	0.97	168a	22a	1.07	184a	220a	215a	31a
HFSD	1.09	126a	19a	0.98	152b	20b	1.05	177a	201b	192b	29b
LFSD	1.18	114a	16b	0.96	130c	18c	1.10	170a	187c	183b	26c

*Column means followed by similar letters are not significantly different at the 95% confidence level, as determined by the Duncan Test on separation of means.

The subsurface drip system was installed in one of the 17 ha blocks and consists of 1.5 L h^{-1} in-line emitters spaced 1.0 m apart along polyethylene tube (Netafim, in-line, turbulent flow path drip system)[1]. Spacing between drip laterals is 2.0 m. Tubes were buried 0.45 ± 0.05 m in nonwheel rows to minimize compaction.

The LEPA system was installed in the remaining 17 ha block and consists of a lateral-move system (Lindsay Manufacturing) converted to a drop tube, pressure regulated furrow bubbler system (Nelson Irrigation, Inc.).

Results shown in Table 2 indicate that subsurface drip irrigation can substantially increase cotton yield and WUE, simultaneously decrease deep percolation and even contribute to drainage outflow reduction by forcing the crop to use water from the shallow saline water table, particularly at the end of the growing season. The practice was successful for two years and is recommended as a short term means of reducing and controlling drainage outflow so that drainage water can be reclaimed or disposed of less expensively.

Smith *et al.* (1991) conducted an economic analysis (excluding cost of drainage disposal) for the four irrigation practices in 1989 (see Table 3) using the grower's records and reported that subsurface drip irrigation had the highest net income (663.66 $/ha), followed by the Historic furrow (321.30 $/ha), the Improved furrow (315.42/ha), and the LEPA system (-201.71 $/ha). They concluded that, based on the 1989 results: (1) increased crop yield and gross returns are needed to compensate for increased subsurface drip and LEPA irrigation system costs; (2) computer-aided

Table 2 Cotton yields total applied water, water use efficiency[1] (from Smith *et al.*, 1991).

Treatment	Year	Seed Yield	Lint Yield	Total applied Water	WUE g/kg	Estimated Drainage
		-----kg/ha-----		mm		mm
Subsurface Drip	1989	3208	1710	585	0.29	-164[2]
	1990	3117	1446	610	0.24	18
LEPA	1989	2062	1138	512	0.22	67
	1990	2034	815	674	0.12	329
Improved Furrow	1989	2417	1192	750	0.16	280
	1990	2793	1371	500	0.27	-46
Historical Furrow	1989	2212	1211	774	0.16	299
	1990	2841	1428	732	0.20	152

[1]Water use efficiency (WUE) calculated by taking the mass ratio of lint yield to water applied. WUE = g lint cotton ÷ g water applied.
[2]Negative number indicates contribution to ET_c from saline water table.

[1]Mentioned of manufacturer's name does not imply endorsement by USDA-ARS but is given only for information purposes.

Table 3 Summary of net income estimate for the Harris Farm Demonstration Project in 1989 (from Smith *et al.*, 1991).

	Subsurface Drip	LEPA	Improved furrow	Historic furrow
	($/0.4 ha)			
Variable costs:				
Water	102.78	89.93	131.68	135.97
Irrigation labor	12.10	13.57	22.03	22.03
Fertilizer	48.85	30.90	30.90	30.90
Fumigant	0.00	0.00	0.00	0.00
WWD assessment	21.24	21.24	21.24	21.24
Cultural	607.94	617.99	583.16	573.69
Total variable cost	792.91	773.63	789.01	783.83
Fixed Cost:†				
Irrigation system‡	287.70	186.99	25.27	25.27
Equipment	39.50	39.50	39.50	39.50
Total fixed cost	327.20	226.49	64.77	64.77
Total production cost	1,120.11	1,000.12	853.78	848.60
Less seed credit	243.44	156.49	183.43	167.88
Net cost of production	876.67	843.63	670.35	680.72
Total income	**1,145.25**	**762.00**	**798.00**	**810.75**
Net return or [loss]	**268.58**	**[81.63]**	**127.65**	**130.03**

*Based on crop yield and production cost data from grower records provided for each irrigation treatment.
†Capital recovery assuming 10 years at 10% interest.
‡Irrigation system capital cost esimated at $1,350 per acre for subsurface drip, $584 per acre for LEPA, and $155 per acre for furrow.

scheduling of furrow irrigation did not result in significant water savings; (3) reductions in subsurface drainwater disposal costs and increases in the ability to sustain long-term irrigation and agriculture in the western San Joaquin Valley may be additional economic benefits and (4) pressurized irrigation systems need further evaluation under SJV conditions to develop a better understanding of the long-term management requirements and profitability.

Saline water reuse for drainage management

A practical water management strategy that maximizes the usability of saline water for irrigation has been reported by Rhoades *et al.* (1980) for cotton grown in the SJV and for a crop rotation system in the Imperial Valley (Rhoades, 1984). This strategy is based on the assumption that farmers will not voluntarily irrigate with brackish water unless it can be used without significant losses in yield, without major restrictions in cropping flexibility, and without extensive changes in farming practices and economic benefit. The saline water reuse concept assumes that the grower has ac to two separate water supplies: water of low salinity and a saline water that can still be consumed through transpiration by salt-tolerant crops without excessive loss in yield (water with electrical conductivity (EC_w) of less than about 8 ds/m). The saline water would be substituted for fresh water to irrigate certain crops in the rotation when they are in a suitably salt-tolerant growth stage; the fresh water would be used at the other times. Rhoades *et al.* (1988) conducted experiments in the Imperial Valley and successfully demonstrated rotations of [wheat: sugar beet: cantaloupe] and [cotton: cotton: wheat: alfalfa] using good quality water to germinate the crop followed by saline water with an EC_w of 4.0 ds/m.

Rhoades *et al.* (1988) concluded that any excessive salt buildup in the root zone from irrigating the

"tolerant" crops in the rotation with the saline water can be alleviated subsequently when a sensitive crop is irrigated with low-salinity water. After a salt-tolerant crop is grown, appropriate irrigation and seedbed management should "reclaim" the soil sufficiently to grow sensitive crops without yield reduction.

Ayares *et al.* (1990) evaluated the long term potential of drip irrigation using saline water of lower quality than used by Rhoades to supply part of the crop water requirement in a five year rotation [cotton: cotton: wheat: sugar beet: cotton]. Treatment T1 was a surface drip irrigated treatment using saline water (7 ds/m EC_w) applied at ET_c rate. Treatment T2 was identical to T1 except that it was irrigated at 1.3 ET_c. Treatment F was furrow irrigated with non-saline water (0.5 ds/m EC_w). All treatments were preplant with non-saline water. When compared to yields from a plot which was irrigated with only non-saline water, there was no yield reduction in either the cotton or sugar beet, which are both salt-tolerant (Table 4). However, there was a 20% yield reduction in the wheat crop. In the drip treatments, saline water made up over 60% of the applied irrigation water; however, the concentrations of B in the plant tissue increased and were nearly toxic. The B concentration in the soil also increased throughout the soil profile in treatment T2, while the EC_e increased primarily in the upper 1 m of the profile. Using the reclamation guidelines in Hoffman (1986) it would take 130 mm of non-saline water to restore the EC_e profile to its previous levels while it would take almost 1 800 mm of water to restore the profile to the original concentration of B levels. these results show that if the saline water being used contains B, Se, or other toxic contaminants, the long-term profitability and sustainability of using saline irrigation water is questionable.

Drainage water treatment to remove selenium

A technique to lower the drainage water and/or soil-selenium (Se) by growing crops that take up large amounts of Se through their root systems is being studied by the Water Management Research Laboratory in Fresno, CA (Banuelos *et al.*, 1990). Se-tolerant plants that might remove soluble Se from the soil have been isolated (Banuelos & Schrale, 1989).

Plants that accumulate Se can probably volatilize Se as well as sequestering it within the plant by binding it with free amino acids, the precursors to proteins. This occlusion mechanism prevents Se from disturbing amino acids for protein synthesis in the plant. Consequently, Se-accumulators can tolerate high Se concentrations.

After having conducted greenhouse and field studies, Banuelos *et al.* (1990) reported that: (1) Se-accumulators, most notably wild mustard, take up Se in the selenate form more readily than in the selenite form; (2) if greenhouse results prevailed in the field, accumulator plants could be evaluated as hypothetical crops to remove Se from the soil; (3) with a plant population of 250 000 plant/ha, and five harvests annually, a total of 3.5 kg of Se/ha could be removed in the hay. Results also indicated that about 1.4 kg of Se/ha was volatilized by either soil micro organisms or the mustard plants. Thus about 4.9 kg of Se/ha could be removed from the soil if the rate of Se uptake in the greenhouse were sustained in the field (Banuelos *et al.*, 1990).

The economics of growing the wild mustard crop compared with biological treatment of the drainage water to remove Se were studied. Biological treatment has been estimated at \$0.25/m^3 drainage water. Drainwater with a Se concentration of 300 μg/kg would contain 300 mg Se/m^3; thus to remove 4.9 kg of

Table 4 Summary of yield data from Murrieta experimental site (1983 -1987) (after Ayars *et al.*, 1990).

Year	Crop	Yield (Mg/ha)		
		Saline Water		Non-Saline Water
		Surface Drip ($1ET_c$) (EC_w = 7.0 dS/m)	Surface Drip ($1.3ET_c$)	Furrow Irrigation (EC_w = 0.5 dS/m)
1983	Seed Cotton	3.3	3.3	2.6
1984	Seed Cotton	5.3	5.4	5.0
1985	Wheat	5.7	5.7	7.0
1986	Beet Sugar	10.6	10.4	10.8
1987	Seed Cotton	4.6	4.9	4.6

Se/ha, the treatment cost would be $4083.00. Thus, the value of harvesting wild mustard five times could be equivalent to $4083.00 less crop production cost (Banuelos & Schrale, 1989).

Conclusion

Water shortages and water quality are two of the major factors increasingly affecting irrigation and water management in California. Proposed management options to sustain irrigated agriculture require that source control be achieved in order for these options to be viable. Source control options include (a) water conservation, (b) drainage management, (c) crop management and (d) alternative land use. Options (c) and (d) do not involve irrigation research, but conversion of intensively irrigated land to other uses where such land would cease receiving imported water; therefore only options (a) and (b) are addressed in this paper. The major source control options proposes the use of subsurface drip irrigation to (a) significantly reduce evaporation at the soil surface, (b) maintain constant soil water and upward hydraulic gradient to minimize deep percolation and drainage outflow and (c) maximize water use efficiency and yield of crops with precise fertility management. These advantages were successfully demonstrated in research plots and large scale commercial applications. Additional source control can be achieved by drainage management through the reuse of saline water for irrigation. Although there was no yield reduction in either cotton or sugar beet and only a 20% yield reduction in wheat when saline water was applied through drip irrigation 60% of the time, the results showed that if the saline water contains B, Se, or other toxic elements the long term profitability and sustainability of using saline irrigation water is questionable unless the toxic elements can be removed. The use of various plant species to accumulate and remove toxic elements from drainage effluents (such as Se) is feasible. Wild mustard has been shown to remove as much as 4.9 kg/ha of Se in greenhouse experiments. In terms of biological treatment costs of $0.25/m^3, the value of the mustard crop, harvested five times, would be $4083.00 per ha.

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IRRIGATION IN ISRAEL - ACHIEVEMENTS AND CHALLENGES

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Abstract

In the last 40 year irrigation has transformed Israel's agriculture from an extensive, largely self-dependent cropping system based on a highly interannually variable rainfall, into an intensive, open system based on fossil fuel-based inputs of water and agrochemicals to produce high-value horticultural crops for export. The 30% reduction in water use per unit irrigated area achieved over this period and the 100% increase in yield per unit water application are ascribed to the national infrastructure of water supply, research and extension services, and legal constraints and economic opportunities which were established for this purpose. The increases in water use efficiency achieved hitherto, while impressive, are insufficient to enable irrigated agriculture to maintain on a sustainable basis its competitive position for the limited, high-quality water resources available. To maintain irrigated agriculture at its current unprecedented magnitude, 50% of the total cultivated area, will require a doubling of crop water use efficiency by the end of the century; it will also demand stringent measures to eliminate the negative effects of intensive irrigated agriculture on the quality of the natural water resources. New directions in research that could enable those challenges to be met are outlined. They call for a substantial improvement in the efficiency of crop water use rather than the increased efficiency in field water application achieved in the past. Although the investments required for such research and the risks involved are considerable, they are less than those needed to develop alternative water sources.

Introduction

When the State of Israel was established in 1948 its agriculture was the same extensive, dryland cropping system based on winter rainfall described in the Bible three millennia ago. The major crops were the same indigenous winter cereals and autumn fruits listed in Deuteronomy XIII.8; their yields were as dependent on the highly variable winter rainfall as the Israelites, returning from their exile in Egypt, were warned in Deuteronomy XI.11, 14-15.

Throughout this long period, irrigated agriculture in Israel had been restricted to the vicinity of the few surface or near-surface sources of water. These sources, largely confined to the central coastal plain and inland Jordan rift valley, were used to irrigate fruit orchards and vegetable gardens from a multitude of shallow wells via simple, open distribution systems (Feliks, 1963; Galton, 1908).

Since the middle of this century, irrigation has transformed the face of Israel's agriculture, to approach the prophetic description of "a watered garden, and like a spring, whose waters fail not" (Isaiah 58.11).

Past achievements and present problems - a quantitative description

The area of Israel which is irrigated has increased more than fivefold in the last 40 years, from 375 km^2 in 1949 to 2 142 km^2 in 1989. This represents a rise from 15% to 49% in the irrigated fraction of the total cultivated area. Over the same period the volume of water used in agriculture rose from 0.400 to 1.840 km^3 per year. This increase is far less than that in the irrigated area resulting in a one-third decrease in water application per unit irrigated area, from 8 530 $m^3\ ha^{-1}yr^{-1}$ in 1949 to 5 780 $m^3\ ha^{-1}yr^{-1}$ in 1989. Expressed as yield of harvested produce per unit of irrigation water applied, irrigation water use efficiency rose from 1.60 kg m^{-3} in 1949 to 2.32 kg m^{-3} in 1989.

The progress in these two measures of the efficiency of water use in Israel's irrigated agriculture, illustrated in Figure 1, has been continuous. The data on water application show a high degree of linearity, with a coefficient of determination on year of $r^2 = 0.89$; its slope indicates an annual reduction in water application of 84 $m^3\ ha^{-1}$, or -1.16% of the mean value for the past 40 years. The annual increase in harvest yield per unit water application is also linear with time, $r^2 = 0.78$. The fitted slope represents a yield increase of 0.04 kg m^{-3} per year, representing an annual increase of 2.15% of the mean.

When water use in Israel's irrigated and processed agricultural produce - produced almost exclusively from the irrigated sector - is expressed in commercial terms, the foreign currency earned per unit water application has risen from US$ 0.04 per m^3 in 1949 to US$ 0.42 per m^3 in 1989. After allowing for US inflation over the same period, the amount of foreign currency produced per unit irrigation water doubled over the period of comparison.

The achievements of the last 40 years highlighted by the above figures are, however, matched by the magnitude of the challenges now facing Israel's irrigated agriculture. The extent of these challenges can be demonstrated by the fact that the cost of water in Israel, estimated to average US$ 0.35 per m^3 in 1989, represents more than three-quarters of the total export earnings. At the same time the agricultural users of this water paid only US$ 0.13 per m^3, barely covering one-third of the water's cost (Grinwald & Bibas, 1989; State Comptroller, 1990).

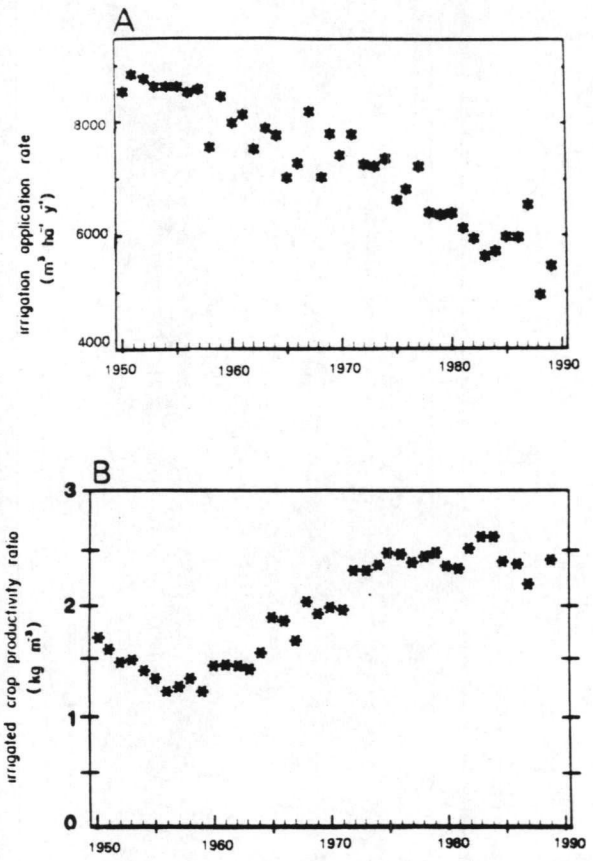


Figure 1 Change in irrigation application rate and its crop yield productivity; mean annual values for irrigated crop area: A) average annual irrigation application per unit irrigated crop area, m^3 ha^{-1}; B) average annual yield of irrigated crop harvested per unit water application, kg m^{-3}. (Source: annual volumes of Statistical Abstract of Israel).

Agriculture's inability to compete with the growing domestic and industrial demands for the over-exploited national water resources is shown clearly by the rapidly declining fraction of the water supply allocated to irrigation. This fell from 80% in 1949 to 68% in 1989; by the year 2000 a decrease to 60% is planned (Grinwald & Bibas, 1989; State Comptroller, 1990).

Clearly, the current expansion in the irrigated area will have to stop if this planned reduction in agricultural water use is to be met. At the present levels of water application a 5% reduction in the irrigated area is needed. However, the present area of irrigated land could be maintained if the current decrease in water application rate illustrated in Figure 1 is sustained.

To maintain both the current area and the total production of the irrigated sector, and at the same time realize the planned reduction of water allocation to agriculture of 1.18% per year by 2000, will require a major increase of water use efficiency in terms of yield. A mean yield of 4.31 kg m^{-3} will be needed by 2000, almost double the current value of 2.32 kg m^{-3} and considerably more than the value of 3.19 kg m^{-3} derived by extrapolating past trends (Figure 1) to the year 2000.

The challenge facing Israel's irrigated agriculture today is, however, much greater than even these figures suggest. One reason is that the reductions in water allocations envisaged even last year did not provide sufficiently for the need to restore water reserves in underground and surface storage systems to higher and safer levels. Nor does it seem probable that the substantial investments needed to provide the projected end-of-century water supply to agriculture will be forthcoming. For these reasons the cuts in water allocation to agriculture now being implemented are one order of magnitude greater then those which were called for by the end of the decade (State Comptroller, 1990).

The second reason is the deterioration in the quality of water available for irrigation. In 1985 only 15% of the agricultural water was supplied from marginal, saline and urban sewage sources; by 2000 it is estimated that such sources will provide 37% of the water used for irrigation. As a consequence the salinity of the national water supply is expected to increase sharply. In 1985 36% of the nation's water had a salt concentration above 170 g m^{-3}; it is estimated that by the year 2010 54% will be above this level (Grinwald & Bibas, 1989; State Comptroller, 1990). The increasing salinity of the ground water, depicted in Figure 2, implies an annual addition of 4 260 t of salts to the aquifers, or 10 kg of salts a year from each cultivated hectare.

Not only will less water of lower quality be available for irrigated agriculture; it will also need to avoid causing any negative impacts on the nation's water quality. The increase in the concentration of nitrates in the national water supply, much of which may be of agricultural origin, provides a pointer to this last challenge. In 1985 14% of the water volume had a nitrate concentration above the threshold value of 45 g NO_3 m^{-3}; by 2010 it is estimated that 27% will be above this level (Figure 2). This increase represents an annual addition of 440 t of nitrates to the ground water, or an annual contribution of 1.1 kg from each cultivated hectare.

Can these formidable challenges concerning the quantity and quality of water availability and environmental impact be met? In particular, can improvements in irrigation application and water use efficiencies of the type achieved over the last 40 years be accelerated to the extent needed to ensure that irrigated cropping retains its major place in Israel's agriculture on a sustainable basis?

To make a realistic assessment of this possibility requires an understanding of how past progress was achieved. An attempt to do so is made in the following

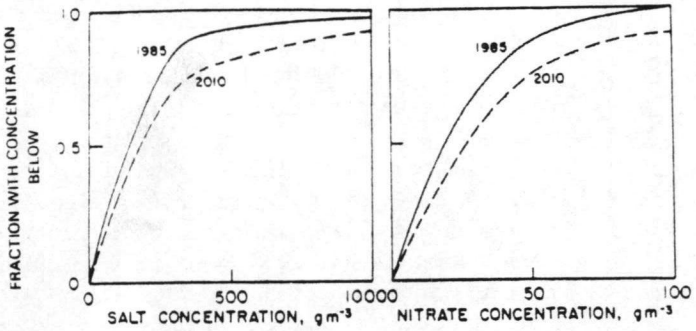


Figure 2 Estimated changes in ground-water quality in Israel from 1985 to 2010: A) cumulative distribution of salt concentration, g m^{-3}; B) cumulative distribution of nitrate concentration, g m^{-3}. (Source: State Comptroller, 1990, Figures 5 and 6).

section.

How past progress was achieved

A major step in the development of Israel's irrigated agriculture was the construction of the National Water Carrier, which links the country's major water resources in a national grid. Construction started in the early 1950s and was completed in 1964, at a cost of US$ 120 million. Since completion, approximately one-third of a km^3 of water is pumped each year from Lake Kinneret - which lies 200 m below sea level - over the 400-m-high hills of lower Galilee to reach the arid, irrigated south (Figure 3). En route, the National Water Carrier connects the Jordan head-waters with the country's two major underground water reserves - the coastal and mountain aquifer systems.

The total working storage capacity of the three reservoirs - Lake Kinneret, the coastal and mountain aquifers - is 2.5 km^3, made up, respectively, of 0.7, 1.0 and 0.8 km^3. It is these reserves, now seriously depleted, which have hitherto allowed the agricultural sector to receive a more or less even supply of water despite the large natural, climatic variation in the water supply. Since the completion of the National Water Carrier, the interannual variation in agricultural water volume expressed as coefficient of variation, has been only 9% (Stanhill & Rapaport, 1988).

The water supply for irrigation is not cheap in terms of the energy needed to lift and transport water through the National Water Carrier. Averaged over the system, 0.8 kWh of electrical power is needed for each m^3 transported; generated at 32% thermal efficiency this implies an average gross energy requirement of 11.2 MJ m^{-3}.

Another important development in the physical infrastructure of Israel's irrigation sector has been the change in equipment used. As soon as pressurized water became available at the field, surface application methods were rapidly replaced by portable aluminium sprinkler lines. Over the last decade these, in turn,

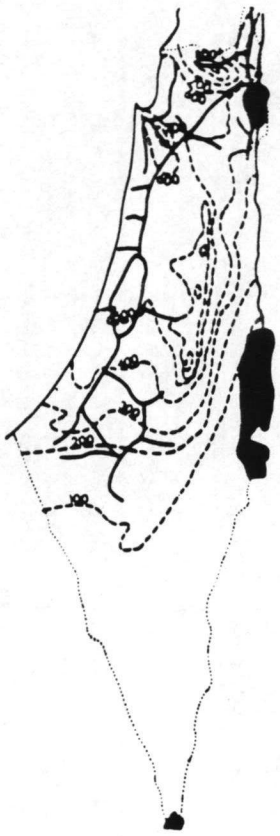


Figure 3 National Water Carrier and Mean Annual Rainfall in Israel, 1931-1960, mm yr^{-1}.

gave way to a range of semi-solid-set precision systems, allowing automatic and exact control of the position, time and volume of water application as well as the addition of fertilizers and pesticides to the irrigation water. It has been estimated that today 60% of the irrigated area in Israel uses drip systems, 10% micro-sprinklers and 5% moving lines, leaving one-quarter of the area irrigated by portable sprinkler systems (Sne, 1991).

These changes in irrigation equipment have almost certainly been responsible for a substantial proportion of the improvement in water application efficiency, i.e, an increase in the fraction of water delivered to the field which is productively transpired through the crop. Unfortunately, field survey data to quantify this improvement are not available. The rule of thumb estimate ascribing a 0.15 increase in efficiency to both the changes from surface to moveable sprinklers and from moveable sprinklers to current, fixed precision systems does, however, seem reasonable and would explain all of the reduction in irrigation rates achieved during the last 40 years.

Another factor that could be partially responsible for the reduction in water application rates is the change

in cropping pattern within irrigated agriculture - from field to horticultural crops. Unfortunately, data on water application according to crops are not available to quantify the importance of this change, but it is well known that the water requirements and indeed allocations for many of the short-season horticultural crops are much less than those of the erstwhile widely grown perennial and annual forage and pasture crops. This is also true of their yields; presumably this explains the surprising lack of change in the gross mean yield of irrigated lands (Table 1).

Table 1 Irrigated agriculture in Israel forty years on.

	1949		1989	
Irrigated area, km^2	375	(1.00)	2142	(5.71)
Water applied, km^3	0.400	(1.00)	1.80	(4.60)
Application rate, m	0.853	(1.00)	0.578	(0.68)
Crop yield, t ha^{-1}	13.65	(1.00)	13.41	(0.98)
Export earnings \$ ha^{-1}	367	(1.00)	2427	(1.51*)
\$ m^{-3}	0.04	(1.00)	0.42	(2.40*)

* Allowing for US dollar inflation

Before discussing the methods adopted to implement the increase in irrigation efficiency, two less-positive aspects should be mentioned. The first is the inevitable reduction in aquifer recharge and salt leaching. Previously, one-fifth of the irrigation water applied was calculated to be available for reuse through aquifer recharge; today the figure is presumably much lower. A second negative aspect is the high energy requirement of water-saving by modern irrigation equipment. Portable aluminium sprinkler lines sequester 0.29 GJ of energy annually per hectare in the amortization of equipment; solid set drip lines amortize 50 times as much, 14 GJ $ha^{-1}yr^{-1}$.

The net energy cost of saving water by using more efficient equipment is considerable. Each cubic meter of water saved by substituting a drip irrigation system with an application efficiency of 0.85 for a traditional, surface application system with an efficiency of 0.55, involves a net energy investment equivalent to one litre of oil: 39 MJ. At this exchange rate, the water saved can be used economically only for the production of very high value crops.

Any explanation of the progress achieved in the last 40 years must include the essential role played by the development of the "intellectual infrastructure" for irrigation in Israel, i.e, the research and extension services and the legislative aspects of water allocation.

Research to determine the optimum irrigation regime for the major crops was begun in the mid-1950s concurrently with the planning of the National Water Carrier. A nation-wide program of large-scale, randomized-block field experiments was carried out by the staff of the Agricultural Research Organization's Institute of Soils and Water at experiment stations established in the major soil and climate regions of the country. Over 250 such experiments have been carried out using commercial irrigation equipment to apply five of six different irrigation treatments in which the effects of different irrigation intervals. depths of wetting and timing of the first and last irrigation on yield and evapotranspiration were compared for two or three seasons. The optimum recommended irrigation treatment derived from these experiments was that which required the least water while at the same time giving a yield statistically not significantly different from (that is, within 10-15% of) the highest yielding treatment.

These crop water requirement experiments are time consuming and they represent the major effort of a group of some ten scientists and fifteen technicians over a period of 20 years. Not only are they costly and difficult to execute, but they lack scientific glamour. For all these reasons a major effort has been made in Israel as well as abroad to generalize the results obtained, in the hope of avoiding the need to continue the program.

The approach followed in analyzing both the Israeli results (Shalhevet *et. al.*, 1981) and those carried out world-wide (Doorenbos & Kassam, 1979), has been to express yield, normalized to the maximum obtained in the experiment, as a linear function of evapotranspiration, normalized to the climatically limited potential. Despite the success achieved by this analytical approach, it is doubtful if it can serve as more than a first step to establishing optimum irrigation treatments, especially in view of the many interacting challenges facing irrigated agriculture in Israel. One reason is the evidence that within-crop variation in the crop response factor, i.e., the slope of the relative yield to relative evapotranspiration relationship, is as large as that between crops (Stanhill, 1985). A second and perhaps related reason is that changes in the quality of water applied and in irrigation equipment used, and in the cost of water and value of crop, can be expected to change the optimum irrigation treatment.

A single crop response factor cannot be expected to allow for the effects of all these variables and there is a growing appreciation that some of the early crop water requirement experiments may have to be repeated, using the different irrigation application methods and water qualities now in us, and imposing the more arid range of treatments appropriate to higher water costs.

Thus, even the major research effort which accompanied and promoted the development of irrigated agriculture in Israel - more than 500 scientific publications dealing with crop response to water are listed in the Institute of Soils and Water's indexed bibliography (Rapaport, 1986) - can only be expected to provide provisional recommendations for field practice.

As soon as such recommendations became available from the research workers, they were rapidly transferred to the farmers by the Ministry of Agriculture's Irrigation and Field Extension Service. Established in 1955 to provide advisory services for both irrigation and fertilization, this service currently consists of a headquarters staff of five with 35 field advisors and 40 technicians stationed at 15 regional laboratories. The total cost of this Extension Service, approximately half of which deals with irrigation, was estimated at US$ million in 1989 (Sne, 1989). Half of this cost is met by the farmers themselves, through their regional councils.

One of the strengths of the Extension Service and reasons for the staff's close relations with the farmers is that it has no responsibility for the supervision or enforcement of the water allocation policy. Presumably, and perhaps unfortunately, this clear separation prevents the use of the Extension Service's expertise and relations from being used to monitor changes in field irrigation practice and thus provide essential information on the distribution and efficiency of irrigation according to crop, and method of application, as well as soil and climate region.

Legal responsibility for allocating water according to national needs and priorities was vested in the Ministry of Agriculture's Water Commissioner by the Water Law passed in 1959. The total volume of water allocated annually to each agricultural holding, and its seasonal distribution, were based on three factors: the area of crops grown at that time, the recommended optimum water requirement for each crop according to the holding's soil and climate and, perhaps most importantly, economic considerations based on the principle of providing each farmer with sufficient water to ensure his livelihood.

This system of water allocation provided farmers with a powerful incentive to increase their water application efficiency and thereby expand the proportion of their holding on which the more profitable irrigated crops could be grown. Freedom to allocate water within each holding according to economic considerations was abetted by the lack of an effective regulatory system as well as by the absence of an updated crop inventory for individual holdings and an up-to-date water requirement data base. The latter values were last gazetted in 1976 under the heading "Maximum Water Requirements in Agriculture". It is worth noting that these figures, as well as the non-mandatory recommendations of the Field Extension Service, show little difference from values published 20 years earlier.

This brief review of how improvements in irrigation practice were achieved in the past points to the complex interaction existing between technological developments and market forces. Implementation of the research findings on optimum crop water requirements was aided by the availability of a suitable water distribution network and irrigation equipment and the operation of an efficient extension service. Motivation was provided by the farmer's need to maximize water application efficiency, as in nearly every case water, not land, was the factor limiting crop production. Substantial government subsidies of the price of water and irrigation equipment, as well as the cost of research and extension services provided additional economic opportunities to the farmer.

Unfortunately, these same forces tended to delay recognition and the treatment of the serious hydrological and economic problems facing irrigated agriculture in Israel. New approaches which could eventually provide solutions to these problems are discussed in the concluding section of this paper.

How present challenges could be met

In the previous section, past progress was attributed to increased efficiency in irrigation application, i.e., a greater proportion of productive transpiration per unit volume of water applied to the field. With efficiencies approaching 0.9 becoming commonplace, the potential for further substantial progress appears to be very limited.

By contrast, little progress has been made and indeed very little attention directed to the alternative more basic approach - the increase of crop productivity per unit transpiration. Progress in this direction requires that the closely linked processes of transpiration and yield formation be decoupled - a formidable task (Stanhill, 1986). However, a breakthrough in this field would allow substantial reductions in agricultural water use, allow farmers to pay higher prices per unit water and help ensure the future of irrigated cropping.

Two distinct directions for research can be distinguished. One would direct the effort to achieving a substantial reduction in crop transpiration without a corresponding decrease in crop yield. Of the limited research in this direction, most has sought to increase crop plant resistance to the diffusion of water vapour through the stomatal, cuticular and boundary layer segments of the pathway between the vapour source within the leaf and the vapour sink in the free atmosphere. As this pathway is significantly shorter than that for CO_2, increased resistances can be expected to reduce transpiration more than assimilation and so increase water use efficiency.

As the resistance to water movement through the leaf cuticle is very high in nearly all crop plants, there appears to be very little opportunity for its increase. The opposite is the case for boundary layer resistance: selecting crop varieties with larger, more hirsute and rigid leaves arranged in canopies with clumped leaf distribution could increase this resistance, as could the use of non-transpiring, open-windbreaks.

The resistance pathway offering the most opportunity and promise for manipulation appears to

be that of the stomates. Attempts to increase stomatal resistance both by the external application of biochemically active and inert physical barrier materials, and by the selection of plants with fewer, smaller and more rapidly closing stomata, have had little success. One important reason is the complex interactions occurring between external and internal conditions and the stomata. These make it extremely difficult to provide the plant breeder, or genetic engineer, with an ideotype of stomatal dimensions or behaviour which could be expected to increase water use efficiency under the diurnally and seasonally varying field conditions.

A more general difficulty associated with methods which increase diffusion resistance is the resulting rise in the equilibrium temperature of the transpiring leaf surface. By increasing the vapour pressure at these surfaces the transpiration potential will be raised and in arid climates leaf temperatures may be above the optimum for photosynthesis; certainly the respiration loss of dry matter will increase. These negative feedback effects of increasing transpiration resistance are most important under conditions of high air temperature and potential transpiration, i.e., in the very situations where transpiration reduction is most needed.

The alternative approach to transpiration reductions - by reducing the absorption of radiant energy - has the theoretical advantage that the conserved energy is radiated back to space rather than convected into the plants' environment. This avoids any negative feedback effects. The complication of this approach is caused by the need to increase reflectivity in those wavelength bands which are strongly absorbed by plant leaves and yet which are relatively ineffective for photosynthesis.

Spectrally selective changes in the radiative characteristics of crop leaves could potentially reduce transpiration without affecting carbon dioxide assimilation. A comparison of radiation absorptance of crop leaves (which differ very little) and relative photosynthetic activity, i.e, micromoles of CO_2 fixed per unit energy absorbed, shows non-agreement over much of the solar spectrum. Below 550 nm, absorption is much higher than is photosynthetic activity. By increasing reflectivity over the shorter, blue wavelengths, energy absorption, and hence transpiration potential, could be decreased by 16%. Within the red wavebands of maximum photosynthesis, 550-670 nm, a reduction in leaf scattering could increase Co_2 fixation and dry matter production by 6%. Eliminating the two major peaks of radiation absorption in the photosynthetically inactive infra-red bands centred at 1450 and 1950 nm could reduce transpiration potential by another 14%. If crop leaf absorption was completely matched to its photosynthetic activity over the entire solar spectrum, energy load and transpiration potential could be reduced by at least 25%.

The feasibility of reducing transpiration by effecting these changes cannot be assessed at this stage. However, there is some evidence that it is feasible from the large and adaptive range of radiative characteristics that has been found among non-crop plant species (Billings & Morris, 1951; Ehleringer, 1980). The lack of such a range in crop species (McCree 1971/2; Gausman *et al.*, 1973) is not surprising in view of the fact that crop plant breeding has largely been for non-water-limiting, potential yielding conditions.

The limited attempts to reduce transpiration in the field by the external application of spectrally non-selective reflectants have not been very successful. Some promising results were obtained in field experiments in which kaolin sprays were applied to sorghum at water-sensitive growth stages (Stanhill *et al.*, 1976), but field applications of reflectants are generally limited to high-value crops under special conditions (Rosenberg *et al.*, 1983).

A second direction for research into increased crop water use efficiency is the search for ways to increase crop yield substantially without a corresponding increase in transpiration. Inadvertently, much progress in this direction has already been achieved by plant breeders by increasing the proportion of total dry matter production harvested in the yield component. For example, in today's high-yielding wheat varieties, grain represents half of the total dry matter as compared with one-third or less at the beginning of the century. As modern varieties have a smaller leaf area and are shorter in height and crop duration, their transpiration may also be less. Thus, the transpiration ratio, the mass of water transpired per unit yield, may now be two-thirds of the value a 100 years ago.

The large potential for further major progress in this direction is evident from the considerable differences in the transpiration ratio of the wide range of crop and weed plants studied by Shantz & Piemeisl over 70 years ago (Figure 4). The transpiration ratios of the 14 plants with C_4 carbon fixation metabolisms - the group which contains the majority of crop plants - were all below 400; their mean, 320 $\pm$ 43, was exactly half of and significantly different from that of the 51 species with C_3 metabolism, with a mean of 640 $\pm$ 165. A comparison of these ratios (Shantz & Piemeisel, 1927) with those of the five species with Crassulacean acid metabolisms (CAM) tabulated by Ting (1976), indicates a much lower mean transpiration ratio for such plants, 103 $\pm$ 45. The six measurements listed for the two CAM crops plants, agave and pineapple, averaged 69.

If the carbon metabolism responsible for the high net dry matter production of C_4 plants could be transferred to C_3 crop species, a major increase in yields could be achieved without any increase in transpiration. The transfer of the very energy-

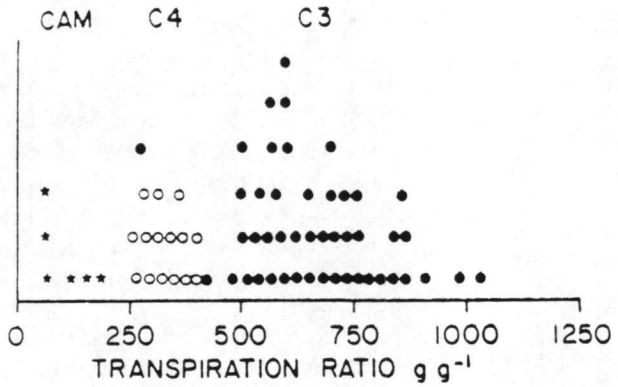


Figure 4 Distribution of transpiration ratios of plants according to carbon metabolism, g H_2O g^{-1} dry matter accumulation. (Source: C_3 and C_4 plant species, Shantz and Piemeisel (1927). CAM plant species, Ting (1976)).

demanding CAM mechanism would reduce the transpiration ratio even more, but at the cost of low absolute levels of dry matter production.

The possibility of transferring the different photosynthetic mechanisms from one species to another has been demonstrated, although not yet in crop plants. The existence of intermediate C_3 - C_4 species and of plants with different carbon pathways, within the same subgenus, and of a number of C_3 plants which switch to CAM under conditions of water stress, all attest to these possibilities.

Attempts to transfer selectively the different photosynthetic metabolisms using the techniques of molecular biology are being made in addition to conventional plant breeding. The difficulties for such genetic engineering are formidable and success on a short-term timescale is unlikely, especially in view of the limited resources being invested.

In concluding this speculative discussion on how present challenges to irrigated agriculture in Israel could be met by increasing the efficiency of crop water use, i.e, by reducing the transpiration rates, it should be stressed that the processes of crop water loss and yield are so strongly linked that a major research effort is needed to uncouple them.

The urgent need for progress in this direction suggests that there is little alternative to investing in such a basic and sustained effort, if the future of large-scale irrigated agriculture in Israel, and eventually over much of the world, is to be assured.

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IRRIGATION : LONG-TERM VIABILITY OF SOIL AND WATER RESOURCES IN SOUTH AFRICA

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Abstract
Irrigation practice plays a vital role in South Africa and contributes almost 30% to the total agricultural production. Little more than one percent of farmland is irrigated yet agriculture is by far the largest consumer of available water resources. It is confirmed that the long-term viability of soil and water resources is in jeopardy. Major threats to these resources result from waterlogging, salinity, sodicity, physical degradation and pollution. It is estimated that over 10 percent of the area under irrigation is already degraded. Apart from problematic soils that occur on most schemes, important causes of degradation include suboptimal farm management, poor planning, leakage from dams and canals, financial constraints and off-site damage. Attempts at reclaiming degraded land have proved successful but costly. Priorities identified to counteract continuing degradation include a national irrigation strategy, improved irrigation and water resource management, research, appropriate monitoring and reliable information systems.

Introduction

In South Africa agricultural output is greatly influenced by the vagaries of rainfall and farm management. Irrigation plays a vital role in stabilizing production, facilitates the growing of high-value crops of strategic importance and allows for the implementation of important socio-economic and political dispensations. Although little over one percent of the agricultural land is irrigated it contributes over 30% to the gross value of crop production.

Irrigated agriculture is also by far the largest consumer of available water supplies (48%). Despite its many advantages irrigation practice has taken its toll on the limited soil and water resources of the country.

Over the long history of irrigation development in South Africa various forms of resource degradation have manifested themselves and have grown in severity. At the very first SA Irrigation Congress held in 1909, much concern was expressed at the extent of salt affected soils, the sediment content of water supplies, the lack of "fit" land and the grave deficiencies in farm management (Kanthach, 1909; Brafield, 1909; Juritz, 1909). At the same time almost 0.23 million ha were under irrigation and it was projected that eventually 1.3 million ha could be irrigated. In his address to Congress Kanthach (1909) stressed that "a scheme which is neither profitable nor protective is not justified". Thus the basic concept of long-term viability was implicit in the views of the decision-makers of that day. The major concerns expressed at that very first gathering held in Robertson have been repeated with monotonous regularity at all subsequent Congresses and Symposia focused on irrigation. Why, it may be argued, have earnest attempts to halt degradation and uplift irrigation standards met with such limited success?

Growing demands for food and fibre, increasing competition for scarce resources of soil and water and greater concern for environmental quality make it appropriate to review the impacts of irrigation practice.

The aim of this paper is to reflect the current status of degradation and to identify the major factors posing a threat to long-term viability. Related issues such as farm management, economic influences and research needs are also considered. Several priorities of paramount importance to the future development of irrigation in South Africa are identified.

It should be appreciated that the review relates specifically to commercial farming in South Africa. The lack of a comprehensive and reliable source of data proved to be a major hindrance and much reliance has been placed on surveys and investigations of State schemes undertaken by government Departments. Almost 150 reports are housed at the Soil and Irrigation Research Institute which detail the occurrence of salt affected soils and waterlogging on such schemes.

Natural resources and irrigation

Climatic conditions in South Africa make irrigation a valuable option for many farmers. With over 60% of the country receiving less than 500 mm rainfall per annum, high evaporative demand in most areas and great variability of rainfall, irrigation plays a vital role in stabilizing agricultural production. Devastating droughts and periodic floods have caused untold damage and financial ruin for many farmers practising irrigation. The soil mantle is diverse, highly complex and vulnerable to man-induced degradation. Even within small areas soils often have wide diversity in terms of physical and chemical properties. Almost 81% of the country comprises slightly weathered and often calcareous soils. This implies unfavourable physical features (e.g. duplex soils) and high levels of natural salts (Scotney & Dijkhuis, 1990).

Soil resources

Traditionally, irrigation schemes were established on almost level alluvial soils along major river systems. These, mostly young soils, vary greatly in textural composition, internal drainage and salt content.

Suitable soils are often intricately interwoven with those with severe limitations. For this reason, it soon (1929) became mandatory for soil surveys and suitability assessments to be undertaken prior to the establishment of State schemes. Review of many such soil surveys, mostly undertaken on a grid system, reveals that soils free of limitations for irrigation are limited in extent. Less than 10% of soils on schemes such as Vaalharts, Nkwaleni and Lower Fish River are of high suitability. On the Pongola scheme such soils occupy 33% of the total area and on most other schemes rarely exceed 30% to 40% of the erea surveyed. The remaining soils are associated with physical and/or chemical limitations of varying severity. The complex spatial distribution of soils on most schemes poses an important problem for farm management.

In recent times improved methods of water distribution have allowed irrigation to expand onto sloping upland areas where problems such as shallow depth and subsurface lateral drainage demand management of high order. Many soil-related problems have been noted by Du Plessis (1986a).

Water resources

Water supplies in South Africa are limited, highly variable and poorly distributed. Already water supplies in some catchments are over-stressed, especially in low-flow periods. Competition for scarce water supplies will increase markedly in future and could be aggravated by changing land-use patterns (e.g. afforestation) and the effects of possible global climatic changes.

Irrigated agriculture is by far the largest consumer of available water resources and will remain so for the foreseeable future. Table 1 summarizes the current and future demands for water by selected consumers.

Table 1 Water demand (million m^3 a^{-1}) by selected consumers: 1990-2010 (after Department of Water Affairs, 1986).

Consumer	1990	2000	2010
Irrigation	8497 (48%)	9707 (47%)	10675 (46%)
Municipalities	2108 (12%)	2745 (14%)	3704 (16%)
Industries	2468 (14%)	3254 (16%)	3888 (17%)
Other	4696 (26%)	4889 (23%)	4994 (21%)
Total	17769	20595	23261

It has been estimated that 60% of the total surface runoff (53 500 million m^3 a^{-1}) could be economically exploited (Department of Water Affairs, 1986). Underground supplies contribute an additional 5 000 million m^3 a^{-1} but less than 2% of this source is used for irrigation (Du Plessis, 1986b). According to Du Plessis (1986b) sufficient water is available to increase the area under irrigation by an additional 0.3 million ha. However, general consensus today suggests that water supply, both quantity and quality, will determine the final extent of irrigation in South Africa. Deteriorating water quality is a major concern for irrigation but may not necessarily have negative effects in all situations.

In the face of dwindling water supplies, improving water use efficiency poses a major challenge. Losses of water result from over-irrigation (10-15%), on-farm distribution systems (20%) and excessive leaching (5-10%) and may reach up to 50% of the total allocation (Du Plessis, 1986b).

There is little likelihood that additional contributions will come from the re-use of industrial, mine and municipal waters. Fuls & Du Plessis (1977) estimated that only 150 million m^3 a^{-1} could be expected from such sources. However, large volumes of acid and neutralized waters have recently become available from the mining industry which could contribute additional water once research is undertaken and policy is reviewed.

In view of the current wastage and inefficient use of irrigation water, review of the current pricing policy appears justified. Present charges are not related to the capital or maintenance costs of providing water nor are prices related to environmental (e.g. salinisation) and social impacts. Since 1986 charges have been determined for each scheme largely on the basis of operating costs.

Irrigation practice

The extent of irrigation in South Africa is generally estimated to be 1.2 million ha (Du Plessis, 1986b). A recent survey has confirmed this estimate and reveals that most (30%) irrigation takes place in the Transvaal region (Departement Landbou-ontwikkeling, 1990). Table 2 reflects the extent of irrigation in each agricultural region while the spatial distribution based on the extent in each magisterial district is reflected in Figure 1.

Major trends have taken place since flood irrigation on State schemes was the order of the day. Today, most irrigation takes place on private farms (59%) followed by that on Board (22%) and State schemes (19%). The most common forms include sprinkler (55%), surface (33%) and micro (12%) systems (Du Plessis, 1986b).

Until very recently there was a major swing to capital intensive centre pivot systems. These systems have not always been to the economic benefit of the farmer and this trend has now changed. There also appears to be greater diversity in production, including livestock enterprises, currently associated with such systems. A further benefit observed from current trends is the tendency for farmers to expand the extent of their irrigation using the same allocation of water.

Table 2 Extent of irrigation per agricultural region (after Departement Landbou-ontwikkeling, 1990).

Agricultural Region	Extent Irrigation (ha)
Transvaal	333 325
Winterrain	257 050
Orange Free State (OFS)	167 435
Karoo	154 504
Natal	152 692
Highveld	81 163
Eastern Cape	73 344
Total	1 230 844

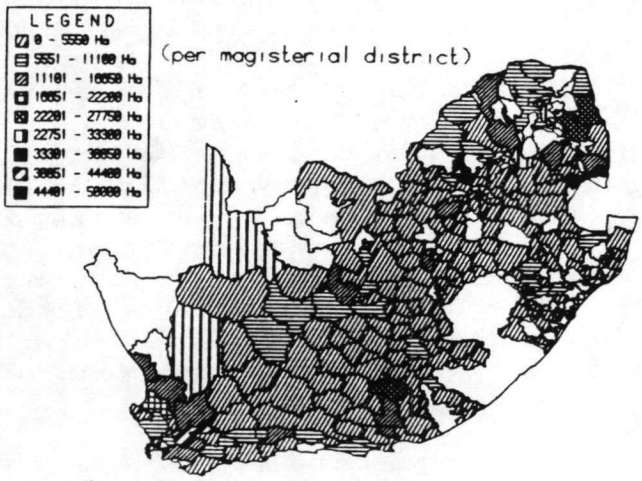


Figure 1 Extent of irrigation in South Africa.

Such practice mitigates against over-irrigation. There also appears to be a general correlation between high-order irrigation efficiency and the production of high value crops.

Excluding cultivated pastures (0.2 million ha), the most extensive crops irrigated are lucerne (0.21 million ha), wheat (0.18 million ha), maize (0.11 million ha), vineyards (0.10 million ha) and sugarcane (0.07 million ha). Maize, the most extensive dryland crop grown, occupies almost 10% of the area under irrigation (Departement Landbou-ontwikkeling, 1990).

The relationship between irrigated crops and pastures and soil potential is reflected in Table 3.

The irrigation of non-adapted crops and the mismatch of crops and soil potential are matters of major concern. High value crops such as vegetables, fruit and vineyards are well-suited to irrigation while those such as grain, sorghum and sunflower are not. An analysis of current cropping patterns suggests that scarce resources of soil and water are not being fully optimized. Table 4 shows that some highly adapted crops are grown on low potential soils and *vice versa*.

Table 3 Extent (%) of irrigated crops and pastures on soil potential classes (after Departement Landbou-ontwikkeling, 1990).

Soil potential	Crops	Pasture
High	51	35
Moderate	34	49
Low	13	16
Unsuitable*	2	-

*Based on departmental norms

Table 4 Crop adaptability to irrigation and soil potential (after Departement Landbou-ontwikkeling, 1990).

Crop Adaptability Class	Area Planted ($x10^6$ ha)	% Grown on Soil Potential Class		
		High	Moderate	Low
Very good	0.6	50	33	17
Good	0.5	40	40	20
Moderate	0.2	31	50	18
Poor	0.01	42	29	28
Very poor	0.01	82	17	1

The results of the recent survey show that an area of 1.23 million ha is currently irrigated. This takes place on 42%, 36% and 22% of high, moderate and low potential soils respectively (Departement Landbou-ontwikkeling, 1990). Furthermore, there appears to be scope to expand irrigated cropland by 0.14 million ha and that for pastures by 0.12 million ha. This is similar to the total of 0.25 million ha previously estimated (Du Plessis, 1986b). Thus the estimated total extent of irrigation including future expansion is between 1.40 and 1.50 million ha. As water resources become limiting it would be prudent to restrict irrigation to adapted crops and soils of high and moderate potential.

Is long-term viability in jeopardy?

Examples of severe degradation of soil and water resources under irrigation can be found the world over. These date back as far 2 400 BC with the disasters that occurred along the Tigris and Euphrates rivers. In South Africa such problems manifested themselves almost a century ago. In 1909, Juritz alluded to the Van Wyksvlei scheme and noted that "the brack area has been continually increasing ... at present there are almost seven miles of soil below the dam incapable of cultivation". In more recent times the seriousness of soil degradation in South Africa has again been highlighted (Scotney & McPhee, 1990). Du

Plessis (1987) noted that inefficient use of water, salinization and waterlogging were major problems on irrigated land and stressed that rehabilitation of degraded areas could only be achieved at great cost.

Extent of resource degradation

In the absence of reliable monitoring systems an assessment of degradation has been made by reviewing studies of selected State schemes. The most common criteria employed include pH, salinity and sodicity levels and the presence of water tables. The degree of waterlogging appears to be strongly influenced by seasonal rainfall.

Soil Resources

Apart from changes in chemical conditions, physical problems such as crusting, compaction, structural breakdown and high water tables render soils incapable of sustained productivity. An assessment of the total extent of degraded soils mainly on State schemes and for selected years was made by Du Plessis (1986a). This assessment was largely based on estimates by Streutker (1982) and is summarized in Table 5.

On the basis of this assessment at least 12% of the total area irrigated had suffered from some form of degradation. In 1950 the area of the affected soils was estimated to be 4% of the total area irrigated which suggests a steady increase in the extent of degradation over time (Streutker, 1982). In 1985 an area of 20 000 ha in the Karoo region was considered to be so severely affected that reclamation was not economically justified (Du Plessis, 1986a).

Table 5 Assessment of degraded irrigated soils in specific years (after Du Plessis, 1987a).

Year	Extent degraded (ha)
1975	111 000
1976	100 000
1985	107 000
1986	125 000

It is appropriate to consider a number of examples of soil degradation as they apply to selected State schemes and to the fields of soil fertility and physical conditions.

A summary of the extent of waterlogging and salt-affected soils on selected schemes as estimated by Streutker (1982) is presented in Table 6. On the basis of these estimates the average extent of degraded soils is of the order of 16% of the area irrigated. The situation as it applies to a number of well-known schemes is discussed in greater detail.

Vaalharts: This scheme was initiated in 1929 and covers some 36 000 ha comprising 1 200 farms. Periodic studies have revealed that severe waterlogging and salinity are major problems on the scheme. Shortly after the commencement of irrigation, water tables on many farms rose to within 0.9 m of the surface (Streutker, 1981a). In 1967 Meyer reported that 30% of the farms were severely waterlogged and/or saline. Following intensive study of the area in 1975 Streutker (1981b) estimated that an area of 3 000 ha or 12% of the total area had been rendered saline and/or sodic. It was also established that water tables rose to depths of between 0.3 m and 0.6 m, especially in wet seasons. Streutker (1981c) also found that rising salinity levels adversely affected wheat yields and established useful salinity-yield curves using chemical and physical data from affected areas.

Mkuze falls: The original soil survey undertaken in 1929 revealed that 30% of this Board scheme was associated with problematic soils. It is of interest to note that Krynauw (1929) claimed that the scheme had a "very progressive and intelligent type of farmer" and that water quality was good. Despite this, continuing degradation led to a detailed survey of part of the scheme in 1976 (Cass & Lawrence, 1976). Of 72 profiles examined 54% were found to be saline and/or sodic. Water was deemed to be of moderate quality (C2S1) and was considered to be a threat to long-term viability. According to Havenga (1978) the Board itself estimated that an area of 150 ha was so severely degraded that reclamation was unlikely to be successful. A further area of 50 ha was severely threatened. On the basis of such surveys 15% of the scheme is deemed to be severely degraded. Drainage waters were also found to be of very poor quality (Cass & Lawrence, 1976).

Pongola: This State scheme was established in 1934 and comprises 9 222 ha under irrigation. It has been the subject of numerous surveys and investigations. In 1980 a detailed study of soil conditions on the original and extension plots revealed that approximately 30% (2 677 ha) of the scheme was degraded (Dohse, 1980). Forty eight percent of the affected area was associated with waterlogging while 76% had problems of a chemical nature. Most soils had both physical and chemical limitations.

Van Woerkom (1966) reported a rapid deterioration of soil conditions on Plot 130 and established that in 1958 there were no signs of degradation. By 1961 the growth of sugarcane was being affected and by 1965 clear signs of severe salinity/sodicity were evident. Once good soils were at that time yielding less than 40 t ha^{-1}.

In 1989 a further soil survey of the scheme and

some adjoining private land was undertaken and revealed that 41 % of the area had limitations including man-induced problems (Soil Survey Staff, 1989). Approximately 33 % of the area was highly suitable for irrigation while 26 % was deemed to be unsuitable. Generally, the black clay soils (e.g. Bonheim form) were associated with highly saline and/or sodic conditions. Isolated patches of such conditions also occurred in duplex soils (e.g. Valsrivier form) derived from Ecca shales. Chemical analysis of samples from 536 soil profiles (grid system) revealed that 30 % to 40 % of soils had limitations for irrigation. Over 30 % and 12 % of the samples had exchangeable sodium percentage (ESP) values exceeding 5 % and 15 % respectively.

Other schemes: A recent study of irrigation along the Vaal River showed that the severity of salt affected soils progressively increased downstream. The salinity levels of several irrigation areas are shown in Table 7.

Table 7 reveals that 37 % of the area surveyed comprised soils of moderate and high salinity. The problem is most severe in the Douglas area where considerable areas of heavy textured soils have already been withdrawn from cultivation (Loxton, Venn & Associates, 1985).

Several surveys of the Loskop scheme have shown that waterlogging is a widespread problem (Van Woerkom, 1972). Similarly, severe salinity/sodicity levels, physical limitations such as crusting and excess levels of boron were identified as severe and growing problems on the Hardap scheme (Du Plessis & Dohse, 1978). Clear evidence of degradation has also been reported on the Lower Fish and Sundays river schemes (Nell, 1987).

Such examples leave no doubt that soil degradation is a serious and growing problem on many schemes, especially State schemes. Little is known of the extent of degradation on private schemes but it would appear that in total the earlier estimates of degradation are conservative (Du Plessis, 1986a).

The maintenance of soil fertility at desired levels is essential for long-term viability. Studies of fertility trends on irrigated land have been limited and sporadic. However, even the scanty information available suggests growing problems of declining organic matter status, nutrient imbalances, deficiencies, toxicities and excessive leaching of nitrogen to underground water supplies.

Scotney & Dijkhuis (1990) recently reported several fertility problems occurring on irrigated land. For instance at Vaalharts 65 % of soil samples were found to have less than satisfactory levels of K. Levels of P appeared to be rapidly increasing. An earlier assessment of this scheme by Van der Merwe (1982) revealed that the organic carbon contents of virgin and cultivated soil samples were 0.5 % to 1.5 % and 0.05 % to 0.28 % respectively. Quantities of fertilizer applied to irrigated land have increased greatly in recent times, and in general, high value crops tend to be over-fertilized. A recent fertility survey in the sugar industry showed that levels of K were especially low in clayey irrigation soils (Meyer, Wood & Harding, 1990). These studies and other reports relating to trace element deficiencies and acidification suggest that current fertility trends will not ensure long-term viability of irrigated land.

There is also strong evidence that physical degradation is a growing problem. However, in many cases physical limitations such as crusting and structural breakdown are related to changes in soil chemistry with sodium playing an important role. According to Bennie & Krynauw (1982) there is also indisputable evidence of compaction in irrigated soils. Well-sorted fine sands with low organic matter content are particularly susceptible. Soil erosion on irrigated land has not been quantified but is an issue deserving special attention.

Water resources

Deteriorating water quality has become a major environmental issue in South Africa and is one of the greatest threats to long-term viability of soil and water resources. Through return flow to river systems, irrigation itself may contribute significantly to this hazard. Heavy sediment loads, salinization and, to a lesser extent, eutrophication and pollution occurring in many dams and rivers are clear evidence of such degradation.

According to Braune & Looser (1989) sedimentation has major impacts on downstream consumers and ecological processes, all of which have important financial implications. Such off-site damage may exceed R94 million a^{-1}. Floods also cause untold damage to irrigated land. For instance, the cost of damage to cropland and irrigation canals caused by the flooding of the Orange River in 1988 amounted to R214 million or 25 % of the total cost of the floods (Braune & Looser, 1989).

In 1980, Du Plessis found that water quality in 90 % of the 64 dams studied, especially those in the Vaal and Limpopo catchments, was not likely to adversely affect salt-sensitive crops. However, the presence of sodium in such waters could indirectly affect production by causing deterioration of the physical properties of soils. Highest sodium levels were found in dams along the seaboard.

Water quality continues to deteriorate as a result of industrial, municipal and mining effluents together with contributions from non-point sources. The total salt concentration in surface waters tends to range from below 400 mg ℓ^{-1} to over 3 000 mg ℓ^{-1}. Over the past 40 years there has been a steady increase in the concentration of total dissolved salts in the Vaal Dam and such trends apply to many catchments throughout the country. The contribution of return-flow from

Table 6 Extent of soil degradation on selected irrigation schemes (after Streutker, 1982).

Scheme	Area Irrigation (ha)	No Farms	Area affected (ha)	% Affected		Year begun	Year assessed
				Area	Farms		
Oudtshoorn	1900	56	50	3	20	1780	1982
Elgin	1500	1400	-	-	-	1900	1982
Golden Valley	2523	20	1800	71	75	1912	1980
Douglas	1200	106	512	43	43	1896	1978
Vaalharts	25000	1000	3000	12	46	1945	1975
Rietrivier	2600	50	2000	78	80	1946	1974
Loskop	25200	630	1250	50	40	1945	1980
Pongola	9200	160	2300	25	67	1951	1978

Table 7 Soil salinity levels along the Vaal river (after Loxton, Venn & Associates, 1985).

Salinity level (mSm^{-1})	Parys		Christiana		Barkly West		Douglas		Total	
	(ha)	(%)	(ha)	(%)	(ha)	(%)	(%)	(ha)	(%)	(ha)
High >200	-	-	100	3	1000	9	3000	33	4100	14
Mod 50-200	900	20	900	23	2500	22	2300	25	6600	23
Low <50	3600	80	3000	74	7700	69	3800	42	18100	63
TOTAL	4500		4000		11200		9100		28800	

irrigation schemes to deteriorating water quality has long been recognized but few meaningful counter-measures have been taken.

Causes of resource degradation

Numerous studies have identified the main cases of degradation on irrigation schemes. These are related to the natural resources themselves, sub-optimal management, poor planning and the indirect consequences of economic pressures. Off-site damage, especially that resulting from sedimentation and effluents has emerged as an important hazard. The following are the major important causes of degradation.

Natural resources: Despite the mandatory soil surveys undertaken prior to establishment of irrigation schemes, it is clear that inherent soil limitations (physical and chemical) have not been adequately accounted for in planning and management. Problematic soils predominate on most schemes, often in complex association with suitable soils. Degradation has resulted where precautionary measures (e.g. drainage works) have been neglected. There is urgent need for appropriate soil interpretations to be developed.

The severe sodicity that occurred on the Mkuze scheme was found to be closely related to the high content of montmorillonite in some soils (Cass & Lawrence, 1976). It is also well known that geological formations (e.g. Ecca shales) may contribute to salinity and/or sodicity. Natural water sources, especially underground supplies, may also contain levels of salts that contribute to soil degradation. Today, natural rainfall is also the cause of poor quality runoff especially in areas affected by atmospheric pollution.

Farm management: Sub-optimal farm management is probably the most important cause of resource degradation. Poor water use efficiency, mainly over-irrigation, has been widely reported as causing waterlogging and low economic returns. Nearly all surveys of irrigation schemes suggest faulty scheduling as a major problem. As early as 1909 Hurley stated that farmers "use too much water and often use it wastefully, even to their detriment". A detailed study of the Vaalharts scheme prompted Streutker (1981a) to conclude that "over-irrigation was prevalent". He also established that the contribution of management to waterlogging was 42% of the total irrigation water demand.

A comprehensive study of the Pongola scheme confirmed that irrigation management "left much to be desired" (Departement Landbou en Visserye, 1981). Widely differing sugarcane yields achieved under the

relatively homogeneous resource conditions at Pongola reflect a wide range of managerial skills. Only 27% of farmers achieved yields above the average of 89 t ha^{-1} while up to 50% achieved less than 70 t ha^{-1}. Management of flood irrigation at Vaalharts was also found to be inefficient (Streutker, 1981a).

Very few, if any, local studies in the human science field have concerned irrigation. However, earlier surveys, especially those of the Vaalharts and Riet River schemes revealed that educational qualifications of farmers were inadequate (Dreyer, 1969). Clearly, there is a general mismatch between available management skills and the demands made by the complex resource situations and sophisticated irrigation processes and systems.

Planning and drainage works: Planning at both the scheme and farm level has not matched the demands for long-term viability and community needs. Despite earnest attempts by the authorities to plan effectively, the "top down" approach with little farmer participation and general lack of flexibility have been important limitations. Problems related to water distribution and drainage networks are common to many schemes. Failure to install and maintain key drainage works has also led to considerable degradation.

Leakage from storage dams, unlined canals and furrows is an important cause of waterlogging. For instance, Van Woerkom (1972) claimed that leaking dams and furrows at the Loskop scheme caused water losses of between 11% and 18% over a 24-hour period. At Vaalharts, the contribution of leaking furrows and canals to waterlogging was 5% to 10% of the demand (Streutker, 1981a). At Pongola, 18% of the plots were found to be in need of special outlets for effective drainage (Departement Landbou en Visserye, 1981).

Financial constraints: The influence of rising input costs, small farm sizes, excessive debt loads and drought have mitigated against the implementation of sound irrigation practice. Original plot sizes on many schemes are today totally inadequate for economic viability. For example, the original size of plots at Pongola was 38 ha which was less than half the economic size (88 ha) recommended in 1981 (Departement Landbou en Visserye, 1981). At that time, 40% of the farmer son the scheme provided for their livelihood for borrowed capital and earned less than R10 000 per annum. Under such conditions there is little likelihood of adequate reclamation works being installed despite the financial assistance offered by the State.

Off-site damage: The adverse effects of off-site damage to downstream consumers, including health hazards are rarely appreciated. Although few detailed studies have been undertaken, it is clear that the cost of such damage is rapidly increasing. Deteriorating water quality, sedimentation and damage by flooding are all aspects of particular relevance to the long-term viability of irrigation schemes.

Reclamation of degraded areas

Successful reclamation of degraded areas demands careful problem identification and attention to detail. Depending on the cause, various treatments can be selected but in nearly all cases reclamation costs will be high. The rule that "prevention is better than cure" is fundamental to long-term viability. However, many attempts to reclaim degraded soils have proved successful. As early as 1909, Oosthuizen claimed "we have already succeeded in reclaiming some brack land". In almost all cases of reclamation, drainage has been employed, either alone or together with ameliorants. Sub-surface drainage together with gypsum played a major role in improving sugarcane growth on degraded soils at Nkwaleni and Pongola (Johnston, 1977, 1982; Swinford *et al.*, 1985). A recent reclamation project at Pongola involving similar treatment resulted in yields of plant cane increasing from 37 t ha^{-1} to over 200 t ha^{-1} (Van der Merwe, J., personal communication). Streutker (1981a) also reported success with sub-surface drainage at Vaalharts but emphasis that poor planning and the lack of attention to detail were important causes of failure.

Du Plessis (1986a) estimated that approximately 14% of the total area of degraded soils (125 000 ha) had been successfully reclaimed. In the OFS Region, almost 41% of affected soils had been successfully reclaimed by drainage but only at very high cost. Over the past decade an average of 326 works with an average value of R1.7 million per annum have been constructed with financial assistance from the State. Almost 7% of the area irrigated at Douglas has been artifically drained (Loxton, Venn & Associates, 1985).

Understanding the interaction between soil properties and water quality is fundamental to reclaiming degraded land. In order to counteract the detrimental effects of poor water quality on soil properties, the addition of electrolytes or use of more saline water is often necessary. Dispersion and the swelling of clay particles are two important soil mechanisms concerned with degradation. Dispersion may occur at relatively low ESP concentrations (<3) if the concentration of electrolytes in the soil solution is below the flocculation value of the clay colloids at that value (Shainberg & Letey, 1984). Surface crusting is largely influenced by organic matter content, exchangeable cations, ESP, type of clay minerals, iron oxides, electrolyte concentration and the sodium adsorption ratio (SAR) of the irrigation water.

The Department of Water Affairs is charged with maintaining the "fitness" of water resources for use on a sustained basis. Pollution control was previously

affected by applying the Uniform Effluent Standards approach through enforcing the General and Special Effluent Standards (Department of Water Affairs & Forestry, 1991). Policy has recently changed to the Receiving Water Quality Objectives approach for non-hazardous substances and to the Pollution Prevention approach for hazardous substances. Such management policies provide the means of achieving long-term viability through quality control but will require the support of research not yet undertaken in South Africa.

Underground water supplies contain variable quantities of salt. Values may range from 200 mg ℓ^{-1} to 7 000 mg ℓ^{-1}. Further deterioration resulting from the leaching of nitrates and other pollutants will need to be addressed. Changing from the traditional steady state approach in root zone salinity to that of non-steady state could facilitate the use of water of higher salt content. Meiri (1991) has listed important advantages of adopting the non-steady state approach.

Needs and priorities

Positive steps are needed to counteract the continuing degradation of soil and water resources under irrigation. This implies acceptance of the "sustainability" concept about which there has been much debate and rhetoric. For the purpose of this discussion sustainability implies that over the long-term environmental quality and the resource base will be enhanced, basic human needs of food and fibre will be met, economic viability will be assured and the quality of life of farmers and society as a whole will be raised (Schadle, 1990). This implies that it has environmental, agronomic, economic, social and even political dimensions. However, Ikerd (1990) has warned that the conflict between long-run sustainability and short-run profitability is perhaps the most significant question confronting today's farmers. Far greater involvement of the farming community in future planning for irrigation development will be needed. Conversely, a change in attitude to environmental issues or the acceptance of a new land ethic by farmers will be necessary. The following needs are seen as priority issues for achieving long-term viability in irrigation.

National irrigation strategy

Development of a comprehensive national irrigation strategy is a matter of great urgency. Such a strategy with clearly defined goals and management policies is seen as a first step to eliminating current deficiencies in irrigation practice. Allocation of responsibilities for implementing specific actions and funding will be necessary.

Part of such a strategy should address research needs in similar fashion to that proposed for Australia (National Irrigation Research Fund, 1990). A strong research programme directed at priority issues will be needed if irrigation is to remain sustainable. Crop management systems, water use efficiency, drainage and technology transfer should feature high on the list of research priorities.

The overall strategy should also address the needs of irrigation in developing areas.

Irrigation management

Promoting improved irrigation management is of the highest priority. This implies effective technology transfer and places great responsibility on both extension and research organizations. There are already extension programmes, such as those in the Winterrain Region, specifically directed at improving irrigation management, but more are needed. These require full support from irrigation specialists and the use of decision support systems. More effective whole-farm planning is needed to ensure the appropriate matching of land-use and management strategies with the resource base. In all these matters greater involvement of the farmers themselves is imperative. Training is also a major requirement, especially for small-scale farmers and labourers.

Water resource management

Water supply and quality are crucial issues for future irrigation development. Promoting water use efficiency, affecting control over water tables and preventing salinisation are major needs. While much can be achieved through improved management, special attention should be given to communal drainage networks, on-farm drainage and preventing leakage. Water quality will only be maintained at acceptable levels if national policies and strategies are whole-heartedly supported. Implementation of integrated catchment management is an approach long overdue in South Africa and is strongly promoted.

Irrigation research

There should be no attempt to curtail irrigation research although there is need to re-focus current programmes. Account will need to be taken of the likely impact of global climatic change. There is a lack of research in the field of human sciences related to irrigation. Studies of farmer needs, knowledge and perceptions, all of which affect practice adoption, are urgently needed. Examples of such studies have already been undertaken in the fields of veld management and conservation (Düval & Botha, 1990).

It is estimated that close to R4 million a^{-1} is currently allocated to irrigation research in South Africa which represents approximately R3 ha^{-1}. Accepting the Australian (National Irrigation Research Fund, 1990) norm of 0.5% of the "farm gate" value of irrigated produce for research, an amount of approximately R23 million a^{-1} or R18 $ha^{-1}a^{-1}$ would be needed.

Monitoring and evaluation

The lack of systematic monitoring and evaluation of irrigation schemes in South Africa is a major limitation. There is need to initiate appropriate and monitoring programmes as a matter of urgency. By this means it will be possible to accurately determine the degree of resource degradation and the response to improved farm management. Establishing procedures and determining criteria are important activities for evaluation. Aspects to be monitored include soils and water degradation, agronomic production, management practices, economic aspects and community upliftment. Remote sensing technology coupled to geographic information systems, as well as collection of geo-referenced soil and water samples, offer special opportunities for monitoring long-term viability.

Data bases

Reliable and up-to-date information relating to irrigation is sadly lacking. The development of appropriate data bases with easy access for users poses a special challenge. The proposed national strategy should also address this important need and allocate responsibility for such developments.

Conclusions

This review has led to the following conclusions:

* Long-term viability of many irrigation schemes is clearly in jeopardy. Studies of State schemes suggest that the extent of soil degradation exceeds 10% of the total area irrigated. Many schemes are being seriously threatened by the rapid decline in water quality. Little is known of the extent of degradation on private schemes but it is evident that the economic viability of many schemes is in doubt.
* Sub-optimal farm management and deficiencies in physical and financial planning, together with fragmented research and extension efforts, are important reasons for poor water use efficiency and resource degradation. Such limitations have persisted over many years.
* There is urgent need for a national irrigation strategy that identifies priorities, allocates responsibilities and ensures co-ordinated effort and realistic funding. Such a government initiative would require commitment and the full support of research, educational and advisory organizations as well as the farming community.
* Initiation of specific technology-transfer programmes is a high priority but should be planned and developed in full consultation with th farming community. Degradation should be approached on a "prevention is better than cure" basis. However, properly planned drainage systems together with soil amelioration have proved highly successful in improving crop performance on degraded areas and should be encouraged.
* Research effort has largely been fragmented. By comparison with other countries there appears to be an under-investment in irrigation research. There is also a need to develop a specific strategy and to encourage a co-operative research effort. The researcher can no longer afford to stand aloof from real needs of the farmer. A realistic balance in emphasis between research and technology transfer is needed.
* Growing competition for scarce soil and water resources will force all industries, including agriculture, to meet the demands for maintaining higher standards of environmental quality. Farmers will need to appreciate that in future society will demand higher standards of resource management.
* The future poses many special challenges if long-term viability of irrigated land is to be safeguarded. Greatest among these is the need to match technology with the natural resource base and the managerial skills of the farmer.

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RESEARCHING AND APPLYING MEASURES TO CONSERVE NATURAL IRRIGATION RESOURCES

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Abstract

This review of developments since the previous National Irrigation Symposium indicates that significant progress was made during the past 25 years with respect to both researching and applying measures aimed at conserving the natural irrigation resources of South Africa. Although waterlogging appears to be an incessant problem countrywide, and even serious on some irrigation projects, the situation seems to be largely under control from a national perspective. Salinisation of both our water and soil resources appear, on the other hand, to pose an increasing threat to sustainable irrigated agriculture. Some research aimed at providing the means to cope with the expected problems have, however, been initiated. Remarkable progress has been made with regard to the understanding of permeability problems and the factors that play a role. The implementation of the acquired knowledge in practice is, however, still mostly lacking. Significant strides with respect to both research and its application to overcome compaction have been made, although much remains to be done. On balance there is reason for guarded optimism and confidence that South Africa will remain able to conserve its natural irrigation resources. The proviso for such optimism is that research efforts are maintained and that an improvement can be brought about with respect to the efficiency with which research results are translated into applied technology.

Introduction

Since early times man has used irrigation to protect himself from the whims of nature and stabilise the production of food supplies. The rise and fall of a number of civilisations over the past 6 000 years have been linked to their ability to sustain irrigated agriculture (Tanji, 1990). The most famous example of these is ancient Mesopotamia, in present day Iraq, where a combination of flooding, seepage, over-irrigation and siltation caused the water table to rise and induce salinisation of the Sumerians' irrigation lands. Increasing soil salinisation and declining wheat yields resulted in wheat's replacement with the more salt tolerant barley. Yields of barley, however, also declined so that eventually, after 1 000 to 1 500 years of successful irrigated agriculture, the Sumerian civilisation declined. Although we do not know for certain what was cause and what was effect, it is illuminating to note that although numerous references to the building of irrigation canals in Sumeria exist, no record of the building of drainage canals are available.

Our understanding of the system and the relative importance of the processes involved have advanced to such a level that we believe that today it is mostly economics and a lack of the management skills required, rather than a lack of technology, that preclude the implementation of sustainable irrigation projects. The often adverse environmental impact of irrigation projects is increasingly realised. In the longer term the environmental acceptability, or not, of irrigation may thus increasingly determine the sustainability of irrigation projects.

Experience has taught that the potential for sustainable irrigated agriculture is greatly improved by the selection of land suitable for the purpose (Dohse, 1991). Not only should soil properties and position in the landscape be considered, but preferably also the geohydrology of the area. Experience has further taught that, after selection of suitable land, judicial management is the most important contribution man can make to conserve natural irrigation resources. Injudicious management can cause problems such as raised ground water tables and waterlogging, salinisation of both soil and irrigation return flow, decreased water penetration and/or soil compaction, which alone or in combination with one another can cause the failure of an irrigation project. Some of the advances that have been made during the past 25 years in all these fields (concentrating on Southern Africa), in order to conserve our irrigation resources, will be discussed in this paper.

Waterlogging

Although a certain degree of over-irrigation is needed to control salt build-up within a soil profile, much more than the required amount is usually applied for a variety of reasons. Depending on the internal drainage properties of the irrigated land, the geohydrology of the area and the amount of over-irrigation, the system will either be able to cope with the additional water input or will experience a rising ground water or perched water table. The waterlogging associated with high water tables is mostly viewed as detrimental to crop production since prolonged waterlogging reduces soil oxygen concentration and consequently also root density and depth.

Streutker (1977), however, found that under low frequency irrigation conditions at Vaalharts and a fairly low salinity ground water, the yield of both cotton and wheat was increased by almost 50% when grown above a 1.2 m rather than a 2.4 m deep water table. The yield increase could be explained by the use crops made of water from the water table. Water tables shallower than 1.2 m, however, do cause problems. In a subsequent study, after above-average

rainfall caused the water table to rise to between 0.3 and 0.6 m from the surface (Streutker, Van Vliet & Molenaar, 1981), it was found that such a high water table caused the soil to salinise, sodicify and compact. This resulted in decreased seed germination, emergence and growth. Yield was therefore depressed considerably more than would have been expected from soil salinity alone.

To a greater or lesser degree, high water tables are a problem common to all parts of the world where irrigation is practised. It is reported (Backlund & Hoppes, 1984 as quoted by Tanji, 1991) that 27% of the irrigated cropland in California have a water table 1.5 m or less from the surface, while 45% of the soils in the Berriquin and 73% of the soils in the Wakool District in the Murray Valley, Australia were judged to be predisposed to waterlogging (Grieve, Dunford, Marston, Martin & Slavich, 1986).

No programme exists to determine the extent of waterlogged conditions on South African irrigation schemes on a regular basis. A total of 138 reports are, however, available on *ad hoc* investigations carried out by the Soil and Irrigation Research Institute (SIRI) staff on request of farmers experiencing problems during the period 1920 to 1980. During the period 1970-1982 a further nine investigations covering complete irrigation schemes and two covering a 10 and 20% representative sample, were carried out. Summarising this information (which covered a mix of both Government and Irrigation Board Schemes) Streutker (1982) reported that 12% of the 101 400 ha area investigated experienced waterlogged or salinity problems in 1975, during a period of above average rainfall. This percentage decreased to 3% during 1980. Extrapolated to a total irrigated area of 885 000 ha, the total affected area would have been 111 000 ha in 1975 and 28 000 ha in 1980. An estimate by SIRI and Regional staff (Du Plessis, 1986) indicated that a total of 107 000 ha was affected during 1985. From the available information it would thus appear as if no more than about 110 000 ha (or 13% of the 850 000 ha of land under regular irrigation) in South Africa is affected by waterlogging and/or salinisation.

Although this figure may increase during years with above average rainfall (and decrease during periods of low rainfall) it is still considerably less than the figure for either California or some irrigation districts in Australia. Possible explanations for this apparently favourable state of affairs are the emphasis on potential for waterlogging and prevention in our selection criteria for irrigated soils, assistance with the financing of drainage works by the State and the fact that our irrigated areas are generally smaller in size, have a greater slope and good surface drainage.

The theory underlying drainage practice in South Africa does not seem to have advanced much over the last 25 years when it was expounded by Streutker (1967). In the meantime much progress has, however, been made with the draining of waterlogged soils. Streutker (1982) reported, for example, that the water table on 40% of the farms of the Vaalharts Irrigation Scheme was at that stage controlled at a depth of 1.2 to 1.5 m by underground drains, while Du Plessis (1986) reported that about the same percentage of all waterlogged/salt affected soils in the Free State Region as a whole had been drained at that stage.

Although there is still ample of room for improvement, it would thus appear that the problem of waterlogging is largely under control on South African irrigation schemes when compared to some other parts of the world. This is, however, no reason to become complacent. In a confidential report Ninham Shand (1985) estimated distribution losses up to the farm border at 30% of gross releases from dams. On farm distribution losses amounted to about 20% of the volume delivered to the farm, while a further 10 - 15% were lost by over-irrigation. Improved water management at both farm and irrigation scheme level would thus undoubtedly result in a further dramatic improvement in the situation.

Salinisation

The irrigation resources, land and water, are both subject to salinisation. There is, furthermore, often an interaction between the two - irrigation with saline water causes soils to salinise and also results in a more saline irrigation return flow. The situation with respect to the salinisation of both soil and water, agronomic practices to cope with increasing salinity, controlling the effect of irrigation on salinisation of water resources and salinity monitoring, will be discussed.

Salinisation of water and soil

With the exception of the drier parts of the country, the salinity of South Africa's irrigation water has, historically, been relatively low (Du Plessis, 1980). Despite the limited availability of data, strong indications have recently (Du Plessis & Van Veelen, 1991) been presented that the salinity of South Africa's water resources has been increasing markedly in some regions of the country. This deterioration is largely associated with urban, industrial, irrigation and other developments. Figure 1 provides an indication of the suitability of our surface waters for irrigation. When it is recognised that water quality would for 90% of the time be better than indicated, and that all surface sampling points were included (dams, from which irrigation water is mostly obtained, would normally have a lower salinity), it is concluded that the salinity of our surface water resources is, by and large, still within acceptable limits for irrigation water. The salinity of our surface waters furthermore compares favourably with the rest of the world judged against the 90th percentile value of about 2 000 mg/L (320 mS/m) found by the US Salinity Laboratory for surface water samples obtained from around the world (Jurinak,

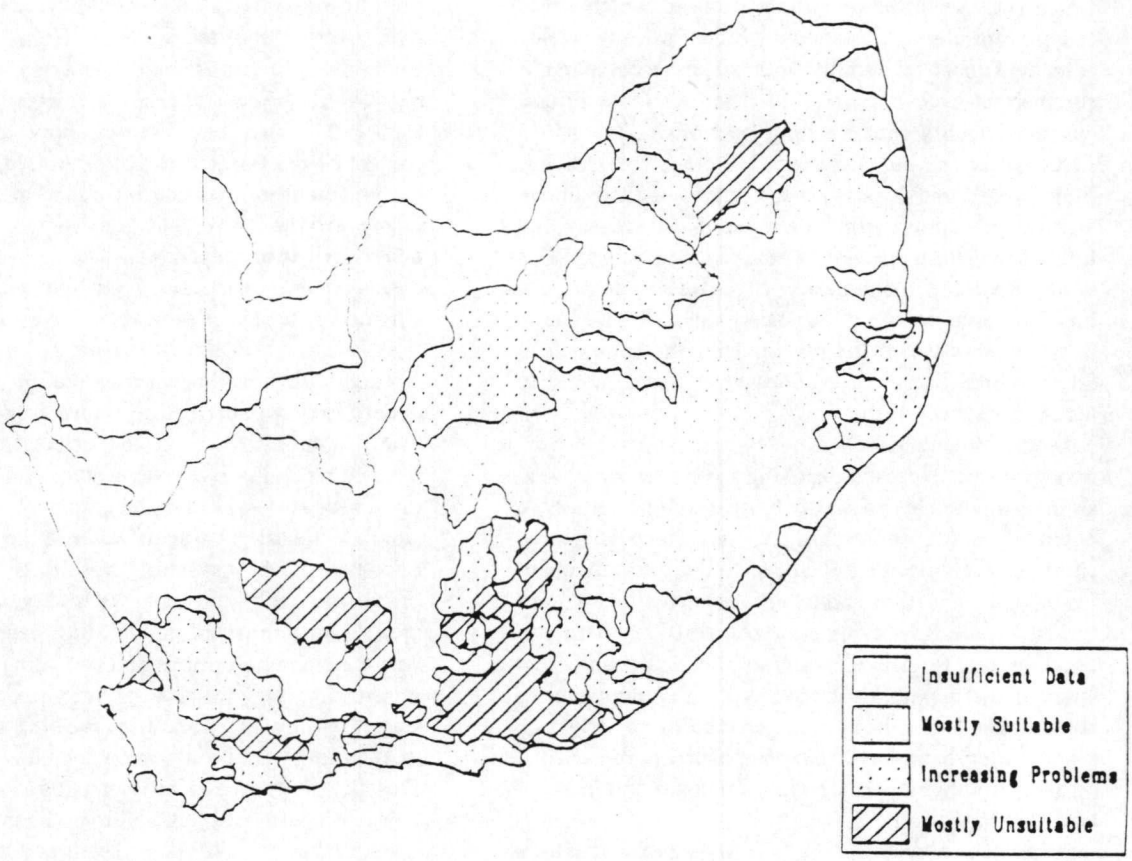


Figure 1 Suitability of water for irrigation as calculated from data for the period 1979 to 1988 (M van Veelen, Dept of Water Affairs, Pretoria, personal communication, 1990). *Mostly Suitable* represent US Salinity Laboratory Staff (1954) irrigation classes C1-S1 to C2-S1, *Increasing Problems* represent classes C1-S2 to C3-S2 and C3-S1 to C4-S1 while *Mostly Unsuitable* represent the other irrigation classes.

1990). Our apparently reasonably favourable water salinities is however no reason to be complacent. The increasing demands on our limited water resources necessitate the more intensive use and re-use of water, which if unchecked, is bound to cause increasing salinisation.

Up to now soil salinisation in South Africa seems to have been largely associated with shallow water tables. In most reports (e.g. Streutker, 1982), waterlogged and salt affected (verbrakte) soils are therefore lumped together. Although there are obvious exceptions, soils generally appear to recover fairly rapidly from excess salinity after installation of drainage to remove the high water tables and allow the leaching of accumulated salts. The rapid recovery can probably be ascribed to the combined effect of soil selection criteria, over-irrigation with relatively low salinity water and the addition of gypsum where needed.

Coping with increasing salinity

It is foreseen that the salinity of irrigation water will increase in future and that over-irrigation will be reduced by improved management of water applications. Under these conditions soil salinity is bound to rise and it will become increasingly important to control soil salinity and the negative effects it has on crop production. Insights into the way in which crops respond to salinity which increases with soil depth (as found under low leaching conditions, in contrast to the nearly uniform salinity profiles associated with over-irrigation) under both low and high frequency conditions, have improved tremendously during the past 10 - 20 years. It has become clear, for example, that crops can be irrigated with water of higher salinity and that the salinity at the bottom of the root zone can be allowed to rise to higher levels than previously thought possible.

Most of the research in this regard was done in the USA and Israel. The principles were, however, confirmed locally for citrus in the Sundays River Valley (Du Plessis, 1985). During a two year period when the irrigation water was highly saline (1 000 -1 800 mg/L) leaching of salts was reduced to much less than the leaching in commercial orchards so that salinity

sensors at the bottom of the root zone recorded maximum values between 1 400 and 1 800 mS/m, which is close to the maximum value to which citrus can concentrate salt. Despite the higher salinity, yields compared most favourably with yields in comparable commercial orchards irrigated from the same source but with much higher leaching fractions.

As far as can be ascertained no other research has been carried out locally to test and demonstrate the viability of coping with the increased soil salinity that follows irrigation practices which reduce leaching. The Water Research Commission is, however, at present funding three research projects that will give us a better perspective of the potential for the approach in South Africa and also provide some of the means to manage it successfully.

In the Breede River valley where apparent over-irrigation and excessive leaching have been observed, an investigation is under way to determine whether the potential to reduce leaching exists. Since irrigation equipment and design have been found to be adequate for sound irrigation management, investigators are presently attempting to ascertain whether there are good reasons for present water application practices or whether the apparently unnecessary high applications are the result of a lack of understanding of irrigation scheduling principles (L. Bruwer, Murray, Biesenbach & Badenhorst, Inc., Robertson. Personal communication, 1991).

With the elevated soil salinity levels that are expected to arise in future, it will become increasingly necessary to monitor the situation on irrigation schemes and within irrigated lands in order to identify salinisation trends and potential problems timeously for remedial action to be taken. Traditional salinity surveys are too time consuming and expensive for this purpose. An investigation is therefore at present being undertaken to determine the applicability of the four electrode conductivity and electromagnetic induction techniques for rapid salinity measurement under South African conditions (M.A. Johnston, Univ of Natal, Pietermaritzburg. Personal communication, 1991). During the past 10 years, the Department of Agriculture has, at the request of the Department of Water Affairs, laid down irrigation water criteria for a number of irrigation schemes. These criteria were calculated from published crop yield/salinity relationships and other overseas findings. An investigation to test one of these sets of criteria (those for vines in the Breede River valley), under field conditions, was started recently (J.H. Moolman, Univ of Stellenbosch. Personal communication, 1991).

Irrigation return flow

Irrigated agriculture is not only at the receiving end of water quality deterioration, it is itself a major contributor to the observed water quality deterioration in many rivers. In the Breede River where, in the absence of summer rain, it can be expected that summer flow is largely determined by irrigation return flow from the irrigated areas, the mean salinity in the river was found to increase from 103 mg/L at Brandvlei Dam (upstream of the irrigation area) to 728 mg/L at the lower end (Hall & Görgens, 1978). From Figure 2 it can be observed how the annual salt content of the Great Fish River at Jordaans Kraal initially decreased after the introduction of low salinity Orange River water, but later increased as the area under irrigation expanded. The increase in salinity corresponds remarkably well with the increase in irrigated area (and presumably also in irrigation return flow) upstream of the measuring point.

Much effort has been invested in improving our understanding of irrigation return flow processes and using models to predict the effect irrigation would have on receiving river water quality. The first attempt in this regard was the development of a model to simulate the salinisation of water in the Great Fish and Sundays River system, resulting from natural processes, irrigation and other development in the area. The calibrated model has been used to various planning options and operating rules aimed at minimising the quantity of imported Orange River water, while at the same time meeting the demand and maintaining salinity at acceptable levels (Hall & Du Plessis, 1984). Good progress has since been made. Görgens (A.G. Görgens, Ninham Shand Inc. Personal communication, 1991) has developed the DISA model (a daily irrigation and systems analysis model) which was used to predict the effect alternative planning options could be expected to have on the salinity of water in the Breede River system. This model makes extensive use of the findings of a great number of research projects and investigations that have been carried out during the past 10 years and more in this area. It thus largely reflects our present understanding of and insight into the operation of the system.

The development and testing of root zone models to describe (primarily) water and salt transport within irrigated lands, has also received attention. The US Bureau of Reclamation model was used with reasonable success by Moolman & Beukes (1980) to replicate the salt and water distribution found in a field experiment at Oudtshoorn over a four year period. The same model was later used (Moolman, Van Rooyen & Weber, 1983) to predict the salinity of water leaving the root zone of irrigated soils in the Poesjesnels River, a tributary of the Breede River. Although the predictions could be reconciled with flow salinity measurements in the river over the period July to December 1979, predictions did not coincide closely with observations for the following six month period.

Part of LEACHM, one of the most advanced and widely accepted root zone models presently available (Wagenet & Hutson, 1989), also originated from

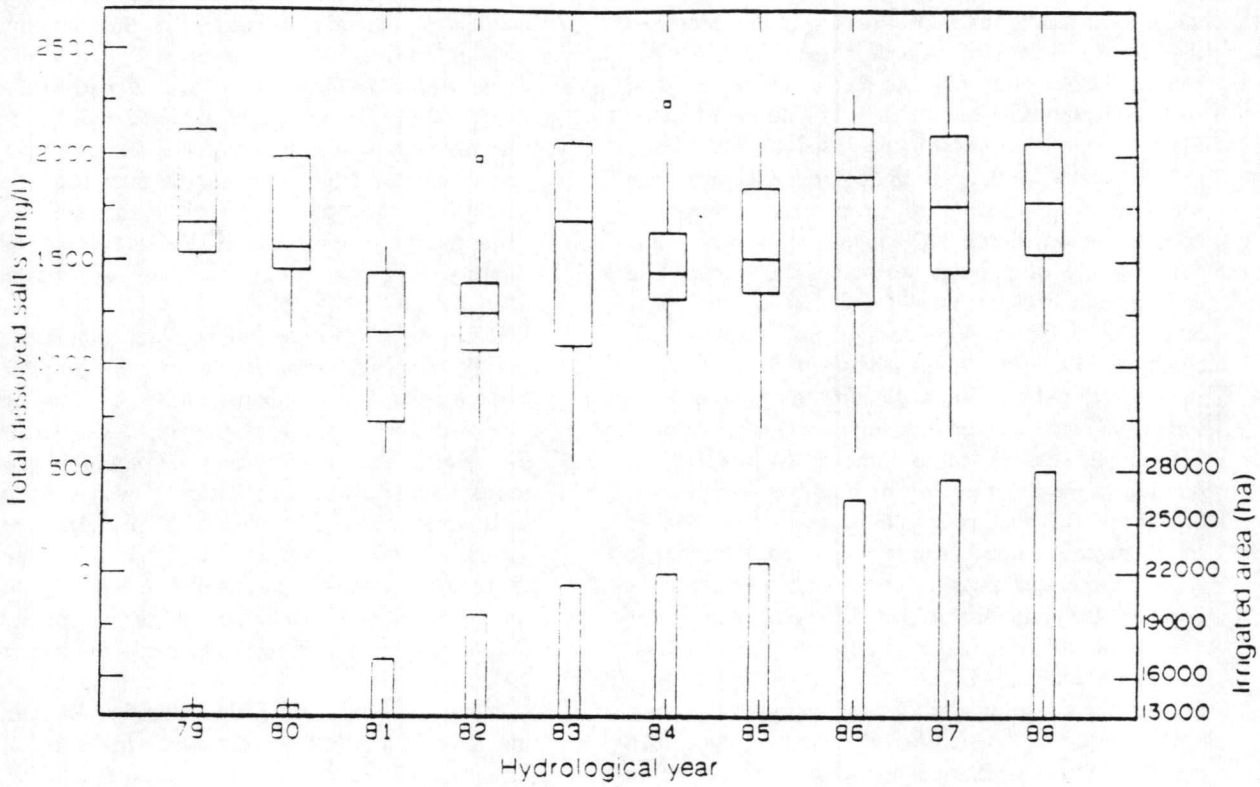


Figure 2 Annual total dissolved salt contents of water at Jordaans Kraal in the Great Fish River over the period 1979 - 1988 and a diagramatic representation of the increase in the upstream area under irrigation. (Du Plessis & Van Veelen, 1991).

research carried out locally (at SIRI) by the second author. More recently J.H. Moolman (Univ of Stellenbosch. Personal communication, 1991) has been comparing the ability of several solute and water transport models to predict the quantity and quality of water leaving the root zone as part of a Water Research Commission project. One of his findings has been that the predictions of simpler models was unable to explain measured field results. Problems with chemical equilibrium stability were, however, also often encountered with LEACHM when used for simulations over time periods exceeding about three years.

Soil permeability

Permeability of soil to water is accepted as a prerequisite for successful irrigation. Although permeability is largely determined by soil texture and mineralogy, it has long been realised that the combined effect of exchangeable sodium percentage (ESP) of the soil and salt concentration of the percolating solution is often of overriding importance in determining permeability. Local advances in the understanding of the processes and factors that are involved, have been influenced to a large degree by the findings of McNeal & Coleman (1966) concerning the existence of a critical (threshold) electrolyte concentration for maintaining hydraulic conductivity (HC) above a critical level at a given ESP, and Agassi, Shainberg & Morin (1981), who drew attention to the fact that infiltration rate (IR) was largely determined by the formation of a surface seal which forms under raindrop impact.

When soil permeability is discussed, it is necessary to distinguish between HC and IR determinations. HC is usually measured under conditions where the soil surface is not disturbed, while considerable disturbance can take place during IR measurements - especially when sprinkler irrigation or rainfall is involved. This disturbance causes the physical disruption of soil aggregates and promotes chemical dispersion of aggregates. These two effects combine to form a surface crust or seal which is much less permeable than the underlying undisturbed soil (Agassi *et al.*, 1981). Although infiltration rate has been determined for quite some time using a variety of techniques, it is only fairly recently that the importance of the electrolyte concentration in determining the value obtained has been realised outside the soil science field (Shainberg & Letey, 1984).

Hydraulic conductivity

Van der Merwe (1969) was the first to apply the threshold concentration concept for soil reclamation under local conditions, while Hensley (1969) proposed the use of the threshold concentration - ESP relationship in the selection of soils that could be irrigated with the water available for irrigation on the Makatini Flats. A similar approach was used by Du Plessis (1974) to calculate the gypsum requirement to decrease soil ESP in the Great Fish River Irrigation Scheme sufficiently to maintain HC above critical levels when the relatively saline irrigation water, that was used up to then, would be exchanged with low salinity water from the Hendrik Verwoerd Dam. Cass (1980) conducted the most systematic study of its kind to date in Southern Africa, although almost exclusively on soils from Natal. He used the relationships he obtained to formulate an empirical sodium stability model which provided a means of evaluating both the susceptibility of soil to HC reductions and the degree of HC change as the percolate concentration is altered. This model was incorporated into a method to quantitatively evaluate the relationship between irrigation water quality and soil structural stability under a specified set of climatic conditions.

From the above-mentioned and other investigations, South African soil salinity specialists have concluded that the critical ESP for Na-sensitive soils is in the range of 5 - 8, while soils high in organic carbon and especially free sesquioxides, have been viewed as relatively stable and able to tolerate ESP levels in excess of 15 (Johnston, 1982).

Infiltration rate

The first study in which the IR for South African soils was determined with a rainfall simulator approximating the characteristics of natural summer rain (Du Plessis & Shainberg, 1985), confirmed that our soils are very susceptible to crust formation at ESP levels as low as slightly above 1. It was also apparent that phosphogypsum applications through rapid dissolution could increase the electrolyte concentration sufficiently to prevent the chemical dispersion of soil clays and the concomitant decrease in IR. Subsequent research, including part of a South African-Israeli co-operative research project, resulted in a significantly improved understanding of the factors determining IR and how our irrigation resources should be managed in order to maintain an acceptable infiltration rate.

Levy (1988) found that a selection of four South African soils had a higher final infiltration rate than smectitic Israeli soils with comparable clay content and sodicity levels. He therefore suggested that as far as clay mineralogy is concerned, smectitic clays are more prone to crusting than illitic clays and that illitic clays are in turn more prone than kaolinitic clays. He also found that while exchangeable Mg was not as effective as Ca in maintaining HC under sodic conditions, their effects concerning IR related crusting were comparable. Nel (1988) found the HC of soils from the Mooi River Irrigation Scheme to be more sensitive to Mg than Ca. Apparently, in these soils, the stabilising Fe in the interlayers of mixed layer clay types were more prone to displacement when Mg-saturated than when Ca-saturated. The generally accepted stability of red soils has been studied by Smith (1990). He found soils that originated from basic parent materials to show higher resistances to crust formation than soils formed from granitic parent material. He also found that the stability of red soils increases as weathering intensifies.

It has been noticed that whereas simulated high energy rain (irrigation) resulted in the formation of surface seals with low permeability, this was not the case with very low energy (fog type) simulated rain. The question has arisen whether it would be practical to maintain IR of soils by reducing the kinetic energy with which water is applied with sprinkler type irrigation. The effect drop size and height of fall have on IR has been studied with a tank drip-type simulator at the University of Potchefstroom as part of a WRC funded project (A. Bloem. Personal communication, 1991).

It has been concluded that although IR could be maintained at higher levels when irrigating at low kinetic energy levels, this result would be difficult to apply in practice because of problems associated with delivering water close enough to ground level and the wind-dispersion susceptibility of small drops. Similar results were obtained by Smith, Levy & Shainberg (1990). They, however, also found that both final IR and cumulative infiltration could be greatly improved upon when the soil surface is treated with both phosphogypsum and PAM (anionic polyacrylamide) prior to irrigation.

A field experiment carried out on soils of the Makatini Experiment station which are prone to crusting under sprinkler irrigation, proved that surface applications of either phosphogypsum or stubble mulch increased both the final infiltration rate and cumulative infiltration (Van der Watt & Claassens, 1991). Best results were, however, obtained with a combination of the two.

A few attempts have been made to determine IR under field conditions using mobile equipment. Up to now the most successful and frequently used equipment (Reynders & Louw, 1985) is employed extensively (about 60 units are in use in Southern Africa) in the planning of irrigation systems, especially centre pivot systems where the size of the system is largely limited by soil IR. Use of this simulator has done much to improve the quality of centre pivot design in this country. An improved version of this simulator, making it possible also to vary drop size, kinetic energy and application rate, is at present being built (C.J. Smit, Univ. of Pretoria. Personal communication

1991).

Soil compaction

Soil compaction limits the rooting volume of crops. Under irrigation, due to the restricted rooting volume, the water storage capacity is effectively reduced with the result that irrigation frequency needs to be increased.

The causes, adverse effects and control of soil compaction were reviewed by Bennie & Krynauw (1985). Much of the research in this connection was carried out by Bennie at Vaalharts, as part of research projects funded by the WRC. The authors reported findings highlighting the importance of a well-sorted particle size distribution, especially well-sorted fine sandy loams and loamy fine sands with a high fine sand fraction and low carbon content, as an indicator of soils with high compactibility and stressed the fact that water content influences the ease with which a soil is brought to its maximum density. While tillage operations were identified as a major external factor causing compaction, they also mentioned that a single flood irrigation of 100 mm was found to compact the plough layer of soil of the Vaalharts Irrigation Scheme to the same extent as one run with a tractor wheel.

The adverse effects of subsoil compaction on plant growth was found to be mostly directly related to the degree to which soil strength impedes root growth. It was found that roots of maize, wheat, cotton and groundnuts had the same relative penetrating ability at a specific soil mechanical resistance. The weaker root system that develops as a result of soil compaction was linked to reductions in topgrowth, nutrient uptake, transpiration, total plant available water, crop water-use efficiency and yield.

Deep cultivation to loosen compacted soil was the only effective means found to overcome the adverse effects of compaction. Recompaction of the loosened soil could be prevented by using a system of controlled wheel traffic for all mechanical operations. A marked improvement could also be brought about by not working with the tractor wheel in the furrow created by the implement (where the water content is usually higher), but rather to use the system of "on land" ploughing where the tractor wheels move outside the plough furrow (Bennie & Krynauw, 1985).

Subsequently, Van Huyssteen (1989) quantified the compaction problem for selected vineyard soils and critically assessed methods to predict soil bulk density from soil texture. Although no critical bulk density or penetrometer soil strength was found to impede roots in a pot experiment using five soils, above-ground grapevine performance decreased linearly with increasing subsoil bulk density. Maximum compactibility could be predicted with fairly good accuracy for most soils with the aid of a multiple regression model fitted to textural data. It was also found that a packing model of Gupta & Larson could be used to predict the equilibrium field bulk density with a fair degree of accuracy.

Conclusions

Significant progress has been made during the past 25 years with respect to both researching and applying measures aimed at conserving our natural irrigation resources. Although waterlogging appears to be an incessant problem countrywide, and even serious on some schemes, the situation seems to be largely under control from a national perspective. Salinisation of both our water and soil resources appear, on the other hand, to pose an increasing threat to sustainable irrigated agriculture. Some research to enable us to cope with the expected problems has, however, been initiated. Remarkable progress has been made with regard to our understanding of permeability problems and the factors that play a role in such problems. The implementation of the acquired knowledge in practice is, however, still mostly lacking. Significant strides have been made with respect to both research and its application to overcome compaction problems, although much remains to be done. On balance, I am of the opinion that we can face the next 25 years with guarded optimism that we will remain able to conserve our natural irrigation resources. We will, however, succeed only if we maintain our research efforts and improve on the efficiency with which research results are translated into applied technology.

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MEASUREMENT OF SOIL SALINITY USING THE FOUR-ELECTRODE PROBE

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Abstract
The reliability of the four-electrode method is demonstrated on a selection of six South African soils showing a very wide range in properties. The slope of the relationship between electrical conductivity of the saturation extract (ECe, as the dependant variable) and electrical conductivity of the bulk soil (ECa) ranged from 3.2 for a heavy clay soil, to 10.2 for coarse sand. These differences were primarily a result of the variations in field capacity water content, at which the ECa measurements were made. A procedure involving a laboratory study is described whereby the ECe value, estimated from ECa, can be adjusted for field water contents other than field capacity.

Introduction

Soil salinity is a problem that affects virtually all of the major irrigation schemes in South Africa. With increased use of the country's water resources, the salinity level in the rivers is bound to rise in the future, and this is likely to exacerbate the extent of these problems. In the interests of minimising the negative impacts of irrigation there is clearly a need to monitor the extent of soil salinity problems in irrigated areas. The standard measure of soil salinity is the electrical conductivity of the extract of a saturated soil paste (ECe).

This laboratory analysis, coupled with field sampling and sample preparation, is laborious, and represents a deterrent to undertaking the monitoring exercise. A salinity sensor that could greatly help in this regard is the four-electrode probe. This equipment has been developed in the United States (Rhoades & Van Schilfgaarde, 1976), based on the resistivity method used in geophysical work (Van Zijl, 1985). The instrument can make rapid *in situ* measurements of EC of the bulk soil (ECa) at any selected depth down to 1.2 m.

For meaningful interpretation of ECa it is, however, necessary to relate it to ECe, or possibly ECw (EC of soil water). Rhoades & Halvorson (1977) have pointed out that ECa can be related to ECw as:

$$ECa = ECw\ (\Theta.T) + ECs$$

where Θ = volumetric water content
T = a transmission coefficient
ECs = surface conductance along clay surfaces

Surface conductance (ECs) and T are properties of the solid phase, while ECw and Θ are properties of the soil liquid phase. More recently Nadler & Frenkel (1980) have shown that ECs is an apparent intercept on the ECa axis, and in reality the relationship between ECa and ECw becomes curvilinear at very low electrolyte levels. For measurements made at a certain water content, such as field capacity:

$$ECa = ECe.A + ECs$$

where A = a constant which embodies both Θ and T.

The constants in the above equations can be determined for any particular soil from paired measurements of ECa and ECw (or ECe) at a number of salinity levels (Rhoades & Halvorson, 1977).

This study was aimed at establishing calibration parameters for a range of South African soils, as well as investigating how the calibration between ECa and ECe is influenced by texture, cation exchange capacity (CEC) and water content.

Procedure

The primary calibration between ECa and ECe was achieved from measurements made in the field at field capacity water content. In addition, a laboratory study was also conducted in order to demonstrate the effect that soil water content has on the calibration relationship.

Field study

Six sites were selected to represent a wide range of soil types in terms of their texture and clay mineralogy (Table 1). At each site the soil was salinised to five levels by applying 50 L quantities of each salt solution. For convenience the outer ring of a double-ring infiltrometer (0.55 m diameter) was used to facilitate ponding of solution on the soil surface. The solutions were made up with chloride salts of Ca, Mg and Na to yield total cation concentrations of 40, 100, 200 and 400 me L^{-1} at a sodium adsorption ratio (SAR) of 8, with equal concentrations of Ca and Mg. The fifth solution comprised unsalinised tap water. The site was then covered with a plastic sheet to prevent evaporation, and the soil allowed to drain for about 48 hours so that a water content simular to field capacity could be attained.

A gouge auger (24 mm diameter) was used to prepare access holes immediately before inserting the four-elctrode probe (model SCT-10, Martek Instruments, Irvine, California) for measurement of ECa in the A horizon of each soil. After measuring ECa, soil samples were augered from the same depth

(0-0.25 m) for determination of ECe (US Salinity Laboratory Staff, 1954) and water content. Duplicate undisturbed cores were taken so that bulk density (Table 1) and retentivity data (not presented here) could be obtained.

Laboratory study

A modified Tempe cell was used in this study on a disturbed sample of Cartref sand. This apparatus has a porous ceramic plate at the base which allows progressive extraction of soil water (by applying pressure) without concentration of salts in the soil water. Sections of PVC piping, 43 mm long and 74 mm in internal diameter, were machined to fit the base and top of the Tempe cell. Eight stainless steel electrodes were mounted into the wall at 45° intervals around the middle of the PVC sleeve. This effectively provided five sets of four-electrode systems, using the electrode combinations 1 2 3 4, 2 3 4 5, 3 4 5 6, 4 5 6 7, 5 6 7 8. This allowed a good average resistance value to be obtained at each soil water content. This apparatus was developed along the lines of that described by Rhoades, Kaddah, Halvorson & Prather (1977).

Soil that had been air dried and passed through a 2 mm sieve was packed into the sleeve to the bulk density measured in the field. The five salt solutions described for the field study were used to wet up the prepared soil "cores". Resistance and temperature readings were taken over a range of soil water contents for each salt solution.

Characterization of soils

Particle size analysis was conducted on each soil according to the pipette method of Day (1965). Dispersion was achieved by treatment with calgon dispersing agent followed by a three minute sonication with an ultrasonic probe (Labsonic 1510) at 400 W output. The CEC was determined by a centrifuging procedure using Sr as the index ion. After saturation with Sr, the soil was extracted with 1M KCl solution, and Sr determined by atomic absorption spectrophotometry.

Results and discussion

The surface layers of the six soils studied clearly show a wide range in properties (Table 1). The A horizon of the Bonheim form soil borders on vertic material and shows very marked cracking on drying, indicating a high level of smectitic clay. The clay mineralogy of the Shortlands form soil is known to be dominated by non-swelling 2:1 layer minerals (illite), while the Inanda soil would be primarily kaolinitic. However, the exact clay mineralogy was not determined.

The marked differences in physical properties are clearly reflected in soil water contents, both at "field capacity" at which ECa readings in the field were taken, and at that of the saturated paste (Table 2). As would be expected, the higher the clay content, the higher these water contents tend to be.

Table 1 Pertinent properties of the 0-0.25 m layer of the soils studies.

Soil form (series)	Texture			C.E.C.	Bulk density
	Clay	Silt	Sand		
	(%)	(%)	(%)	(cmol$_c$ kg^{-1})	(kg m^{-3})
Cartref (Cf 30)	5	8	87	1.5	1676
Inanda (Ia 11)	43	18	39	6.7	1294
Oakleaf (Oa 36)	19	19	61	7.6	1658
Shortlands (Sd 22)	66	23	12	20.1	1226
Bonheim (Bo 41)	44	46	11	14.9	1356
Valsrivier (Va 40)	15	26	59	5.5	1619

Table 2 Calibration data for the six soil types.

Soil form	Salt level	ECa	Mass water content at ECa reading	ECe	Mass water content of paste	Regression ECe vs ECa
		(mS/m)	(%)	(mS/m)	(%)	
Cartref	1	1.1	10.0	26.9	16.7	ECe = 10.1898ECa
	2	23.6	10.3	218.0	16.9	-13.767
	3	51.9	10.9	478.0	16.7	R^2 = 99.4%
	4	84.2	9.8	848.0	15.8	
	5	143.4	9.7	1460.0	15.6	
Inanda	1	7.4	25.5	11.9	50.3	ECe = 4.4486ECa
	2	23.6	26.0	98.1	50.7	-7.558
	3	47.9	24.6	209.0	48.0	R^2 = 99.5%
	4	93.1	23.5	434.0	49.4	
	5	144.9	23.6	619.0	48.5	
Oakleaf	1	16.8	16.3	56.9	37.7	ECe = 5.5142ECa
	2	43.2	14.4	183.9	36.3	-44.617
	3	56.3	14.4	270.3	37.5	R^2 = 99.9%
	4	129.2	14.3	654.2	34.2	
	5	177.5	14.1	944.2	32.0	
Shortlands	1	36.2	35.9	17.3	68.7	ECe = 3.1887 ECa
	2	60.0	36.7	79.6	70.2	-110.97
	3	90.0	36.8	177.0	67.4	R^2 = 99.2%
	4	171.1	37.1	394.0	68.9	
	5	246.8	34.4	699.0	67.0	
Bonheim	1	45.5	30.1	34.6	75.5	ECe = 3.6535ECa
	2	50.1	30.0	64.9	76.4	-118.673
	3	74.4	28.2	164.0	76.1	R^2 = 99.0%
	4	92.0	29.5	230.0	76.7	
	5	126.0	29.7	330.0	73.7	
Valsrivier	1	5.3	17.3	34.9	28.8	ECe = 5.2604ECa
	2	36.2	17.5	188.0	29.3	+16.328
	3	56.9	17.0	346.0	29.6	R^2 = 99.8%
	4	132.1	18.7	715.0	31.4	
	5	231.4	17.8	1227.0	30.0	

The regression relationships between ECa and ECe were all statistically significant at the 1% level with R^2 values in excess of 99% (Table 2). These calibrations clearly conform to those of Rhoades & Halvorson (1977). In general, the slope of the linear relationships is ranked in order of clay content, and volumetric water content at field capacity, with the lighter textured soils having steeper slopes than the heavier ones. This means that for a particular ECe value the corresponding ECa will be relatively much lower for a sandy soil than for a clay, due to the lower water-filled porosity and hence greater tortuosity of the

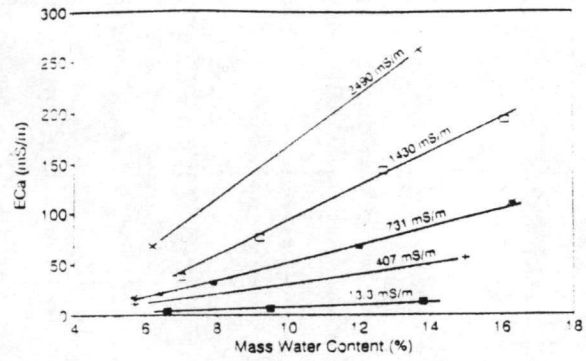


Figure 1 Effect of water content on ECa for the Cartref soil at various ECw levels.

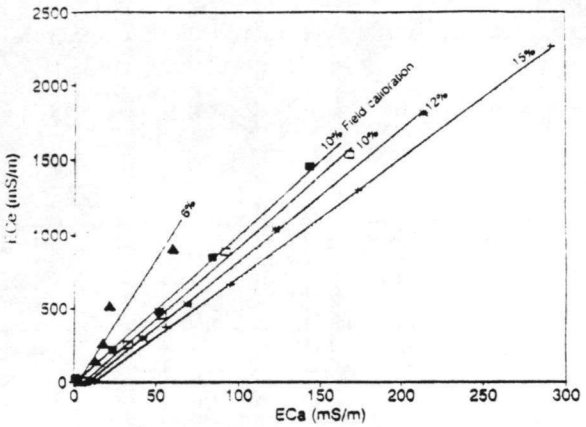


Figure 2 Relationship between ECa and ECe for the Cartref soil at various mass water contents.

current flow-path in the case of the sand.

The laboratory study on the Cartref soil demonstrated the dramatic influence that soil water content has on the measured ECa value (Figure 1). A two fold increase in water content at any particularly ECw level results in an increase greater than two-fold in ECa. This occurs presumably as a result not only of a doubling of the proportion of water-filled pores, but also due to reduction in tortuosity of the current flow-path.

The data in Figure 1 has been recalculated and expressed as a relationship between ECe and ECa at various selected water contents (Figure 2). This required the establishment of ECw values at each particular water content and then conversion of ECw to ECe using the water content of the saturated paste. The data obtained from the field for the Cartref soil (Table 2) are also presented in Figure 2, and agreement between the two methods of calibration is very good.

Figure 2 would allow the estimation of ECe from ECa at water contents other than field capacity. This clearly has practical value in that it is a constraint to the technique if measurements can only be taken at field capacity. The additional ECe - ECa relationships at different water contents therefore increase the flexibility of the method in regard to soil water content that is acceptable for ECa measurement. The results of this study suggest that this relationship can be obtained by means of a laboratory study.

Conclusions

The four-electrode probe has been shown to offer a reliable means of measuring the salinity level in soil. For meaningful interpretation of readings it is, however, necessary to calibrate the instrument readings against ECe. While it is most convenient to take readings at field moisture capacity, calibration relationships can be developed that allow for the influence of the water content of the soil under investigation.

An attractive feature of the technique is that measurements can be made rapidly in the field. In comparison with conventional methods, the time required to diagnose a salinity problem can thereby be greatly reduced.

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THE EFFICACY OF POLYACRYLAMIDE AS A SOIL CONDITIONER IN CONSECUTIVE IRRIGATIONS IN SOME SOUTH AFRICAN SOILS

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Abstract
Overhead irrigation, either stationary or moving, enhances seal formation at the soil surface and results in large amounts of runoff water and soil erosion which in turn may lead to lower yields. The effect of an anionic polyacrylamide (PAM) on improving soil structure and preventing seal formation, runoff and erosion in consecutive irrigation was studied on four South African soils varying in their clay mineralogy and content. The soils were exposed to consecutive simulated irrigation events, 55 mm each, using tap water. PAM was applied either via the irrigation water or was sprayed directly onto the soil surface prior to irrigation. In the former method, additional two concentrations of PAM, 10 and 100 ppm, were studied. In the latter method, prior to the irrigation events, PAM dissolved in tap water was sprayed onto a soil to which the equivalent amount of 5 t ha^{-1} of phosphogypsum was added. Alternatively, PAM was dissolved in 20 $mmol_c$ L^{-1} $CaCl_2$ solution and sprayed onto the soil surface. PAM had a favourable effect on increasing the infiltration rate (IR) and decreasing runoff and erosion of the soils studied excluding the illitic Glenrosa from the Karoo. The most favourable effect of PAM was observed in the Msinga soul from Dundee, whose IR was generally limited by the irrigation intensity and hence no runoff and erosion were observed in all the PAM treatments. Of the various PAM application methods tested, addition of 10 ppm PAM to the irrigation water had the strongest and most lasting effect on limiting seal formation and increasing aggregate stability irrespective of the soil studied.

Introduction

Low water infiltration leading to runoff, erosion, inefficient water use and plant injury due to water ponding is a critical problem in many of the arid and semi-arid regions in the world (Agassi, Morin & Shainberg, 1985; Oster & Singer, 1984). Reduction in soil infiltration rate (IR) and the resultant increase in soil erosion are caused mainly by seal formation at the soil surface. Surface sealing is enhanced among others by the beating action of water drops from sprinkler irrigation (Aarstad & Miller, 1973). Surface seals are thin (<2-3 mm) and are characterized by greater density, finer pores and lower saturated conductivity than the underlying soil. Seal formation in soils exposed to the beating action of falling drops is due to two mechanisms (Agassi, Shainberg & Morin, 1981; McIntyre, 1958): (i) physical disintegration of soil aggregates and their compaction caused by the impact action of the drops hitting the soil surface; and (ii) a physico-chemical dispersion and movement of clay particles into a region of 0.1-0.5 mm depth, where they lodge and clog the conducting pores. The chemical dispersion depends on the soil clay mineralogy (Stern, Ben-Hur & Shainberg, 1992), exchangeable ion composition and the electrolyte concentration in the soil solution. The physical disintegration and the physico-chemical dispersion act simultaneously as the first enhances the latter.

Interril soil erosion is a function of soil detachment by raindrop impact and transport capacity of thin sheet flow (Meyer, Foster & Romkens, 1975). However, seal formation might affect soil erosion by two opposing mechanisms. Seal on one had increases the shear strength of the soil surface (Bradford, Ferris & Remley, 1987) which reduces soil detachment (Moore & Singer, 1990). On the other hand, this compacted layer increases runoff and its transport capacity for entrained materials (Moore & Singer, 1990).

Preventing seal formation and thereby obtaining high IR values and possibly reducing soil erosion could be achieved by improving soil structure and aggregate stability at the soil surface. the use of organic polymers, especially polyacrylamide (PAM) for improving soil structure and soil permeability has been studied recently (Helalia & Letey, 1988; Shainberg, Warrington & Rengasamy, 1990; Smith, Levy & Shainberg, 1990). It was further reported that the presence of electrolytes, which assured the flocculation of the soil clay, was essential for the effectiveness of PAM application (Shainberg *et al.*, 1990; Smith *et al.*, 1990). Current interest in polymers as soil conditioners is enhanced by their low price ($3-4 kg^{-1}) and application rate (20 kg ha^{-1}), which make their use in agriculture economically viable. The low application rate results from our understanding of the role of seal formation in water infiltration, runoff and soil erosion which allows for the concept of treating only the soil surface rather than mixing the polymer with the cultivated soil layer.

The objectives of the present study were: (i) to compare the effect of PAM on IR and soil erosion for various application methods; and (ii) to evaluate the long term effect of PAM over consecutive irrigation events (i.e., simulating the irrigation season).

Materials and methods

Soils

Four soils samples varying in their clay mineralogy and content were collected from different sites in South Africa. The soils were identified and classified according to Soil Taxonomy (Soil Survey Staff, 1975) and the South African binomial system (MacVicar, de Villiers, Loxton, Verster, Lambrechts, Merryweather, le Roux, van Rooyen & Harmse, 1977). Some physical and chemical properties of the soils, determined by standard analytical methods, are given in Table 1.

Irrigation simulator

Infiltration, runoff and erosion were studied using an irrigation simulator producing waterdrops with a median diameter of 1.9 mm; median drop velocity of 6.02 ms^{-1}; and kinetic energy of 18.1 J mm^{-1} m^{-2}. Irrigation intensity was maintained at 33 mm h^{-1}.

Air-dried aggregates, crushed to pass through a 4.0 mm sieve, were packed in 300 x 500 mm perforated plastic boxes, 20 mm deep over a 80 mm thick layer of coarse sand. The boxes were placed in the simulator at a slope of 5%, saturated from underneath with tap water (TW) (EC = 0.5 dS m^{-1}) and exposed to irrigation events of 55 mm each. During each event, water infiltrating through the soil was collected in graduated cylinders placed at the bottom of the boxes and its volume recorded as a function of time. Runoff samples were collected at regular intervals. Eroded materials was determined gravimetrically after drying the runoff water and the amount of soil loss was calculated. Infiltration data from the simulated irrigation events were analyzed as described by Levy, van der Watt & du Plessis (1988), using a nonlinear regression equation proposed by Morin & Benyamini (1977).

PAM treatments

The PAM tested was an anionic low charge (20% hydrolysis) with the high molecular weight ($\sim 10^7$ g mol^{-1}). PAM was added to the soil either via the irrigation water or by spraying it onto the soil surface prior to the irrigation events. In the case where PAM was added via the irrigation water, the treatments studied were the following:

1. The soil was exposed to two consecutive irrigation events of TW to which 10 ppm of PAM were added, thereafter the soil was exposed to additional three events of TW only; finally the soil was exposed to one more event to which 10 ppm of PAM were added to the TW.
2. The soil was subjected to 10 mm of TW containing 100 ppm PAM, which were followed by three consecutive events of TW only.

In the case where PAM was sprayed on the soil surface, two portions of 2.0 L m^{-2} each, separated by 1 h of drying, of (i) a 20 $mmol_c$ L^{-1} $CaCl_2$ containing 500 ppm PAM solution in the Glenrosa (K) soil or (ii) TW containing 500 ppm PAM solution in the other soils were sprayed. In the latter application method, phosphogypsum (PG) at the equivalent rate of 5 t ha^{-1} was spread on the soil surface prior to the spraying of PAM. After 24 h of drying the soil was subjected to three consecutive events of TW only.

The control treatment included two consecutive events of TW. For all treatments, the soil was allowed to dry in an oven at 48°C for 48 h between consecutive events. Three replicates were performed for each treatment concurrently. Statistical analyses were done using the ANOVA procedure. The Tukey range test was used with a 95% confidence level for comparing between the means.

Results

The present study included 4 soils, 5 treatments (four different methods of PAM application and a control), and 3-6 consecutive irrigation events for each

Table 1 Some physical and chemical properties of the soil is used.

Location	SA binomial system	Soil taxonomy	Dominant clay minerals[a]	Particle size			CEC[b]	ESP[c]	pH	OC[d]
				Sand	Silt	Clay				
				----------%		----------	$cmol_c kg^{-1}$	%		%
Dundee	Mesinga	Paleudalf	K(5), I(2)	57.4	18.8	23.8	12.1	2.5	6.1	2.0
Aliwal North	Glenrosa	Haplustalf	I(5), Is(K,V)*(5)	72.9	12.5	14.6	5.8	1.0	6.0	0.5
Potchefstroom	Shorrocks	Xerochrepts	K(5), I(1), S(1)	72.1	12.1	15.8	4.8	3.1	5.0	1.4
Karoo	Glenrosa	Naturgid	I(5), K(1), S(1)	35.2	30.8	34.0	13.6	5.2	7.8	0.2

[a] I = Illite, K = Kaolinite, V = Vermiculite, (1) = weak .... (5) = strong.
[b] CEC = cation exchange capacity.
[c] ESP = exchangeable sodium percentage.
[d] OC = organic carbon.
* A rare composition where vermiculite is involved together with kaolinite in the interstratification (Is).

treatment. This experimental design made it difficult to appropriately report the results. Hence we have decided to present the infiltration curves only for the control treatment. For the other treatments the discussion focuses on the following: (i) infiltration rate obtained at the end of the event (herein referred to as FIR); (ii) amount of runoff (expressed as percent of irrigation depth); and (iii) total soil loss. The results are presented separately for each treatment and are then followed by a general discussion. In the following discussion the Glenrosa soils from Aliwal North and the Karoo will be identified as Glenrosa (AN) and Glenrosa (K), respectively.

1. Control

The changes in the infiltration rate (IR) during the irrigation events for the various soils in the control treatment (no addition of PAM) are presented in Figure 1. From the IR curves it was evident that the soils differed in their sensitivity to the beating action of the waterdrops. The FIR values ranged between 3 and 19 mm h^{-1}; the amount of runoff ranged between 16 and 74% (Figure 2); and total soils loss ranged between 476 to 2 920 g m^{-2} (Figure 3). From these data, the soils' susceptibility to seal formation and erosion could be summarized in the following decreasing order: Glenrosa (K)> Shorrocks> Glenrosa (AN)> Msinga. Several factors dominated the response of these soils to raindrop impact: i) the illite is more susceptible than koalinite (Levy & van der Watt, 1988); ii) koalinitic soils which contain small amounts of smectite (Shorrocks; Table 1) are more susceptible than kaolinitic soils free of smectities (Msinga; Table 1) (Stern *et al.*, 1991; 1992); and iii) the high silt and sodium content in the Glenrosa (K) soil, markedly affected the sensitivity of this soil to seal formation, runoff and erosion. Among the three soils (excluded the Glerosa (K)), the order of stability seems to be linked also to organic carbon (OC) content (Table 1). The higher the OC content the more stable the soil.

With the exception of the Msinga soil from Dundee, similar infiltration curves were obtained for each one of the other three soils in all the consecutive irrigation events. This indicated that in these soils the seal formed was fully developed already at the end of the first event. In the stable Msinga soil a further decrease in the IR and thus a further development in the seal occurred in the second irrigation event (Figure 1). The FIR and percent runoff obtained in the Msinga in the second event were similar to those in the Shorrocks soil (Figure 2). However, soil loss in the Msinga was lower not only from that in the Shorrocks soil, but was also lower from the soil loss observed in the Msinga in the first event (Figure 3). The latter observation suggested that infiltration parameters (i.e., FIR and percent runoff) and soil loss are not necessarily directly linked, and that further compaction

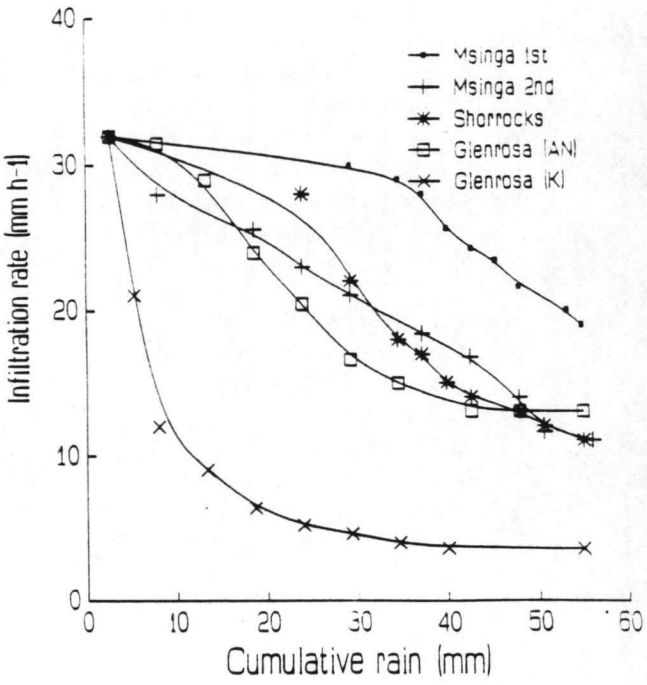


Figure 1 Infiltration rate of the four untreated soil samples in the 1st irrigation event as a function of cumulative irrigation. Curves from both 1st and 2nd irrigation events are presented for the Msinga soil.

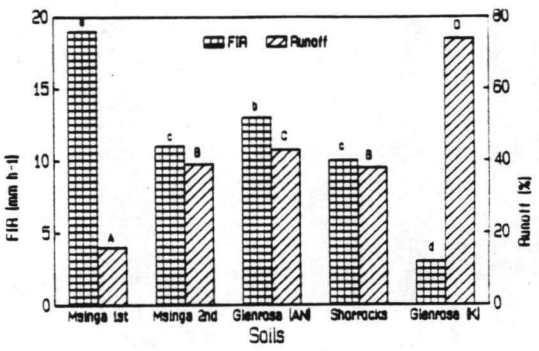


Figure 2 Final infiltration rate (FIR) and percent runoff for the four untreated soil samples at the end of the 1st irrigation event. For the Msinga soil values of both 1st and 2nd irrigation events are presented. Bars followed by the same lower case letter do not differ significantly at the 0.05 level. Bars followed by the same capital letter do not differ significantly at the 0.05 level.

of the seal might increase its resistance to soil detachment (Bradford *et al.*, 1987).

2. Addition of 10 ppm PAM to the irrigation water

Addition of 10 ppm PAM in the first two irrigation events, which were then followed by three events of TW only, and an additional one where again PAM was added to the irrigation water, affected the 4 soils studied differently. The IR of the Msinga soil was

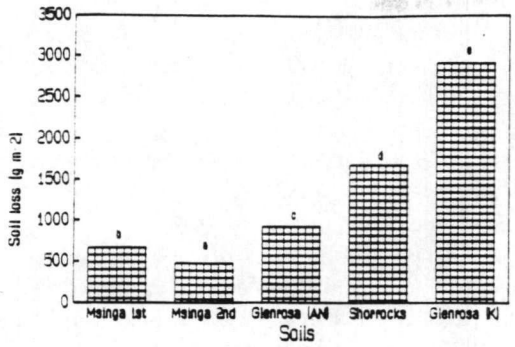


Figure 3 Total soil loss obtained from the four untreated soil samples at the end of the 1st irrigation event. For the Msinga soil values of both 1st and 2nd irrigation events are presented. Bars followed by the same lower case letter do not differ significantly at the 0.05 level.

limited by the irrigation intensity to 33 mm h^{-1} in all six consecutive irrigation events of this treatment. Consequently, no runoff and hence no soil erosion were observed (Table 2). With respect to soil erosion, splash from the soil boxes positively correlated with the soil removed by runoff water (Young & Wiersma, 1973). Apparently, the PAM added to the soil in the first two events was enough to stabilize the aggregates at the soil surface and increased their resistance to the beating action of the water drops in the following three events (i.e., events 3, 4 and 5), where TW only was used. Seal formation, runoff and soil erosion were hence prevented.

Similarly, the IR in the Glenrosa (AN) was limited by the irrigation intensity (33 mm h^{-1}) in the first two events where PAM was added to the irrigation water and also in the 3rd event (the first in a series of three, where TW only was used). A decrease in the IR was observed only in the 4th and 5th consecutive events, and the FIR obtained were 28 and 18 mm h^{-1}, respectively (Table 2). These values were, however, significantly higher than the FIR obtained in the control. Following the decrease in the IR some runoff and soil loss were observed in the 4th and 5th irrigation events (Table 2). It was evident that the effect of PAM in stabilizing the aggregates at the soil surface wore out gradually with the increase in irrigation depth in these two events. However, drying of the soil between consecutive events which may disrupt the structure of the seal formed and increase its permeability (Levy, Shainberg & Morin, 1986), as well as reintroduction of 10 ppm PAM to the irrigation water, resulted in high IR during the last (6th) consecutive event (Table 2).

The FIR in the Shorrocks was also limited by the irrigation intensity during the first two events where PAM was added to the irrigation water. During the following three events of TW only, the FIR decreased gradually to 14 mm h^{-1} and runoff amounted to 40% at the 5th event (Table 2). Subjecting the soil to an additional event with PAM did not improve the FIR and resulted in more runoff (52%). Compared with a decrease of only 35% and an increase of 79% in the FIR and percent runoff, respectively, soil loss increased more than twofold from the 3rd to the 6th event (Table 2). This observation supported the conclusion drawn previously, that infiltration parameters and soil loss are not directly linked.

Unlike its effect on the Msinga, Glenrosa (AN) and Shorrocks soils, an addition of PAM to the irrigation water did not have any effect on the Glenrosa (K) soil (data not presented). The IR decreased immediately from the beginning of the event and reached a low final IR value (4 mm h^{-1}), similar to that obtained in the control. Percent runoff and soil loss obtained in this treatment were also similar to those obtained in the control.

3. Addition of 100 ppm PAM in 10 mm of irrigation

In the present treatment, by contrast to the previous treatment, PAM was added to the soils via the irrigation system prior to the simulated irrigationevents. The Msinga soil was proven again to be the most stable of the soils studied. In the first two

Table 2 Final infiltration rate (FIR), percent runoff and soil loss obtained in the 10 ppm PAM treatment.

Soil - location - form		Dundee Msinga			Aliwal North Glenrosa			Potchefstroom Shorrocks	
Irrigation event no.	FIR	Runoff	Soil loss	FIR	Runoff	Soil loss	FIR	Runoff	Soil loss
	mm h^{-1}	%	g m^{-2}	mm h^{-1}	%	g m^{-2}	mm h^{-1}	%	g m^{-2}
1	33.0	0.0	0.0	33.0	0.0	0.0	33.0	0.0	0.0
2	33.0	0.0	0.0	33.0	0.0	0.0	33.0	0.0	0.0
3	33.0	0.0	0.0	33.0	0.0	0.0	20.0	29.0	480.0
4	33.0	0.0	0.0	28.0	6.0	196.0	20.0	29.0	613.0
5	33.0	0.0	0.0	18.0	23.0	336.0	14.0	40.0	595.0
6	33.0	0.0	0.0	33.0	0.0	0.0	13.0	52.0	1070.0

consecutive events the IR was limited by the irrigation intensity to 33 mm h^{-1}. Only in the 3rd event the FIR dropped to 20 mm h^{-1} and consequent runoff and soil loss were observed (Table 3). However, both percent runoff and soil loss were smaller in this event than those obtained in the 2nd event in the control. It should be noted that the soil loss was approximately 9-fold lower than that in the control. Thus, for the Msinga soil, more than 150 mm of irrigation is needed to diminish the positive effect of PAM (as applied in the current treatment), on aggregate stability and soil permeability. Similarly, the IR of the Glenrosa (AN) soils remained at a high value during the first two consecutive events and decreased slightly during the 3rd event. Hence, the soil loss from the Glenrosa (AN) during the 3rd event was much higher than that from the Msinga soil. In the Shorrocks soil this PAM treatment was less pronounced than in the former two soils. Already at the end of the 1st irrigation event, the FIR decreased to 28 mm h^{-1}, and eventually reached 13 mm h^{-1} at the end of the 3rd event. Consequently, substantial amounts of runoff and erosion were observed in the three consecutive events (Table 3).

As was the case in the former treatment, PAM application in the current method was totally ineffective in preventing seal formation, runoff and soil erosion in the Glenrosa (K) soil. All parameters studied were indistinguishable from those obtained in the control (data not presented).

4. Combined application of PAM and PG

This treatment, where PAM at the equivalent rate of 20 kg ha^{-1} was sprayed over the soil surface after the spreading of PG at the equivalent rate of 5 t ha^{-1} prior to the irrigation events, was studied on the Msinga and Shorrocks soils. In the Msinga soil the IR was limited by the irrigation intensity in all three consecutive events, and hence no runoff and soil loss were noticed (Table 4a). In the Shorrocks, PAM was not as effective, and a gradual decrease in the FIR, and increase in runoff and soil loss, were observed over the three irrigation events (Table 4a). However, at the end of the 3rd event, the rates of runoff and soil loss were significantly lower than those obtained in the control. Thus, in the current treatment, PAM had a residual favourable effect on aggregate stability and soil permeability beyond the first 55 mm of irrigation water.

5. Spraying of PAM dissolved in a $CaCl_2$ solution

In this treatment, PAM was dissolved in a 20 $mmol_c$ L^{-1} $CaCl_2$ solution and sprayed onto the Glenrosa (K) soil surface until an amount equivalent to 20 kg ha^{-1} had been applied; thereafter the soil was exposed to three simulated irrigation events. In the current treatment, and by contrast to all other PAM application methods tested in the Glenrosa (K) soil, PAM was effective in improving the FIR, and decreasing runoff and soil erosion during the first irrigation event (Table 4b). In the following two consecutive events, these parameters had similar values to those obtained in the control.

Discussion

With the exception of the illitic Glenrosa (K), addition of PAM through various application practices to the soils studied resulted in higher IR values and reduced runoff and soil loss levels. These favourable effects of PAM were attributed to its ability, as a soil conditioner, to enhance aggregate stability and soil structure at the soil surface. However, this effect varied for each of these soils over the consecutive irrigation events. The Msinga soil was the most favourably affected by the addition of PAM. In the Msinga, PAM application generally resulted in a complete stability of the surface aggregates. No runoff and erosion were observed as the IR was limited by the irrigation intensity for all the irrigation events but one (see Table 3). The Glenrosa (AN) was more favourably affected by PAM than the Shorrocks soil. However, the susceptibility of the non-treated soil samples of these two soils to seal formation was similar. It appears that the PAM added interacts differently with various soil types and thus enhances

Table 3 Final infiltration rate (FIR), percent runoff and soil loss obtained in the 100 ppm PAM treatment.

Soil - location - form		Dundee Msinga			Aliwal North Glenrosa			Potchefstroom Shorrocks	
Irrigation event no.	FIR	Runoff	Soil loss	FIR	Runoff	Soil loss	FIR	Runoff	Soil Loss
	mm h^{-1}	%	g m^{-2}	mm h^{-1}	%	g m^{-2}	mm h^{-1}	%	g m^{-2}
1	33.0	0.0	0.0	33.0	0.0	0.0	28.0	6.0	188.0
2	33.0	0.0	0.0	31.0	0.0	0.0	19.0	21.0	1028.0
3	20.0	26.0	59.2	19.0	15.0	363.0	13.0	53.0	996.0

Table 4a Final infiltration rate (FIR), percent runoff and soil loss obtained in the combined PAM and PG application.

Soil - location - form		Dundee Msinga			Aliwal North Glenrosa			Potchefstroom Shorrocks	
Irrigation event no.	FIR	Runoff	Soil loss	FIR	Runoff	Soil loss	FIR	Runoff	Soil loss
	mm h^{-1}	%	g m^{-2}	mm h^{-1}	%	g m^{-2}	mm h^{-1}	%	g m^{-2}
1	33.0	0.0	0.0	33.0	0.0	0.0	28.0	6.0	188.0
2	33.0	0.0	0.0	25.0	9.0	320.0	19.0	21.0	1028.0
3	33.0	0.0	0.0	16.7	18.0	840.0	13.0	53.0	996.0

Table 4b Final infiltration rate (FIR), percent runoff and soil loss obtained in the PAM dissolved in the CaI_2 solution treatment.

Soil - location - form		Karoo Glenrosa	
Irrigation event no.	FIR	Runoff	Soil loss
	mm h^{-1}	%	g m^{-2}
1	10.0	43.0	2344.0
2	4.0	79.0	3720.0
3	3.5	82.0	3260.0

their inherent stability differently. This aspect of PAM application to soils was beyond the scope of the current study and should be investigated in future studies. The inability of PAM to improve the stability of the illitic Glenrosa (K) is not fully understood. Presumably, more soluble salts should be introduced with the applied water in order to induce flocculation in this highly dispersive soil, after which the stabilizing effect of the PAM will be more pronounced.

Of the various PAM application methods tested, addition of 10 ppm PAM to the irrigation water had the strongest and most lasting effect on controlling seal formation, increasing IR and reducing soil erosion. This was so in spite of the fact that only the equivalent amount of 11 kg ha^{-1} of PAM was added to the soil compared with 20 kg ha^{-1} in the other methods used.

Adsorption of the polymer at the soil surface should enhance its ability to promote the stability of particles and aggregates at the soil surface. However, adsorption of anionic polymers in general and that of PAM in particular is limited (Aly & Letey, 1988). It was assumed that the non-adsorbed fraction of PAM moved with the percolating water into the soil profile during the irrigation event, and thus became ineffective in stabilizing aggregates at the soil surface and preventing seal formation. In the 10 ppm PAM treatment there was a constant supply of PAM to the soil surface during the first two events, i.e., during the first 110 mm of water. By contrast, in the other treatments the total amount of PAM applied was added prior to irrigation events. It is possible that the adsorption efficiency of PAM depends on the way PAM is added to the soil. It is hypothesized that in the 10 ppm PAM treatment, PAM adsorption was superior to that in the other methods. Consequently, although a smaller total amount of PAM was added, more PAM was adsorbed to the aggregates at the soil surface in the 10 ppm PAM treatment. Hence, this treatment was more effective in controlling seal formation, runoff and erosion over three consecutive irrigation events compared with the other methods tested. The above hypothesis must be further examined.

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USING THE PROBABILITY DENSITY FUNCTION OF SOIL WATER CONTENT TO LOCATE REPRESENTATIVE SOIL WATER MONITORING SITES IN A DRIP IRRIGATED VINEYARD

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Abstract

This study investigated whether the probability density function of spatially measured soil water content at the first stage of a field study can be used to identify statistically important field locations. The soil water content at 14 sites was monitored at 15 different times over a period of 18 months in a drip irrigated vineyard. It was found that certain sampling locations conserve the property of representing the mean and extreme values of the field water content over time. The presence of transpiring vines and irrigation applications increased the variability of the measured values without any large influence on the ranking position of the various monitoring sites as they initially appear on the probability density curve. The locations that were identified as being representative of the field mean water content during summer, also represented the mean during winter when irrigation and transpiration were absent. However, the positions representing the field mean and extreme water contents of the topsoil differ significantly in space from the corresponding subsoil positions. It is concluded that, because of the temporal stability of the ranking position of the measuring sites, the probability density curve of one sampling only can be used to identify representative sites (e.g. the median), that can be used for soil water monitoring and irrigation scheduling. However, cognizance should be taken of the confounding effects that are likely to occur with depth.

Introduction

Proper scheduling of irrigation involves two aspects, namely how much water should be applied and when. Several techniques are available to accomplish this, e.g. monitoring of the soil water content and matric potential, or monitoring of crop and/or atmospheric factors (Campbell & Campbell, 1982). These two authors argue that since the soil is the primary recipient of the irrigation water, monitoring of the soil water content should be the logical method of scheduling.

Although irrigation scheduling does not require knowledge of the field average soil water content (Campbell & Campbell, 1982), the site or sites used for monitoring the status of soil water, should be representative of the field. Because of soil spatial variability the selection of a representative site is difficult. Previous studies indicate that a large number of samples have to be collected and analyzed before such a representative site or sites can be decided upon, e.g. Nielsen *et al.* (1973), and Moolman (1989). However, a study of Vachaud *et al.* (1985), showed that some sampling locations conserve the property of representing the mean and extreme values of the field water content at any time during the year. In view of this, Wagenet (1985) suggested that a gravimetric sampling and analysis at the first stage of a field study could identify statistically important field locations at which a wider range of more intensively monitored sampling devices could then be located. If the results of Vachaud *et al.* (1985), are generally applicable, their technique can be extended to select a limited number of monitoring sites which can then be used for both irrigation scheduling as well as to estimate the mean and variance of water storage of an irrigated yield. However, the degree to which the temporal stability of the spatial distribution and variability of soil water content is influenced by the method of irrigation, the presence of evapotranspiring crops, and other soil factors such as salinity, has not been investigated.

The aim of this study is, therefore, to report on the application of the concept of temporal stability (Vachaud *et al.*, 1985) in a drip irrigated vineyard in which the water uptake varies with soil properties and depth, season, and spatial differences in root and crop activity.

Materials and methods

Theory of temporal stability of the probability density function

The concept of the temporal stability of the probability density function of spatially measured soil water content, is described by Vachaud *et al.* (1985). According to this concept, at a given time t, sufficient field observations are available to determine their classical statistical parameters. If the location of each observation within the field is known, the spatial distribution of the variable allows the nature of the spatial structure to be identified. By ranking the observations from the smallest to the largest values, and identifying the cumulative probability density function as normal, the particular location associated with a probability of 50% can be found. The observation at that location taken at the time of sampling will then characterize the mean of the soil water content for the entire field. Similarly the locations associated with cumulative probabilities of, for example, 17% or 83%, can be selected to identify values one standard deviation from the mean.

In order to evaluate the temporal stability of a

particular location's ranking position in the cumulative probability density function, Vachaud *et al.* (1985), calculated the temporal mean relative difference in soil water content. This was achieved by obtaining the difference Δ_{ij} between an individual determination of soil water content S_{ij} at location $i(i=1...n)$ at time $j(j=1...nn)$, where n and nn are the number of sampling locations and times of sampling respectively, and the mean water storage $S\acute{j}$ at the same time:

$$\Delta_{ij}=S_{ij}-S_j'$$

$$with\ S_j'=(1/n)\sum_{i=1}^{n} S_{ij}$$

This corresponds to the relative difference:

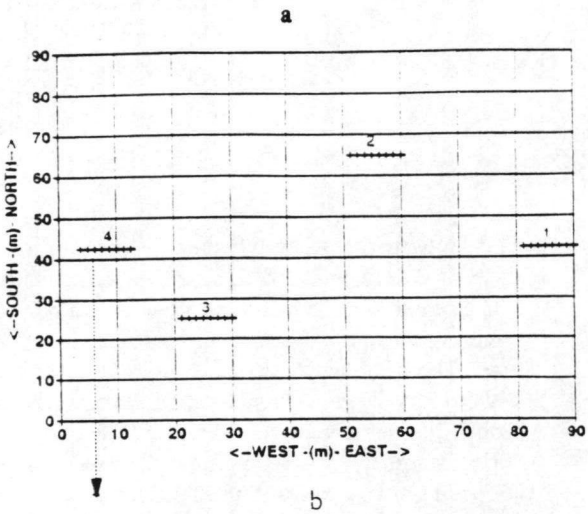
$$\delta_{ij}=\Delta_{ij}/S_j'$$

Therefore, for any location i, the time average $\delta\acute{i}$ and the temporal standard deviation $\sigma(\delta_i)$ can be calculated for the whole series of nn soil water content observations. It follows from the above that for the field mean soil water content, Δ_{ij} will be 0.

Soil and crop information

The study was conducted on 5 000 m^2 of a 3-year old drip irrigated vineyard in the Robertson area, situated in the south-western part of South Africa. The soil of the study area is moderately to very saline (Moolman, 1989) and belongs, for the most part, to the Westleigh Rietvlei series (MacVicar *et al.*, 1977). From 0.45 m downwards, the B-horizon is mottled, indicating hydromorphic conditions in the subsoil. The interrow spacing of the vineyard is 2.5 m, with the drip emitters spaced at 1 m intervals within the row.

In May 1987, as part of a long term study of the spatial variability of soil water content in this vineyard, thirty neutron access tubes were installed to a depth of 1.5 m. The access tubes were installed as fifteen pairs that were divided into four groups (Figure 1). A pair consisted of one tube located 0.3 m from an emitter within the vineyard row, while the other tube was installed midway between two vineyard rows 1.25 m from an emitter. Only the information from the 15 sites located 0.3 m from the emitter, was used to test the concept of temporal stability of the probability density function. The rationale was the need to identify representative sites for irrigation scheduling. In practice it is unlikely that a position midway between two vineyard rows, i.e. near to the maximum distance from a drip emitter and outside the wetted zone, will be useful for irrigation scheduling. Early on during the course of the investigation, one of the access tubes was damaged by a tractor wheel, leaving only 14 locations from which the data could be used. These 14 sites were numbered with a 2-digit identification code, where the first digit indicates the group position and the second the position within the



Detail layout of measuring sites within group 4.

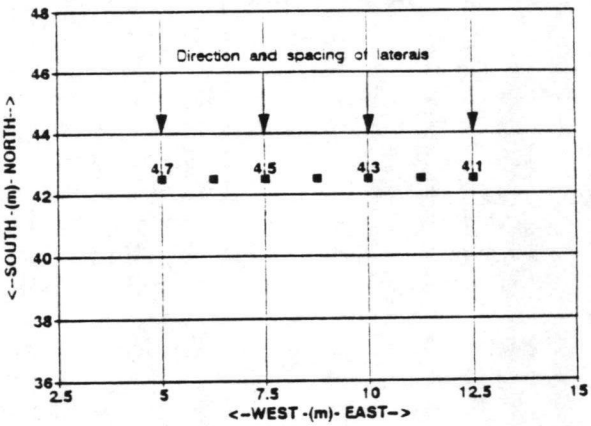


Figure 1 Location of: a) the 15 neutron access tubes distributed as four groups within the drip irrigated field, and b) spacing, location and identification within group 4.

group (Figure 1b).

During the installation of the tubes the soil was sampled in 0.3 m increments to a depth of 1.2 m and the gravimetric water content and soil texture of each sample determined. Bulk densities were determined with a gamma probe and the gravimetric water contents converted to volumetric units. Following the installation of the access tubes and during the winter of 1987, the so-called field capacity of each of the 15 sites was determined. This was done by saturating the soil to a depth of 1.2 m and determining the soil water content after 4 days of drainage in the absence of evapotranspiration. Because of the hydromorphic and saline subsoil conditions (Moolman, 1989), root growth and water uptake are restricted to approximately 1 m depth.

Subsequent to the initial measurements, the soil water contents at each of the 14 sites within the

vineyard row were determined at variable time intervals, but never more than 7 weeks apart, at 15 different times from July 1987 to December 1988. This was done by measuring the soil water content in 0.3 m depth increments to a depth of 0.9 m using the neutron moderation technique. For the 0-0.3 m depth two 0.15 m increments were used. Assuming that the neutron probe measured soil water in a sphere with a radius of 0.15 m, the total soil water storage to a depth of 1.05 m could be calculated. At any one time the soil water storage could furthermore be split into the topsoil (0-0.45 m) and subsoil (0.45-1.05 m) components. The 15 temporal observations could also be divided into 10 measurements made during the active growing season of the vines (October to March, referred to as the summer measurements), and 5 measurements made during the winter (April to September) when the vines were dormant.

The statistical uniformity of emitter flow in the area where the soil water content was monitored, was determined as 93%. This was done by measuring the flow at 25 randomly selected emitters, all in close proximity to the access tubes, and using the following equation (Bralts & Edwards, 1987):

$$U_s = 100(1-S_q/\bar{q})$$

with U_s = statistical uniformity, S_q = standard deviation of emitter flow, and $\bar{q}$ = mean emitter flow rate or volume.

Results and discussion

The mean and standard error of the water content of the 10 summer and 5 winter measurements are given in Figure 2. The standard errors of the summer values for the depth shallower than 0.3 m are substantially larger than those for the winter values and must be attributed to differences in crop water uptake between the various sites. The increase in soil water content with depth is also much steeper during summer than during winter.

The probability density function of the soil water content established during the initial survey of May 1987 when gravimetric samples were taken, is given in Figure 3.

Although the total sample size of 14 was too small to test for normality, the shape of the cumulative probability curve (P) suggests a normal distribution. It should be borne in mind that for a normal distribution the numerical values of the 50th percentile, median and arithmetic mean are the same.

Sampling positions 2.1 and 2.5 are both very close to the median value, with positions 1.5 and 1.7 slightly further away from the median position. Positions 1.1 (P=81%) and 4.3 (P=19%) are approximately one standard deviation from the median (or mean), while positions 2.7 and 3.7 represent the driest and wettest sampling locations, respectively. According to this

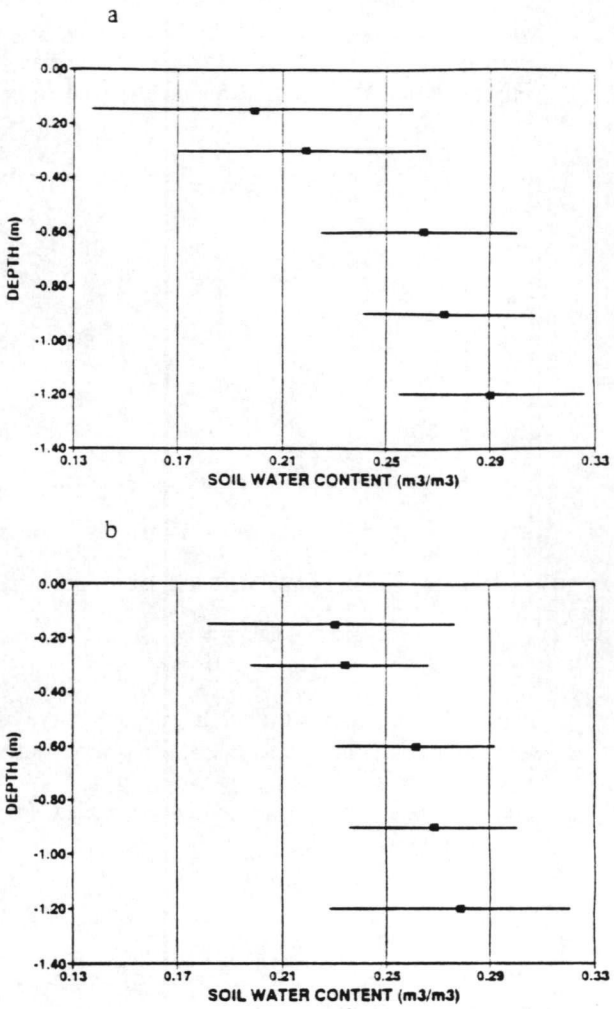


Figure 2 Mean and standard error of the volumetric soil water content at 14 monitoring sites in a drip irrigated vineyard near Robertson: a) Summer measurements ($n=10$), and b) Winter measurements ($n=5$).

result any one of positions 2.1 or 2.5, or even 1.5 and 1.7 can be used to represent the mean soil water content of the 14 sampling positions, and hence, this particular drip irrigated vineyard. The soil water information of these sites can therefore be used to regulate irrigation applications.

The intertemporal relative deviation from the mean soil water content, calculated using all 15 measurements (Figure 4), however gives a slightly different ranking order than Figure 3. According to Figure 4, position 4.5 should be a better approximation of the field mean (=0 in Figure 4) because on average it is only 0.4% (± 6.6%) higher than the field mean at any one time. The water content at position 2.5 is 4.6% (± 4.2%) lower than the field average, while position 2.1, in spite of its smaller domain of uncertainty, is 8.2% higher than the temporal field average. Of importance, however, is the

fact that compared to the ranking position obtained with the initial survey, 13 of the 14 sampling locations maintained their positions relative to the median. The only exception is location 2.3 which moved from a

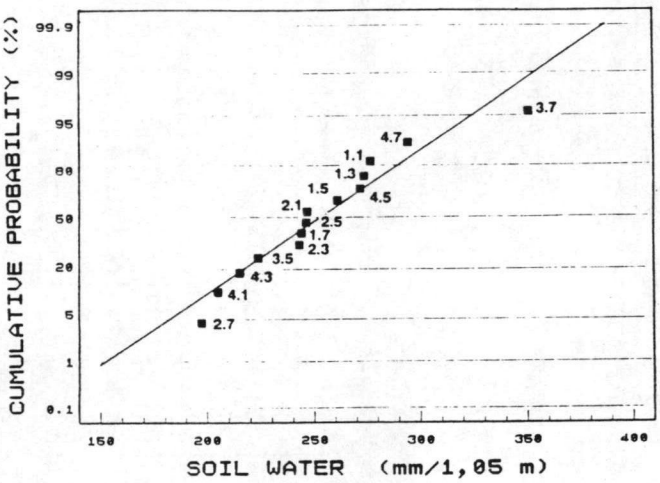


Figure 3 Cumulative probability density curve of the soil water content that was gravimetrically determined at 14 sites in a drip irrigated vineyard in May 1987. The numbers are the identification codes for the sampling sites.

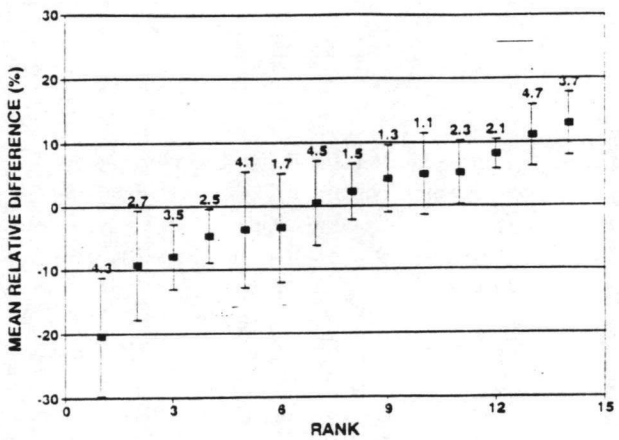


Figure 4 Ranked intertemporal relative deviation from the field mean profile (0-1.5 m) soil water content based on 15 measurements made during summer and winter. The vertical bars indicate the associated temporal standard deviation, while the numbers refer to the 14 sampling sites.

position below the median to one that is 5.5% (± 5.1%) above the temporal mean of the field average (Figures 3 and 4). The cause of this change in the ranking order between measurements obtained using gravimetric samples and the neutron probe is not clear. A possible explanation is that the volume of soil sampled with the gravimetric technique is considerably smaller than the volume measured by the neutron probe. The volume sampled gravimetrically for each 0.3 m depth increment was 498 cm^3. By assuming a radius of 0.15 m as the zone of influence of the neutron probe, it can be shown that for each 0.3 m depth increment, the volume of soil measured by the neutron thermalization method, was 14 137 cm^3. This is 28 times larger than the volume of the gravimetric samples. Hawley *et al.* (1982), found that the size of the sample influences the degree of measured variability of field soil water content. In his study the water content of the smaller samples were more variable than the larger ones. In another study of volume-accuracy relationships, Lauren *et al.* (1986), found that an increase in the physical size of a sample produced a general decrease in the mean and variance of the measured saturated hydraulic conductivity values. It therefore seems as if the size of the gravimetric sample might influence the variability and hence the probability density function and ultimately the selection of representative sites for soil water monitoring.

When the soil measurements are split into summer and winter values, most of the sampling locations maintain their ranking positions on the relative scale of mean differences (Figures 5 and 6).

Locations 4.3 and 3.7 remain the driest and wettest of the 14 sampling sites, while 4.5 and 1.5 stay within 3% of the field average during summer and winter. The biggest difference caused by splitting the data into two sets of seasonal values is the smaller temporal standard deviation of each location during winter. In view of the measured high statistical uniformity

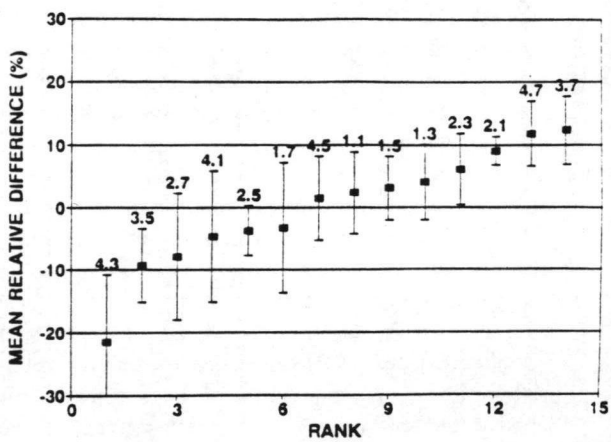


Figure 5 Ranked intertemporal relative deviation from the field mean profile (0-1.05 m) soil water content based on 10 different measuring dates during summer. The vertical bars indicate the associated temporal standard deviation, while the numbers refer to the 14 sampling sites.

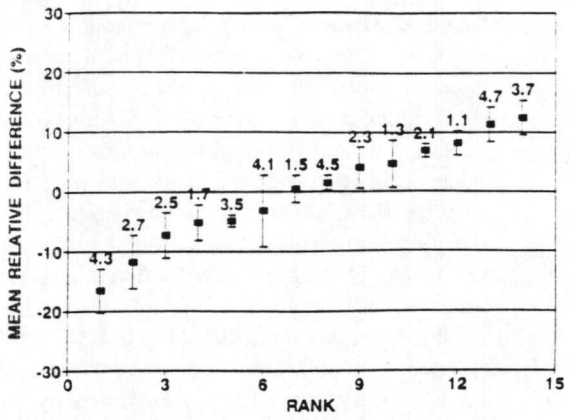


Figure 6 Ranked intertemporal relative deviation from the field mean profile (0-0.05 m) soil water content based on 5 different measuring dates during winter. The vertical bars indicate the associated temporal standard deviation, while the numbers are the identification codes for the 14 sampling sites.

coefficient of emitter flow (i.e. 93%), the significant reduction in the domain of uncertainty must for the most part be attributed to spatial differences in crop water uptake. It seems as if the intrinsic variability in the water retention properties of the soil is substantially smaller than the variability imposed by the crops and method of irrigation. Wagenet (1985) referred to this variability imposed by external factors as the extrinsic variability. It furthermore seems that location 2.5 which, based on the results of the initial sampling, would have been a logical choice to monitor the soil water content for irrigation scheduling purposes, moves further away from the field mean during winter. During summer it was 3.7% (± 4%) lower (Figure 5) and in winter 5.8% (± 3.2%) lower than the field mean (Figure 6).

The ranking order of several of the sampling locations changes drastically when the water content of the topsoil only (i.e. 0-0.45 m) is considered (Figure 7). Based on the total profile water content, locations 3.7 and 2.7 are 12.8% (± 4.9%) above and 9.2% (± 8.6%) below the field mean respectively. However, the topsoil data show that both sites are within 1% of the mean. Therefore, if soil water content of the topsoil (0-0.45 m) only was determined during the initial survey, the probability density function and ultimate selection of a representative soil water monitoring site would have been markedly different. The ranking of the sampling locations on the scale of mean relative differences (Figure 7) also shows that the temporal mean of each location is associated with a large measure of uncertainty. For example, location 2.7 is only 0.5% smaller than the field mean, but is associated with a standard error which exceeds 11%. In contrast, the standard errors of the subsoil water contents are much less. The subsoil water measurements yielded a ranking order which is more similar to that of the profile water content (Figure 4 and 8). This indicates the degree to which the subsoil dominates the total profile water

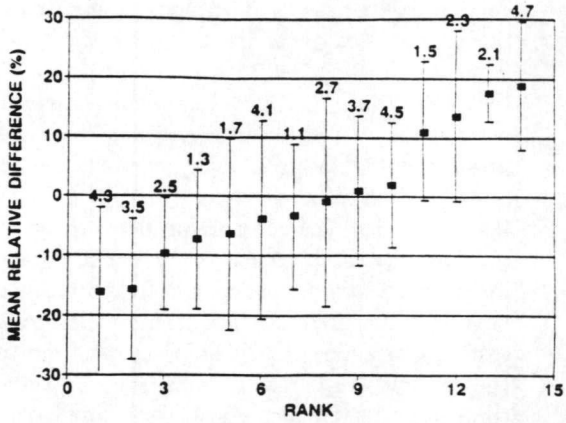


Figure 7 Ranked intertemporal relative deviation from the field mean topsoil (0-0.45 m) water content based on all 15 measurements made during summer and winter. The vertical bars indicate the associated temporal standard deviation, while the numbers are the identification codes for the 14 sampling sites.

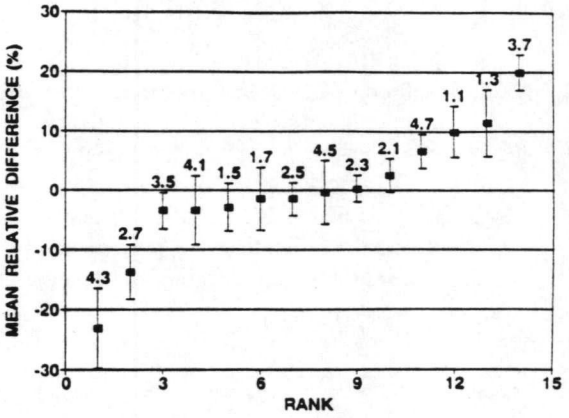


Figure 8 Ranked intertemporal relative deviation from the field mean subsoil (0.45-1.05 m) water content based on all 15 measurements made during summer and winter. The vertical bars indicate the associated temporal standard deviation, while the numbers are the identification codes for the 14 sampling sites.

conditions. On a temporal basis the soil water content of the 0.45-1.05 m layer in this vineyard is also less variable.

The rank of each measurement location based on the interannual deviation from the temporal relative mean of all 15 observations of the profile soil water content, i.e. 0-1.05 m, is listed in Table 1. Also indicated are the depth weighted mean clay (<0.002 mm) and silt

plus clay (<0.02 mm) percentages, as well as the field capacity values determined as previously described. In the study of Vachaud *et al.* (1985), the wettest location had a higher silt and clay content than the driest position. They consequently explained the time stability of particular locations on the basis of the relationship between soil texture and water content. In the present study, the location with the lowest clay content, namely site 4.3, was also the driest of the 14 locations (Table 1). However, the converse is not true, because the wettest location, i.e. site 3.7, was not the position with the highest clay content. The location with the highest clay content, site 1.1, had a rank number of 10. The relationship between the ranking order and total silt plus clay was equally vague. The association between the apparent field capacity and the ranking order is more clear. The wettest and driest sampling locations had the highest (344.5 mm/1.05 m) and lowest (259.0 mm/1.05 m) field capacity water contents, with the positions closest to the temporal mean, i.e. locations 1.7, 4.5 and 1.5, having values close to the arithmetic mean field capacity. The Spearman's rank correlation test also shows that the field capacity values correlate better with the temporally based ranking order than the textural variables. The r-coefficients are 0.86, 0.27 and 0.21 for the field capacity water content, clay, and silt plus clay contents, respectively (Table 1).

Conclusions

In a 0.5 ha drip irrigated soil with a highly variable soluble salt content, it was found that certain sampling locations conserve the property of representing the mean and extreme values of the field water content over time. The presence of vines and application of irrigation increased the variability of the measured values without any large influence on the ranking position of the various monitoring sites as they initially appear on the probability density curve. The locations that were identified as being representative of the field mean water content during summer, also represented the mean during winter when irrigation and transpiration were absent.

If the soil water content is split into top- (0-0.45 m) and subsoil (0.45-1.05 m) components, different ranking orders on the probability density curve are obtained. Positions representing the field mean and extreme water contents of the topsoil differ significantly in space from the corresponding subsoil positions. This indicates that the sampling depth will have a profound effect on the actual selection of monitoring sites and that the rooting depth of the particular crop will have to be carefully considered if this technique of an initial field scale sampling and computed probability density function is used to identify sites representative of the mean and extreme values.

Another factor which might influence the selection of the soil water monitoring sites is the physical size of the soil sample. In this study it was found that a set of physically smaller sized gravimetric samples had a probability density function in which the ranking order of certain locations differed from that of soil water contents measured with a neutron probe. It is speculated that these volume differences had an effect on the ranking order of locations. This aspect will have to be investigated in greater detail.

It is concluded that, because of the temporal stability of the ranking position of the measuring sites, the probability density curve of one sampling only can be used to identify representative sites (e.g. the median), to be used for soil water monitoring and irrigation scheduling. However, cognizance should be taken of the confounding effects that are likely to occur with depth and sample size.

Table 1 Rank of each sampling location in terms of the relative deviation δ_i', from the temporal mean of the field soil water content and corresponding values of field capacity, depth weighted mean clay and silt plus clay contents.

Location	Rank	Field Cap.[a]	Clay %	Silt+clay %
11	10	313.6	23.5	70.6
13	9	313.9	21.5	67.1
15	8	296.3	23.1	69.3
17	6	297.6	22.5	70.7
21	12	291.3	19.0	49.1
23	11	297.8	17.9	49.4
25	4	286.4	18.8	47.5
27	2	239.9	19.9	46.6
35	3	285.5	20.1	52.0
37	14	344.5	22.0	63.1
41	5	268.0	19.3	63.1
43	1	259.0	18.0	61.1
45	7	293.2	22.1	65.8
47	13	315.2	20.3	53.4
Spearman r		0.86**	0.27	0.21

[a] Field Cap = field capacity

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EFFECTS OF FURROW IRRIGATION METHOD AND PHOSPHOGYPSUM ON WATER INTAKE BY SOIL AND SUGARCANE YIELD AT MHLUME

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Abstract

A field study was conducted on a first ratoon sugarcane crop. The effects of four furrow irrigation methods and surface applied phosphogypsum on water intake by the soil and cane yields were determined. The beds (twin-row planting) and in-row irrigation methods resulted in about 70% more water intake compared to inter-row irrigation. The latter also produced low soil water contents, particularly in the ridge. Phosphogypsum increased water intake and reduced runoff. It also increased soil wetness with the inter-row irrigation methods, but did not seem to do so in the case of the in-row and bed methods, possibly because these had high water contents even without phosphogypsum. Inter-row irrigation produced low cane yields compared to in-row and the beds when phosphogypsum was not applied. Phosphogypsum however resulted in comparable yields on all furrow methods, except on the inter-row with cultivation method.

Introduction

Many irrigation projects on soils of low structural stability are affected by poor soil physical properties. Studies reported by Quirk & Schofield (1955), McNeal & Coleman (1966) and Johnston (1973) have shown some of the problems to include low hydraulic conductivity, low infiltration rates and poor water holding capacities. The use of phosphogypsum has been shown to improve poor soil physical conditions (Johnston, 1977; Agassi, Shainberg & Morin, 1986; Jayawardane & Blackwell, 1986; Frankel, Gerstl & Alperovitch, 1989). At Mhlume about 4 800 ha of land is under irrigated sugarcane. About 54% of this area is on structurally unstable soils with a high risk of salinity and sodicity problems (Nixon, Workman & Glendinning, 1986; Workman, Scott & Nixon, 1986). Furrow irrigation is the main method of irrigation used at Mhlume. The policy has been to in-row irrigate the plant crop and then convert to inter-row irrigation in the first ratoon. From the early 1980's, widespread drought stress and low ratoon yields made inter-row irrigation questionable. Hence in 1987 a decision was made to maintain in-row irrigation on as many ratoons as possible. Unfortunately the precise potential of in-row irrigation on the structurally unstable soils was not known. It has been shown by Gosnell & Pearce (1971) and Pearse (1973), that large differences in water intake can occur between in-row and inter-row irrigation because of the effects of cane stalks and trash. Studies by Aarstad & Miller (1980) showed that the presence of straw in the irrigation furrow could increase infiltration rates by as much as 50%.

The purpose of this study was to compare the effects of four furrow configurations and phosphogypsum on total water intake by the soil and sugarcane yield.

Material and methods

Soil type

Some of the important properties of the soil on which the study was done are shown in Table 1. The soil is similar to that described by Murdoch (1972) as a Homestead series. It resembles closely the Estcourt and Kroonstad forms described in the binomial system for South Africa (MacVicar, de Villiers, Loxton, Verster, Lambrechts, Merryweather, le Roux, van Rooyen & Harmse, 1977).

Table 1 Some soil physical and chemical properties of the soil.

Depth (mm)	Texture %			Bulk density g cm^3	pH (H_2O)	EC (mS m^{-1})	SAR
	Sand	Silt	Clay				
0-0.30	67	3	28	1.72	7.0	54	3.63
0.30-0.60	56	3	38	1.69	7.5	88	7.15

Experimental design and treatments

A split-plot design was used to study the effects of two levels of phosphogypsum (0 and 10 t ha^{-1}) as the m plot treatments. These were replicated three ti Each main plot was split into four subplot treatments for irrigation methods. These were: 1. in-row; 2. beds (or twin-row planting); 3. inter-row with cultivation; and 4. inter-row without cultivation. Both the in-row and inter-row methods have previously been described by Gosnell & Pearse (1971). A planting method similar to the beds has been described by Roach (1976). In this study the twin rows were planted 0.70 m apart in wide and flat bottomed furrows. The irrigation methods were established at planting in 1988. Germination problems with inter-row methods made it necessary to re-establish these with in-row irrigation and then convert to inter-row irrigation methods at about three months after germination. For this reason, phosphogypsum application was postpc until the first ratoon crop. Application was done by means of a tractor drawn applicator. Following this,

inter-row cultivation was done once on the "Inter-row plus cultivation" treatment.

Each subplot had six rows of 220 m length and 1.5 m spacing. The spacing between two sets of twin rows on the beds was 1.5 m. A furrow slope of 0.5% was used. Water into each furrow was applied at a rate of 4.3 L s^{-1} by means of 63 mm diameter spile pipes. Application was stopped when water in two furrows reached the furrow end.

Measurements

Net water infiltration was obtained from the difference between gross application and runoff. Gross application was calculated as the product of the spile flow rate and the duration of application. Runoff was measured by means of 75 mm Parshall flumes in a way similar to that described by Bos (1978). For each plot runoff from all rows was channelled through one flume. To get an indication of the effect of phosphogypsum on infiltration, double cylinder infiltrometers were used as described by London (1984) to determine the infiltration rate. Measurements were only made on in-row and inter-row plots. Soil water content was determined from soil samples taken 24 hours after irrigation by the gravimetric method (London, 1984). Sampling was done at two depths, 0-0.10 and 0.30-0.40 m on the cane row and at 0.75 m from the row (inter-row). Two samples were taken from each plot. For harvesting, nine small plots of four rows by 10 m were cut in each subplot and weighed to determine yield per hectare. Sixteen stalks were taken from each plot for sucrose percentage determination. From the cane yield and the sucrose content, sucrose yield was determined.

Results

Water intake by soil

Figure 1 shows the effect of furrow irrigation method and phosphogypsum on water intake by the soil. It can be seen that the in-row and bed methods applied comparable quantities of water, which were about 70% more than that applied by the inter-row methods. In all cases phosphogypsum resulted in increased water intake. This is partly because phosphogypsum improved the infiltration rate of the soil (Figure 2). Initial infiltration rates were about doubled when 10 t h^{-1} of phosphogypsum was applied.

The effect of irrigation method and phosphogypsum on the proportion of gross application lost as runoff is shown in Figure 3. Runoff as a proportion of gross application was highest on inter-row irrigation and least on beds. With all irrigation methods phosphogypsum resulted in reduced runoff.

Soil water content

Figure 4 shows the effect of irrigation method and phosphogypsum on soil water content at two soil depths. In both Figure 4a and 4b "int-c" and "inter" refer to inter-row irrigation with and without cultivation, respectively. For in-row and beds "Furrow" corresponds to samples taken from the cane row, and "Ridge" to samples from between cane rows. For inter-row irrigation (inter-c and inter) the reverse is true. From Figure 4a it can be seen that except for the bed treatments, the main differences in soil water content were between the furrow and the ridge. For all the irrigation methods soil from the furrows had comparable soil water contents. For samples taken from the ridge, only the beds had markedly wetter soil than the other methods.

Sugarcane yields

The sugarcane yields in tonnes cane per hectare (t ha^{-1}) for all the treatments are shown in Table 2. The results suggest that inter-row irrigation produces lower yields than in-row or bed. The differences between irrigation methods were not, however, statistically significant. Although not statistically significant, phosphogypsum treatments produced higher cane yields than the control. The highest response was on inter-row irrigation. Sucrose results were very similar in all treatments.

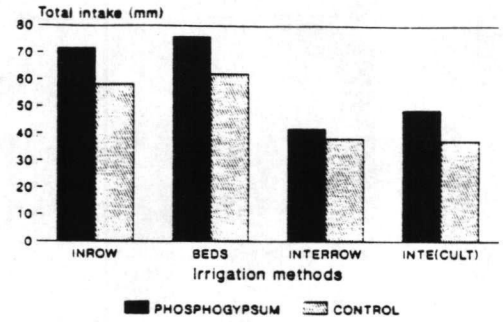


Figure 1 Effect of irrigation method and phosphogypsum on water intake.

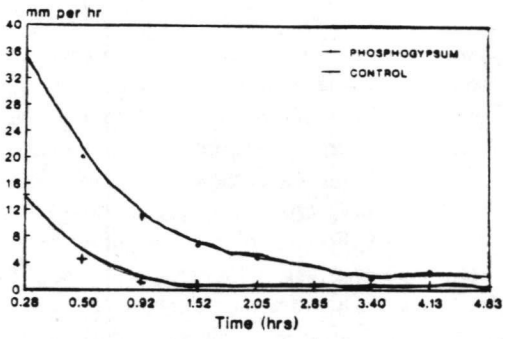


Figure 2 Effect of phosphogypsum on intake rate.

Discussion and conclusion

The results obtained concerning the effect of furrow irrigation method on water intake confirm previous results reported by Pearse (1973) and Gosnell & Pearse (1977), that a furrow irrigation method with the

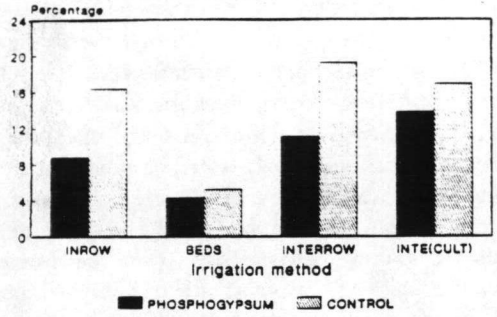


Figure 3 Effect of irrigation method on runoff.

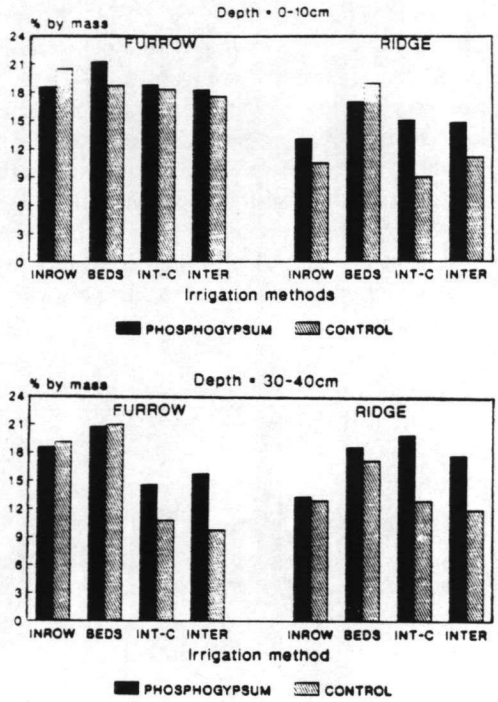


Figure 4 Effect of irrigation method and phosphogypsum on soil water content.

cane growing in the furrow (as in in-row and the beds) leads to very large quantities of water being taken in by the soil compared to when the cane grows on the ridge (inter-row irrigation). When the cane grows in the furrow, the cane stalks and trash reduces water advance rates which necessitates longer application periods. In this study flow restriction by cane stalks and trash was also observed to increase the wetted perimeter. This effect is known to increase the water intake rate of a soil (Trout, 1986). The increased water infiltration rate of the soil due to phosphogypsum also resulted in increased total water intake. While soil water contents for in-row and bed methods did not indicate any response to phosphogypsum, measurements on inter-row methods consistently showed an increase in soil wetness due to phosphogypsum. The higher water intake from in-row and bed methods could have maximised soil wetness even

Table 2 Effect of irrigation method and phosphogypsum on cane yield.

Irrigation method	Phosphogypsum 0 t ha^{-1}	Phosphogypsum 10 t ha^{-1}	Mean
In-row	89.70	90.60	90.15
Bed	84.69	89.68	87.19
Inter-row	* 69.75	* 92.21	80.98
Inter-row and cult	75.95	82.87	79.41
Mean	80.02	88.84	84.43

* Significantly different means (P = 0.05)
SE of differences between means (t ha^{-1})
Phosphogypsum = 2.23 (2)
Irrigation method = 6.02 (12)
Interaction = 7.70 (12)
( ) gives degrees of freedom for error

without phosphogypsum. The increased soil water content and yield for inter-row methods with phosphogypsum suggest that these methods of irrigation cannot adequately wet the soil profile unless measures are taken to improve infiltration properties of the soil.

Further investigations into the high soil water intake under in-row and bed methods in relation to the soil water holding capacity are required, otherwise over-irrigation can easily result in waterlogging of these unstable soils.

Acknowledgements

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STRUCTURE AS AN INDEX OF THE IRRIGABILITY OF SOILS

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Abstract
Soils distributed all over South Africa (15 drainage regions) have been used in this investigation to determine as far as possible, the effect of various soil forming processes on pedogenesis and soil use. The main object of this investigation was to characterise and evaluate soils with neocutanic, pedocutanic, prismacutanic, red structured and vertic horizons in terms of their irrigability. Soil structure influences plant development, cultivation, drainability and irrigability of soils. An increase in the degree of structural development from neo-< pedo-< prismacutanic horizons coincided with an increase in clay content, water retentivity, plasticity index, clay activity, AWR, CEC and sodium content.

Introduction

Successful irrigation schemes are based on, among other things, a sound knowledge of the soils concerned. The first step in this knowledge-collecting process is usually the classification of the soils according to their morphology. Morphological characteristics of a soil reflect soil genesis and are interrelated to other chemical, physical, mineralogical and biological properties. Morphological properties are commonly used as a substitute for more meaningful properties that are seldom measured on a routine basis.

Changes in methods of cultivation and irrigation has necessitated a revision of the present norms for selecting soils for irrigation planning purposes. Most of these norms place a high priority on easily observable morphological properties, such as soil structure. The importance of soil structure in soil classification and soil productivity can scarcely be overemphasized. According to Soil Survey Staff (1975) the suitability of any soil for the growth of plants and its response to management depends as much on its structure as on its fertility.

The objective with this investigation was to characterise and evaluate soils with neocutanic, pedocutanic, prismacutanic, red structured and vertic horizons in terms of their irrigability.

Materials and methods

Soils distributed all over South Africa have been used in this investigation to examine the properties of various diagnostic materials in terms of quantitative physical and chemical parameters (Table 1). Soils were selected from 15 different drainage regions in this country (Nell, 1991). More emphasis was put on the calcareous and pedocutanic soils of the Sundays and Great Fish drainage regions because a number of these soils are incorporated in the Orange River Project.

Samples were taken from 333 soil profiles which were classified according to Soil Classification: A binomial system for South Africa (MacVicar *et al.*, 1977). The Munsell Soil Color Charts (1975) were used to describe soil colour.

Table 1 Number of sampling sites per soil form and drainage regions.

	Soil form				
	Valsrivier	Oakleaf	Arcadia	Sterkspruit	Shortlands
Drainage regions					
Sundays River	39	25	-	1	1
Great Fish River	28	7	-	1	-
Little Fish River	9	5	-	2	-
Pongola River	16	7	9	11	14
Steelpoort/ Olifants River	12	4	3	1	2
Sand-/Vet River	5	1	4	-	-
Modder-/Riet River	36	10	1	2	-
Limpopo River	2	2	4	1	5
Boesmans River	3	3	-	-	1
Duiwenhoks River	6	4	-	3	1
Pienaars River	7	1	2	1	1
Berg River	2	2	-	1	-
Upper Vaal River	2	1	5	1	1
Doorn River	2	4	1	1	-
Breë River	4	1	-	2	1
Total	173	77	29	28	26

Elementary statistical techniques (Statistical Graphics Corporation, 1988) were used to identify relationships between the various morphological, chemical and physical parameters. The sampling procedure and the analytical methods were the same as described by Land Type Survey Staff (1988). Atterberg limits were determined by standard procedures (TMH 1, 1979). Infiltration measurements were made on some diagnostic horizons using double ring infiltrometers, with a 710 mm inner ring. A constant hydraulic head of 150 mm was maintained for 360 minutes after which the infiltration rate was calculated. Water used had an EC of 103 mS/m. *In situ* hydraulic conductivity measurements were made on 2.5 m x 2.5 m plots using the method described by Hillel *et al.* (1972). Tensiometers at 300 mm, 600 mm and 900 mm depths and a neutron probe were used to measure the temporal changes in matric potential and soil water content, respectively. Loss of water by evaporation was prevented by covering the sides and the top of the plots by PVC sheeting. The general flow equation (Equation 1) describing water flow in a vertical direction was used to calculate hydraulic conductivity:

$$\frac{\partial \theta v}{\partial t} = \frac{\partial}{-\partial z}[K(\theta)\frac{\partial \psi h}{\partial z}] \quad (1)$$

where θv = volumetric water content;
t = time
$K(\theta)$ = hydraulic conductivity, functionally dependant on θ
ψh = hydraulic potential
z = vertical depth co-ordinate, negative downward

Results and discussion

Physical properties

Water movement in and through the soil is one of the most important processes giving rise to horizon differentiation and structural development. An increase in the degree of structural development from neocutanic to pedocutanic to prismacutanic horizonscoincided with an increase in clay content and a larger clay ratio between the B and A horizons (Table 2). These clay differences between the diagnostic B horizons and the relative increase in clay content from the A to the B horizons can be used to give a broad indication of the suitability of soil forms for irrigation in the different regions included in this investigation.

The characteristic water retention curves (Figure 1(a) and (b)) for the various soil forms have been obtained by the use of median volumetric water content at -15 kPa, -80 kPa, -500 kPa and -1 500 kPa matric potential. Soils of the Oakleaf form show little difference in the retention properties between the A and B horizons. The differences between the A and B horizons increase with structural development in the B horizon with a remarkable difference between the horizons of the Sterkspruit form. Soils with a strong degree of structural development (Arcadia form) or a distinct duplex character (Sterkspruit form) hold large quantities of water at low matric potentials, which is unavailable for plant growth.

To determine the infiltration and hydraulic conductivity of soils regarded as marginal for irrigation purposes, a typical pedocutanic duplex soil of the Sundays river drainage region has been used.

The drastic decrease in infiltration rate (Table 3) that was observed from the A to the B horizon, can mainly be attributed to the increase in clay- and Na-content occurring with depth in this duplex soil. During the removal of the A horizon to determine the infiltration rate of the B horizon, it was frequently observed that horizontal water movement above the B horizon had occurred. This will give rise to the development of temporary perched water tables in these soils when irrigated. The productivity of irrigated land is fundamentally dependent upon internal drainage of the soil (Cass & Sumner, 1982). Internal drainage itself is a function of profile morphology, pore size distribution, and stability of pore structure. A typical pedocutanic duplex soil has been used in Table 4 to illustrate that drainage may take up to a few months to cease. The large difference in volumetric water content between the relatively sandy upper soil (0.3 m depths) and the more clayey subsoil (0.6 m and

Table 2 Summary statistics of clay ratio between the B and A horizons, clay percentage, air-water permeability ratio and clay activity of different soil forms.

Soil form	Oakleaf		Valsrivier		Sterkspruit		Shortlands		Arcadia
Diagnostic horizon	Orthic A	Neocutanic B	Othic A	Pedocutanic B	Orthic A	Prismacutanic B	Orthic A	Red structured B	Vertic A
Clay ratio between the B and A horizons									
Median	1.18		1.43		1.75		1.18		
Lower quartile	0.95		1.06		1.24		1.00		
Upper quartile	1.45		1.90		2.70		1.32		
Sample size	101		235		38		41		
Clay percentage									
Median	19	24	24	37	21	38	42	49	53
Lower quartile	13	16	19	29	14	27	30	40	47
Upper quartile	25	31	34	44	26	52	51	59	61
Sample size	71	101	148	247	28	38	26	41	45
Clay activity									
Median	0.38	0.40	0.43	0.50	0.35	0.64	0.41	0.45	0.84
Lower quartile	0.32	0.38	0.38	0.45	0.29	0.44	0.39	0.40	0.66
Upper quartile	0.46	0.47	0.56	0.59	0.44	0.75	0.50	0.52	0.94
Sample size	10	13	29	61	4	11	9	12	6
Air-water permeability ratio (AWR)									
Median	12	9	12	86	12	999	16	21	511
Lower quartile	7	6	7	27	7	160	6	7	78
Upper quartile	199	68	34	999	27	999	60	102	999
Sample size	20	22	54	86	14	19	18	29	30

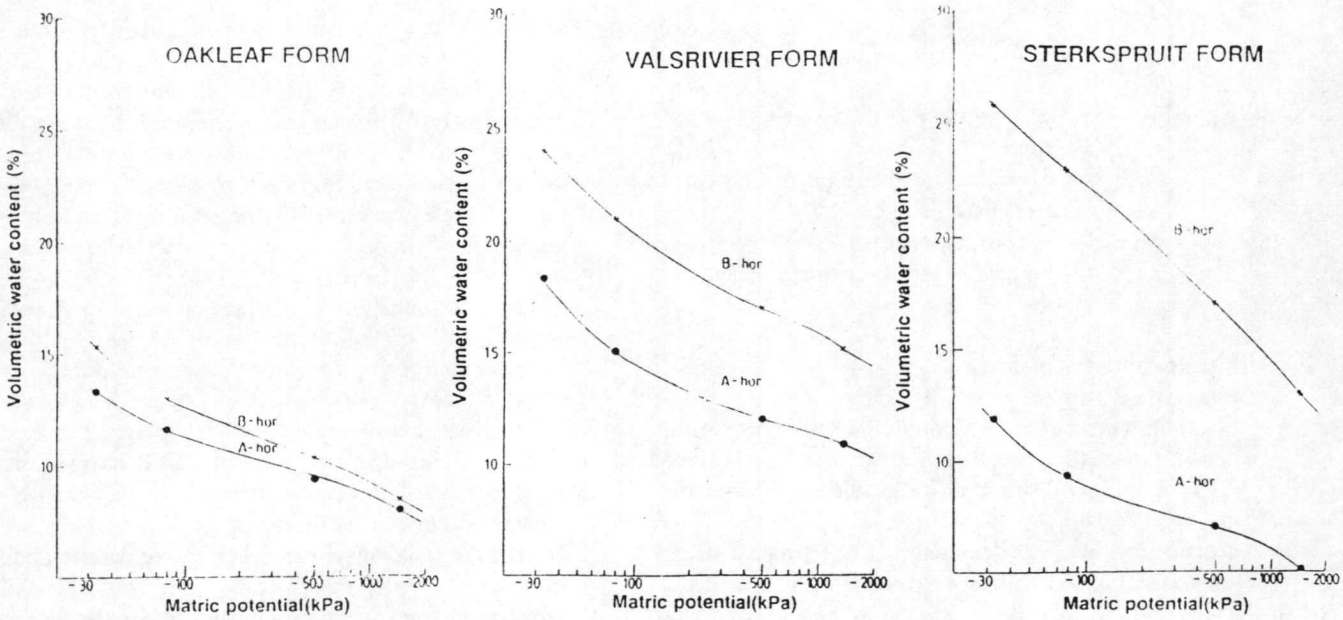


Figure 1 (a) Water retentivity curves of soils of the Oakleaf, Valsrivier and Sterkspruit forms.

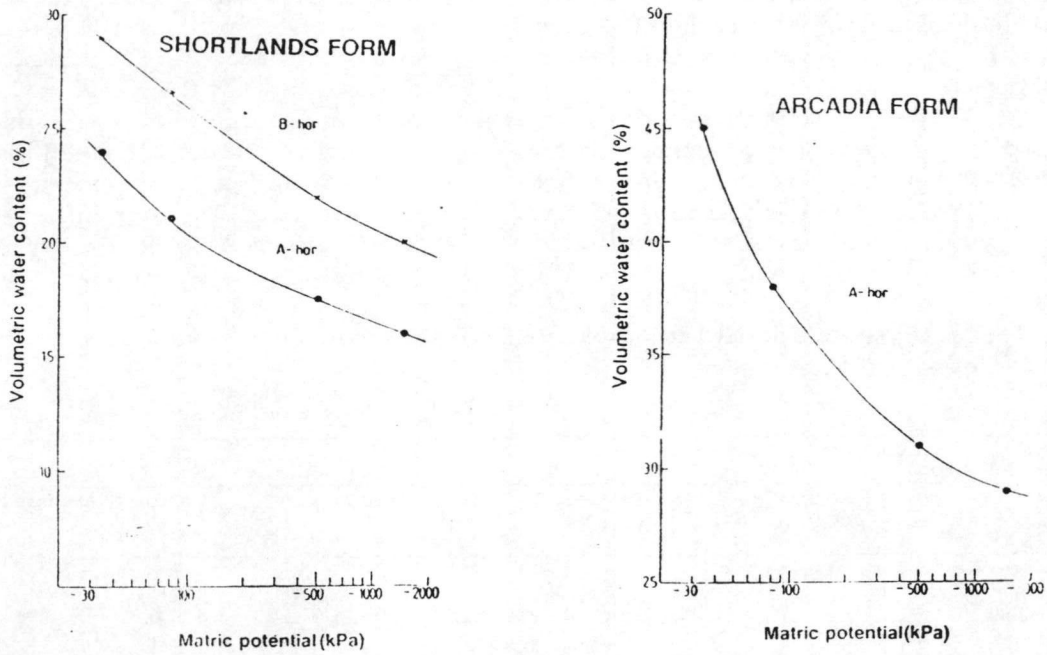


Figure 1 (b) Water retentivity curves of soils of the Shortlands and Arcadia forms.

Table 3 Infiltration rate of a typical pedocutanic soil in the Sundays River drainage region.

A-horizon	27.5 mm h^{-1}
B-horizon	4.2 mm h^{-1}
C-horizon	2.2 mm h^{-1}

0.9 m depths), indicates that waterlogging can develop in the subsoil with over-irrigation of the more sandy topsoil. The large variation in hydraulic soil properties could possibly be better understood if the description of degree, type and aggregate size of structure could be quantified with specific parameters. The air-water a quantitative measure of structural stability. According to Hutson (1983), it is difficult to define threshold AWR-values. Van Huyssteen (1989) however used the following stability classes for AWR: stable (1-20), variable stable (20-40), variable unstable (40-70) and unstable (>70) and stated that it roughly

Table 4 Variation of soil water content, tensiometer pressure potential and hydraulic conductivity of a typical pedocutanic soil in the Sundays River drainage region.

Depth z	Time	Θ_v	$\frac{\partial\Theta_v}{\partial t}$	$\frac{\partial\Theta_v}{\partial t}dz$	$\psi\phi$	ψh	$\frac{\partial\psi h}{\partial z}$	q	K(Θ)
m	Days		day^{-1}	(m/day)	(kPa)	(m)	(m/m)	(m/day)	(m/day)
0.30	0	0.270			0				
	2	0.242	$-1.1x10^{-2}$	$3.3x10^{-3}$	- 1	-0.4	1.0	$3.3x10^{-3}$	$3.3x10^{-3}$
	4	0.226	$-5.5x10^{-3}$	$1.7x10^{-3}$	- 1	-0.4	1.3	$1.7x10^{-3}$	$1.3x10^{-3}$
	5	0.221	$-3.0x10^{-3}$	$9.0x10^{-4}$	- 2	-0.5	2.0	$9.0x10^{-4}$	$4.5x10^{-4}$
	22	0.210	$-6.0x10^{-4}$	$1.8x10^{-4}$	- 4	-0.7	1.7	$1.8x10^{-4}$	$1.1x10^{-4}$
	44	0.195	$-4.0x10^{-4}$	$1.2x10^{-4}$	- 5	-0.8	2.3	$1.2x10^{-4}$	$5.2x10^{-5}$
	77	0.190	$-2.0x10^{-4}$	$6.0x10^{-5}$	- 5	-0.8	2.7	$6.0x10^{-5}$	$2.2x10^{-5}$
	126	0.188	$-1.7x10^{-4}$	$5.2x10^{-5}$	- 9	-1.2	1.7	$5.2x10^{-5}$	$3.1x10^{-5}$
0.60	0	0.354			0				
	2	0.310	$-1.3x10^{-2}$	$7.5x10^{-3}$	- 1	-0.7	1.0	$7.5x10^{-3}$	$7.5x10^{-3}$
	4	0.304	$-5.0x10^{-3}$	$3.0x10^{-3}$	- 2	-0.8	1.3	$3.0x10^{-3}$	$2.3x10^{-3}$
	5	0.292	$-3.5x10^{-3}$	$2.1x10^{-3}$	- 5	-1.1	2.0	$2.1x10^{-3}$	$1.1x10^{-3}$
	22	0.284	$-3.0x10^{-4}$	$1.8x10^{-4}$	- 6	-1.2	1.7	$1.8x10^{-4}$	$1.1x10^{-4}$
	44	0.276	$-2.3x10^{-4}$	$1.4x10^{-4}$	- 9	-1.5	2.3	$1.4x10^{-4}$	$6.1x10^{-5}$
	77	0.273	$-1.0x10^{-4}$	$6.0x10^{-5}$	-10	-1.6	2.7	$6.0x10^{-5}$	$2.2x10^{-5}$
	126	0.272	$-1.5x10^{-4}$	$9.0x10^{-5}$	-11	-1.7	1.7	$9.0x10^{-5}$	$5.3x10^{-5}$
0.90	0	0.334			0				
	2	0.309	$-8.3x10^{-3}$	$7.4x10^{-3}$	- 2	-1.1	1.3	$7.4x10^{-3}$	$5.7x10^{-3}$
	4	0.301	$-3.0x10^{-3}$	$2.7x10^{-3}$	- 6	-1.5	1.0	$2.7x10^{-3}$	$2.7x10^{-3}$
	5	0.298	$-2.0x10^{-3}$	$1.8x10^{-3}$	- 8	-1.7	2.0	$1.8x10^{-3}$	$9.0x10^{-4}$
	22	0.287	$-4.0x10^{-4}$	$3.6x10^{-4}$	-12	-2.1	3.0	$3.6x10^{-4}$	$1.2x10^{-4}$
	44	0.280	$-2.0x10^{-4}$	$1.8x10^{-4}$	-16	-2.5	3.3	$1.8x10^{-4}$	$5.5x10^{-5}$
	77	0.276	$-1.5x10^{-4}$	$1.4x10^{-4}$	-18	-2.7	3.7	$1.4x10^{-4}$	$3.8x10^{-5}$
	126	0.273	$-6.0x10^{-5}$	$5.4x10^{-5}$	-19	-2.8	3.7	$5.4x10^{-5}$	$1.5x10^{-5}$

Θ_v = Volumetric water content

t = Time

z = Depth

$\psi\phi$ = Tensiometer pressure potential

ψh = Hydraulic potential

K(Θ)= Hydraulic conductivity

q = Flux density

conformed with field observed stabilities. When these classes were used, there was a tendency to believe that orthic, neocutanic and red structured horizons represent mostly a stable structure, pedocutanic horizons intermediate and prismacutanic and vertic horizons unstable structure (Table 2).

The relationship between plasticity index and clay content, known as the activity of the clay, is frequently used by engineers as an indication of soil stability. If however the activity divisions of Head (1980) is used (<0.75 inactive, 0.75 - 1.25 normal and >1.25 active) all of these soils are inactive, with the exception of vertic soils (Table 2). Although there is an increase in activity with an increase in structural development, the differences are so small that it is not advisable to use this method as an irrigation norm, especially not where the soils have mainly the same clay mineral composition.

Chemical properties

The cation exchange capacity values (CEC) influence the use of soils for irrigation in various wasy: It gives an indication of the water retention of a soil (Banin & Amiel, 1969; Lambooy, 1983), of the capacity of soils to adsorb harmful salts (Fitzpatrick, 1983), of the dispersion potential of a soil (Gerber, 1986) and of the inherent fertility of soils (FAO, 1979). The increased CEC values with increased degree of structural development (neocutanic to pedocutanic to prismacutanic to vertic) can be used as an indication of increasing inherent fertility and water retention. It also increases the danger of accumulation of damaging salts. This is also evident from the increased exchangeable sodium percentage values and decrease in electrical resistance with increased degree of structural development (Table 5).

Morphological properties

Fitzpatrick (1983) uses the silt to clay ratio to indicate genetic processes such as clay migration. The decrease in silt to clay ratio (Table 6) coinciding with increasing structural development, indicate an older

Table 5 Summary statistics of cation exchange capacity (CEC), exchangeable sodium percentage (ESP) and electrical resistance of different soil forms.

Soil form	Oakleaf		Valsrivier		Sterkspruit		Shortlands		Arcadia
Diagnostic horizon	Orthic A	Neocutanic B	Othic A	Pedocutanic B	Orthic A	Prismacutanic B	Orthic A	Red structured B	Vertic A
Cation exchange capacity (cmol (+) kg)									
Median	9.0	10.0	11.0	14.3	8.0	15.7	14.9	16.0	37.5
Lower quartile	7.0	8.0	8.3	11.6	4.6	12.9	17.3	13.3	28.3
Upper quartile	12.0	13.0	15.3	17.1	12.3	19.0	11.4	25.0	46.5
Sample size	71	113	138	267	26	34	26	41	45
Exchangeable sodium percentage									
Median	4.5	7.0	5.6	12.7	4.2	15.5	2.0	2.2	4.9
Lower quartile	2.5	3.4	2.1	4.4	2.5	8.8	1.0	1.0	2.5
Upper quartile	10.0	13.2	9.9	22.9	6.5	24.1	3.7	5.2	10.4
Sample size	67	107	135	254	25	34	26	41	45
Electrical resistance (Ω)									
Median	1000	610	620	340	1750	335	690	700	290
Lower quartile	480	320	430	203	900	180	500	470	205
Upper quartile	1400	1200	1050	550	2300	670	1400	1300	400
Sample size	69	109	147	273	26	32	26	41	44

Table 6 Summary statistics of the silt to clay ratio of different soil forms.

Soil form	Oakleaf		Valsrivier		Sterkspruit		Shortlands		Arcadia
Diagnostic horizon	Orthic A	Neocutanic B	Othic A	Pedocutanic B	Orthic A	Prismacutanic B	Orthic A	Red structured B	Vertic A
Silt to clay ratio									
Median	1.18	0.93	0.64	0.54	0.40	0.26	0.31	0.31	0.28
Lower quartile	0.59	0.45	0.47	0.30	0.27	0.12	0.25	0.19	0.25
Upper quartile	1.59	1.35	1.11	0.83	0.28	0.44	0.46	0.47	0.41
Sample size	69	104	146	238	28	38	26	41	45

stage of pedogenesis. The soils of the Oakleaf form are clearly in an early stage of pedogenesis, whereas the soils of the Sterkspruit and Arcadia forms are in a more advanced stage of pedogenesis.

Soil colour is sometimes used as a norm to determine irrigability of pedocutanic soils. Red soil colour is frequently associated with soils rich in iron oxides and that are also well drained. This implies that these soils do not have a tendency for dispersion and weak structural stability. This is often the case with apedal soils but not so much with pedocutanic soils.

No meaningful differences have been found between exchangeable sodium percentage, sodium adsorption ratio, pH, electrical resistance, air-water permeability ratio, Fe-CBD and Al-CBD of red and non-red pedocutanic soils (Table 7). It is clear that there exists little justification to use soil colour as an irrigation norm for pedocutanic soils. It seems that the effect of dehydrated iron oxides on structure stability is overestimated and the influence of the kind and amount of salts together with the type of clay minerals are more important.

Conclusion

From a statistical analysis of soil samples representing the Oakleaf, Valsrivier, Sterkspruit, Arcadia and Shortlands soil forms it is proposed that the following characteristics can be of value to determine the effect of structure on the suitability of these soils for irrigation: differences between the diagnostic horizons in hydraulic conductivity, infiltration rate, water retentivity, air-water permeability ratio, exchangeable sodium percentage and cation exchange capacity.

There is a decrease in irrigability of soils with an increase in degree of structural development within the cutanic horizons. This is mainly the result of an increase in swelling and build up of harmful salts, which have a negative effect on structural stability. Deterioration of soil structure by any mechanism usually leads to greatly reduced internal drainage. This is directly responsible for waterlogging and salination, the main problems of irrigation schemes.

The abrupt increase in clay and sodium content of duplex soils appear to be major reasons for the drastic reduction in water movement with depth in these soils.

Table 7 Some chemical and physical characteristics of red and non-red pedocutanic horizons.

		Red	Non-red
Exchangeable sodium percentage	Median	15.8	10.1
	Lower quartile	5.3	3.7
	Upper quartile	25.0	17.9
	Sample size	134	120
Sodium adsorption ratio	Median	8.9	6.8
	Lower quartile	5.3	3.0
	Upper quartile	14.9	19.0
	Sample size	58	31
pH (water)	Median	8.2	8.3
	Lower quartile	7.5	7.4
	Upper quartile	8.7	8.7
	Sample size	137	116
Electrical resistance (Ω)	Median	285	380
	Lower quartile	180	230
	Upper quartile	550	580
	Sample size	142	131
Air-water permeability ratio	Median	86	84
	Lower quartile	27	25
	Upper quartile	999	999
	Sample size	63	23
Al-CBD	Median	0.08	0.13
	Lower quartile	0.07	0.09
	Upper quartile	0.10	0.30
	Sample size	60	23
Fe-CBD	Median	1.2	1.6
	Lower quartile	1.0	0.9
	Upper quartile	1.7	2.3
	Sample size	60	23

The more abrupt the change, the more effective it is as a barrier to water movement.

Theoretically any type of soil is irrigable if enough capital and management skills are available. These ideal conditions are however seldom, if ever, complied with. Therefore irrigation development on structured soils, which have a tendency to undergo swelling, dispersion and aggregate failure, cannot be justified in most circumstances.

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IRRIGATION RESEARCH AND DEVELOPMENT FOR HORTICULTURAL CROPS

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Abstract

In horticulture, the number of irrigation experiments increased sharply from 1967 to 1991 with most attention given to grapevines followed by citrus, potatoes and tomatoes. The introduction of drippers and micro-jets heralded a dramatic change with regard to both irrigation practices and research. Subsequent horticultural literature abounds with comparative studies between irrigation systems in respect of water saving and crop response. Experimental determination of crop factors to relate evapotranspiration with Class A pan evaporation, was a constant scientific endeavour over the past 25 years. However, tensiometers proved to be a better practical scheduling tool than the Class A pan. No attempts have yet been made to develop water balance models for horticultural crops in South Africa. Responses to water stress of the vegetative and reproductive parts of crops are discussed comprehensively. Fruit quality was normally more favoured by drier conditions than yield and above-ground vegetative growth, which benefited from shorter irrigation cycles and wetter soil water conditions. Considerable effort went into measuring the sensitive physiological processes underlying morphological, yield and quality responses. In conclusion this paper discusses future research needs in horticulture. Irrigation research should provide for the needs of both the developed and developing farming sectors of South Africa. Their research needs are distinctly different.

Profile of Irrigation Experiments

A global view of South African irrigation research on horticultural crops published between 1967 and 1991, revealed much progress and specific trends, but also areas of deficient knowledge. In 47 irrigation experiments perused, both the number of trials and the number of crops studied, increased significantly from five crops in eight trials to 11 crops in 17 trials in the first and last 5-year periods respectively (Table 1). Grapevines received the most attention followed by citrus, potatoes and tomatoes. Many of the crops in Table 1 received only scant attention and research on those will have to increase with regard to both depth and width of study, before significant contributions to irrigation practices will be possible. Especially noteworthy is the absence of a number of important horticultural crops such as plums, apricots, pears, mangoes, litchis, nuts, flowers and several vegetables.

Irrigation treatments in the different experiments consisted mostly of different levels of soil water extraction before the soil water content was recharged, either by determining the soil water content or the soil water potential (Table 2).

Before 1970, a soil water content of 60% total available water (TAW) was typically considered as wet. However, the introduction of drippers and micro-jets in the early seventies heralded a dramatic change in the nature of irrigation treatments applied in trials. In ensuing years, a soil water status approaching field capacity as well as daily or twice-daily irrigation cycles were frequently included in treatments.

A further practical approach employed in 23% of the studies, was to irrigate according to different evapotranspiration (E_T)/pan evaporation (E_o) ratios.

In many experiments E_T was determined experimentally and new E_T/E_o ratios (crop factors) determined afterwards.

Weighing lysimeters were used for irrigation studies in citrus, potatoes and tomatoes. At Stellenbosch, the response of grapevines and peaches to irrigation was studied in drainage lysimeters. In the only study of its kind, water stress was applied to grapevines through the use of polyethylene glycol in water culture.

Approximately 33% of the irrigation studies took plant phenological stages into account. This allowed assessment of plant response to water stress during different parts of the growing season.

It is often stated that the plant itself should be the best indicator of its own water needs. In addition to vegetative and reproductive responses of horticultural crops to water stress, measurement of plant physiological response was also included in later irrigation studies. However, none of these studies attempted to schedule irrigation with the aid of plant parameters.

Irrigation Systems

The development of drippers and micro-jets profoundly affected both the horticultural industry and irrigation research. The horticultural farmer was faced with the new question of which irrigation system to choose, while research was suddenly confronted with the possibilities of short irrigation cycles, partial soil wetting, continuous high soil water potentials and the unknown effects of these on crop response, especially quality.

Initially, horticultural literature only discussed the underlying principles and functioning of drip systems (Weber, 1970; Bredell, 1971) cautioning against too high expectations of this new irrigation system. This was followed by the description of the use of micro-jets (Bredell & Barnard, 1972) and of norms for the choice between systems (Piaget, 1973). The latter author emphasized that choice between systems depends basically on the soil, water and management.

Table 1 Crops on which irrigation studies were performed during various five-year periods between 1967 and 1991.

1967 - 1971	1972 - 1976	1977 - 1981	1982 - 1986	1987 - 1991
Onions (1)*	Onions (1)	Grapevines (3)	Green peas (1)	Bananas (1)
Grapevines (1)	Citrus (2)	Citrus (2)	Grapevines (3)	Citrus (2)
Grean Peas (1)	Macadamia(1)	Bananas (1)	Potatoes (1)	Cabbage (1)
Cabbage (1)	Peaches (1)	Peaches (1)	Avocado (1)	Peaches (1)
Tomatoes (1)	Potatoes (1)	Potatoes (2)	Apples (1)	Grapevines (3)
			Bananas (1)	Guavas (1)
			Carrots (1)	Granadilla (1)
			Tomatoes (1)	Onions (1)
				Tomatoes (3)
				Potatoes (2)
				Strawberry (1)
(5)	(6)	(9)	(10)	(17)

()* Number of studies

Table 2 Scheduling methods in irrigation experiments on horticultural crops.

Scheduling method	1967 - 1971	1972 - 1976	1977 - 1981	1982 - 1986	1987 - 1991
TAW level (%)	4	2	2	4	5
A pan		1	2	2	6
Soil Water Potential	1	1	1	2	4
Fixed Cycles		1	3		2
Weighing Lysimeter		1	1	1	4
Osmotic Potential				1	
TOTAL	5	6	9	10	21

TAW - Total available water

Since then a fair number of comparative studies regarding different irrigation systems in horticulture, have been undertaken.

Water saving with drippers, envisaged by many people, was indeed obtained in several experiments: a 47% water saving in bananas in the first year after planting with drip compared with under-canopy sprinklers (Robinson & Alberts, 1987); a 25 to 30% water saving in full-bearing grapevines (Van Zyl & Van Huyssteen, 1988) with drip compared with sprinklers, flood and micro-jets and approximately 50% less water with drippers under plastic compared with full-surface wetting by micro-jets on strawberries (Karsten, Beukes, Kotze & Laubscher, 1991). No crop losses were reported in any of those experiments. The possible water saving by partial irrigation was also illustrated in an experiment where border irrigation was compared with furrow irrigation (Van Zyl & Van Huyssteen, 1988). Grapevines irrigated in furrows produced the same pruning mass, grape yield and grape quality as with border irrigation, provided the irrigation cycle was reduced from 21 days to 14 days. However, the installation of drip irrigation is not a guarantee for saving water (Wessels, 1982; Van Zyl & Van Huyssteen, 1988).

A characteristic of both micro-jets and drip irrigation viz., partial wetting of the soil, has been inadequately investigated in South Africa. This aspect is of particular importance for tree crops with large canopies and extensive root systems. According to Bredell & Barnard (1977) it is regarded as desirable to irrigate at least 80% of the shallow feeder roots of citrus trees, i.e. approximately the area under the canopy of the tree. In practice this means more than one micro-jet per tree and a ring of drippers around each tree.

In a case study in an apple orchard with 6 m rows, the negative effect of attempts to irrigate the full surface with micro-jets was illustrated (Myburgh & Piaget, 1990). Much water was wasted and an

unacceptably long irrigation period was needed to wet the soil to the desired depth.

Despite theoretical benefits, subsoil irrigation with drippers yielded no practical advantage over drippers installed on the soil surface (Koegelenberg, 1989; Karsten, *et al.*, 1991). In fact the first-mentioned author found a decrease in tomato production with subsurface drippers, apparently due to the poor water distribution in the clayey soil. In the same study, 2 L/h and 4 L/h drippers gave similar tomato yields, proving that 2 L/h drippers can be used successfully, provided that climatic conditions are not too harsh.

In most comparisons of irrigation systems regarding plant response, results indicated that irrigation frequency is more important than irrigation system and, if managed properly, most irrigation systems can produce high yields of good quality (Bredell, Kuhne, Du Plessis & Van Zyl, 1978; Van Zyl & Van Huyssteen, 1988; Karsten *et al.*, 1991). However, there are notable exceptions. A macadamia orchard produced twice the yield with micro-jets compared with sprinklers (Bredell & Barnard, 1975). The irrigation cycles were, however, vastly different in this study. In bananas, drip proved superior to under-canopy sprinkler at comparable irrigation frequencies (Robinson & Alberts, 1987). The negative effect of sprinklers in this case, was due to cooling of the soil and pseudostems. Earlier it was shown that overhead sprinkler irrigation increased decay in bananas (Bredell *et al.*, 1978).

Fruit quality can also be affected by the irrigation system. In citrus, drip irrigation resulted in inferior fruit quality, i.e. low juice and total soluble solids, thickest rind and toughest rag (Bredell & Barnard, 1977). In contrast, drip irrigation increased sugar content in grapevines due to less shoot growth and a more favourable micro-climate around the clusters (Van Zyl, 1984b).

Water Requirements of Horticultural Crops

Successful irrigation planning and scheduling start with knowledge of the total annual water requirements of the crop. With only a few exceptions, these figures were determined in all irrigation experiments throughout the 1967-1991 period. The irrigation requirement is, however, amongst other factors, strongly dependent on soil water status (Van Rooyen, Weber & Levin, 1980b; Beukes & Weber, 1982; Fourie, 1989), irrigation system (Robinson & Alberts, 1987; Van Zyl & Van Huyssteen, 1988; Karsten *et al.*, 1991) and trellising system (Van Zyl & Van Huyssteen, 1980). The dependency of water requirement on soil water status was, for instance, dramatically demonstrated by Beukes & Weber (1982) who found an E_T of 1 099 mm at 85% TAW compared with only 272 mm at a 25% TAW level in an apple orchard.

Water production functions in horticulture were mostly developed for vegetables, namely potatoes (Burgers & Nel, 1984; Du Plessis, Steyn & Nortjé, 1989), carrots (Nortjé & Henrico, 1986) and tomatoes (Fischer & Nel, 1990). With regard to perennial tree crops, the only water production function was presented for table grapes (Van Rooyen, Weber & Levin, 1980b). In the coastal region grape yield increased with the first three irrigations compared with dryland grapevines. A levelling off in yield with more than three irrigations occurred (Van Zyl, 1981).

Although there is a clear need for more water-production functions in horticulture, two problems are counter-productive in this respect, viz.:

1) Response of tree crops in the field is often absent, very slow (long term) or confounded by sensitive phenological stages.
2) A large number of crops limits the number of experiments which can be conducted on one crop.

Irrigation Scheduling

Successful irrigation scheduling answers the question of how much and when to apply irrigation water. Scheduling methods acceptable to the farmer should be inexpensive, reliable and not time-consuming. Irrigation researchers in horticulture employed the gravimetric method, neutron water meters, lysimeters, the Class A-pan and tensiometers, to very accurately schedule water application in irrigation trials. However, with a view to practical implementation, research, development and technology transfer concentrated on the Class A-pan and tensiometers. The only meteorological formula considered for irrigation scheduling and planning purposes was that of Blaney and Criddle. Empirical plant coefficients (K) to be used in this formula were calculated for onions (Strydom, 1967) and for grapevines (Van Zyl & Weber, 1977), but to the authors' knowledge, were never applied in practice to estimate evapotranspiration.

Irrigation scheduling models such as BEWAB (Bennie, *et al*, 1988) have not been applied to horticultural crops in South Africa.

Pan evaporation and crop factors

To equate evapotranspiration with the product of free water evaporation from the standard Class A-pan, E_T/E_o ratios or crop factors have been determined on most irrigation trials involving horticultural crops. The experimental determination of crop factors was, in fact, a constant scientific endeavour over the past 25 years.

Crop factors, including values for horticultural crops, collated by Green (1985) represent a 100% wetting of the soil surface and a maximum crop yield as target. Less than maximum yields and micro-irrigation synonymous with short irrigation cycles, high soil water content and partial wetting of the soil volume, clearly require different crop factors. Such

factors are not available for most crops.

In horticulture, crop factors for different soil water regimes were determined for table grapes (Van Rooyen, Weber & Levin, 1980b; Fourie, 1989) and apples (Beukes & Weber, 1982). Crop factors for different irrigation systems, including drip, exist for grapevines (Van Zyl & Van Huyssteen, 1988) and strawberries (Karsten, *et al.*, 1991). However, a lack of differentiation in crop factors regarding canopy size, and cultural practices, seriously hampers better estimation of evapotranspiration. Notable studies where this was done, include different grapevine trellising systems (Van Zyl & Van Huyssteen, 1980) and mulched versus unmulched soil for potato growing (Burgers & Nel, 1984).

A special word on crop factors for citrus is in order. According to Streutker (1990), E_T/E_o ratios for citrus, contrary to the accepted convention, have been calculated for many years using E_T values from the wetted soil surface area and not from the total area. Citrus crop factors determined in South Africa are therefore 33% higher than normal crop factors would have been.

Historical climatic data together with crop factors and soil characteristics can be used to calculate E_T values and irrigations cycles (Green, 1985). Such estimates are invaluable for regional irrigation planning and design of farm irrigation systems. Van Zyl (1981) also used this technique as a first step for introducing irrigation scheduling to farmers. A second, more advanced, step in the scheduling hierarchy would be to use real time evaporation data. Many researchers emphasized that on-farm irrigation scheduling with the Class A-pan should always be checked by monitoring the soil water status (Green, 1985; Robinson & Alberts, 1986; Van Zyl & Fourie, 1988). In this respect tensiometers are ideal.

Tensiometers

Horticultural literature abounds with information on tensiometers. Over many years the instrument has been described, its benefits as a scheduling tool stressed, preparation, installation, maintenance and the application of results explained (Bredell, 1967; Piaget, 1975; Van Rooyen, 1977; Van Zyl, 1981; Kotze, 1985; Van Zyl, 1985). Of special interest are the recommendations regarding placement of tensiometers. Most researchers agree that soil type will determine the spatial distribution. Every major soil type in an orchard or vineyard should be represented by at least one set of tensiometers. A set normally consists of two tensiometers, one positioned in the zone with maximum roots and the other one deeper down at the lower boundary of the root zone. Positioning of tensiometers relative to drippers poses a problem. Van Zyl (1985) recommends placement of tensiometers 250 mm distant from a dripper, while Robinson & Alberts (1986) placed theirs 200 mm from the drip emitter.

The superiority of tensiometers in the irrigation scheduling of grapevines compared with historical Class A-pan data together with crop factors, was aptly illustrated by a water saving of 236 mm of water per season (Van Zyl & Booysen, 1983). Du Plessis (1988) demonstrated a water saving of 4 300 m^3 ha^{-1} per year in citrus compared with scheduling using the evaporation pan and crop factors. The tensiometer fared even better than irrigation scheduling done with the aid of a neighbouring weighing lysimeter and also yielded the highest net income. However, despite all the scientific evidence and continuous promotion of tensiometers over almost 25 years, the use of these instruments in practical irrigation scheduling of horticultural crops remains minimal and is restricted to a handful of farms. Reasons for this situation are debatable, but most probably revolve around the difficulty to fit in the laborious task of taking and interpreting tensiometer readings into a busy farming schedule. Furthermore, tensiometers often indicate the need for an irrigation at inconvenient times. From a managerial viewpoint it would therefore be much better to irrigate at fixed irrigation cycles and to only use tensiometers as a control measure to avoid over or under-irrigation.

Evapotranspiration of citrus

It was suggested that irrigation scheduling for citrus in different localities can be based solely on evapotranspiration data provided to farmers (Du Plessis, 1990). Evapotranspiration of citrus was determined accurately in a few areas for trees of different ages. The validity of this simplified approach is based on the assumption that the water use of citrus remains fairly constant between areas (Du Plessis, 1988).

Plant Response to Irrigation

Vegetative growth of aerial parts

It is generally accepted that cell growth (division and enlargement) is one of the most sensitive indicators of plant water stress. It can therefore be expected that plant morphology and vegetative growth will readily respond to irrigation and soil water status.

The above-ground vegetative response of vegetables to irrigation did not receive much attention in South African irrigation experiments, except in those crops of which the vegetative parts are harvested. In the case of cabbage (Nortjé & Henrico, 1988) yield and head mass were enhanced by increasing the TAW from 10% to 70%. Adverse effects of water stress prior to head formation could be rectified by regular irrigation in the phenological stage following head formation.

Much more attention was given to the effect of irrigation on the vegetative growth of perennial crops. In almost all experiments, some parameter of vegetative growth responded positively to higher TAW levels, and shorter irrigation cycles. Among these

responses are shoot elongation and pruning mass of grapevines (Van Zyl & Weber, 1977; Van Rooyen, Weber & Levin, 1980a), shoot growth rates and trunk circumferences both in apples (Lötter, Beukes & Weber, 1985) and grapevines (Van Zyl, 1984a), plant height and stem circumference in bananas (Robinson & Alberts, 1986), leaf area in grapevines (Van Rooyen, Weber & Levin, 1980b), bananas (Robinson & Alberts, 1986) and peaches (Tormann & Heyns, 1988) as well as number of nodes in granadilla (Staveley & Wolstenholme, 1990).

Since growth of most vegetative parts is periodic in nature, it is favoured by irrigation during specific parts of the growing season. Despite the sensitivity of vegetative response to water stress, the periodicity of vegetative growth rules out its use in irrigation scheduling. However, this same characteristic offers the possibility of controlling superfluous growth through regulated irrigation.

Root Growth

Reliable irrigation research depends on knowledge regarding root behaviour and especially the effective root zone of the crop to which irrigation water should be applied. Consequently root distribution was determined in many irrigation trials prior to commencement of treatments. In a few trials the opposite, namely the effect of irrigation on root systems, was also investigated.

Root growth of many perennial crops shows strong periodicity. In grapevines two main peaks of root growth were found in spring time and in the post-harvest period (Van Rooyen, Weber & Levin, 1980a; Van Zyl, 1988). Mean maximum extension rate of primary roots of bananas occurred in late summer while root growth ceased completely in winter (Robinson & Bower, 1988).

Irrigation regime influences both number of roots and root distribution. In lysimeters grapevine root growth was favoured by a high soil water potential (Van Rooyen, Weber & Levin, 1980a), but under field conditions moderate water stress (50% TAW) enhanced root growth compared with either wetter or drier treatments (Van Zyl, 1988). This finding lends weight to the belief that young grapevines can be forced by moderate water stress to produce more roots. Root studies on onions (Strydom, 1964), also indicated better root development at a 60% TAW treatment than at very low TAW levels.

Root development of horticultural crops in deeper soil layers is generally enhanced by low soil water levels. This is the finding with onions (Strydom, 1964), apples (Beukes, 1984a) and with sub-optimal drip irrigation on tomatoes (Fischer & Nel, 1990). In the study on apple trees, root development at a 85% TAW treatment was confined to the top 600 mm of soil while the root system at the 25% TAW treatment, although much sparser, extended down to 1 000 mm.

In localised irrigation, root distribution can be a function of the wetted soil volume. In a comparison between micro-jet and drip irrigation, grapevines under both systems produced approximately the same number of roots (Van Zyl, 1988). However, in contrast to an evenly lateral distribution of roots between rows with micro-jets, drip irrigation produced a high rooting density with roots mostly confined to the wetted soil volume. Experimental evidence suggested that root distribution will increasingly be shaped by the irrigation system, the lower the rainfall.

Crop yield

In approximately 80% of the 29 studies summarised in Table 3, either total yield or fruit size and in most cases both these parameters of reproductive response, increased with shorter irrigation cycles i.e. wetter soil conditions. The definitions of these wetter conditions come in many different forms e.g. soil water potential (SWP), % TAW, % of E_o and others. Best treatments in quite a number of experiments are only the best of a selection of treatments which do not cover a wide enough range of possibilities. This is demonstrated particularly well in irrigation experiments up to 1971. The optimum soil water status found was low, obviously because the water status levels tested did not include wet treatments.

Results should only be interpreted after close scrutiny of experimental conditions which can vary drastically in different experiments with the same crop. Contradictory results become less of a puzzle once this prerequisite is fulfilled. Totally different crop loads, localities, cultivars and the fact that one study was conducted in lysimeters and the other in a vineyard can, for instance, account for the different SWP optima found by Van Rooyen, Weber & Levin (1980a) and Fourie (1989) with table grapes. Similarly, with peaches Haulik (1979) found optimum yield response at 20% TAW while Tormann & Heyns (1988) found no response to irrigation. However, Haulik worked under summer rainfall conditions and in very high yielding orchards, while Tormann did her studies in lysimeters under winter rainfall conditions with exceptionally poor yielding trees of a different cultivar altogether.

Realisation of the above compounding experimental background information underlines the difficulty of extrapolating research results to practical farm conditions. Furthermore, irrigation studies on many horticultural crops are so few that implementation of results is risky although "contradictory results" in such cases do not pose a problem.

The no-response results as well as a fair number of experiments which showed no significant yield differences over a range of soil water conditions (Lötter, Beukes & Weber, 1985; Van Zyl, 1984a; Nortjé & Henrico, 1988; Tormann & Heyns, 1988; Fourie, 1989) prove that many horticultural crops do

have a safety buffer against inaccuracies in irrigation scheduling. Irrigation scheduling need not be correct to the nearest 1 mm to be of practical use. This safety buffer is partly located in the plant itself, but also in the size of the soil reservoir, as was aptly demonstrated with deficit drip irrigation on tomatoes (Fischer & Nel, 1990). Logically, irrigation scheduling will become more critical with decreasing soil depth and decreasing wetted soil volume and increasing sensitivity of the phenological stage to water stress.

Phenological stages during which water stress has particulary large detrimental and irreversible effects, are of special importance to horticulture.

Water stress during these critical phases may not only harm total yield, but also fruit size, a most important marketing factor. Furthermore, an exact knowledge of crop water requirements during critical phenological stages, opens the possibility of controlled deficit irrigation (CDI), as advocated by Chalmers, Mitchell & Jerie (1984). Critical phenological stages, which have been studied in South Africa regarding water requirements are the pod-filling stage in peas (Strydom & Van Eeden, 1969), the berry growth phase in grapes (Van Zyl & Weber, 1977), the tuber initiation stage in potatoes (Mould & Rutherfoord, 1980), the ripening stage in apples (Lötter, Beukes & Weber, 1985) and head formation in cabbage (Nortjé & Henrico, 1988).

An especially disappointing feature of all but one irrigation trial summarised in Table 3, is the absence of an economic analysis of the results. Obviously the technically and economically best recommendations may differ quite drastically. In this respect no progress has been made over the past 25 years.

Quality effects

Crop quality, a poorly defined property and subjectively judged in many cases, has become of paramount importance to the modern consumer. Horticultural produce which relies heavily on the export market and is often consumed fresh, is especially sensitive to quality. Consequently irrigation effects on quality received an increasing amount of research attention in the period 1967 -1991.

In early studies on vegetables, save for fruit size, quality aspects received no attention (Strydom, 1967; Strydom & Van Eeden, 1969; Van Eeden & Myburgh, 1971). This changed drastically during the 1980s. Water stress during the early growth stages of potatoes was more detrimental to chip quality and SG values than stress 6 weeks before harvest (Mould & Rutherfoord, 1980). However, a decrease in chip colour with increasing irrigation frequency in a second experiment (Du Plessis, Steyn & Nortjé, 1989), underlined the intricate relationship between water relations and quality aspects.

In cabbage water stress had little effect on quality, provided regular irrigations were applied during the head development stage (Nortjé & Henrico, 1988).

The shelf life of tomatoes was improved by long irrigation intervals, especially during ripening (Fischer & Nel, 1990). Water stress during the vegetative and early fruit growth stage increased the percentage of fruits displaying cracks, but those with cat face decreased.

In experiments with citrus and subtropical fruit, drip irrigation yielded poor quality valencias (Bredell & Barnard, 1977). Increased water contents resulted in an increase in total soluble solids (TSS) and total titratable acidity (TTA) in guavas, but vitamin C-content and thickness of fruit walls were not affected (Fourie, 1988). In a comprehensive study with avocado, Bower (1985) established a definite link between tree water relations, especially during the first 3 months of fruit growth, and the subsequent fruit quality. Polyphenol oxidase (PPO) activity, an indicator of the rate and intensity of fruit browning, was lowest in fruit from trees maintained at a SWP of -55 kPa. Wetter (SWP = -35 kPa) and drier treatments (SWP = -80 kPa) both yielded higher levels of PPO activity.

Much effort went into assessing irrigation effects on the quality of deciduous fruit, grapes and wine. Van Niekerk (1968) already recommended a decreasing soil water content during the ripening stage of deciduous fruit and grapevines to obtain good fruit quality. He acknowledged the fact that the effect of water stress on fruit quality was almost the reverse of its effect on yield.

Physiological disorders which can drastically affect fruit quality, are in deciduous fruit also linked to soil water relations. In apples sunburn decreased, but the incidence of bitter pit and water core increased at increased TAW levels (25% & 45% TAW as against 65% & 85% TAW) (Lötter, Beukes & Weber, 1985). Pitburn of Kakamas peaches was also significantly reduced by correctly timed irrigation before harvesting (Kotze & Bothma, 1989).

The early part of the growing season, before ripening commences, is the most important regarding quality of grapes. In general, increased irrigation frequencies and quantities increased TTA in grapes (Van Zyl & Weber, 1977; Van Rooyen, Weber & Levin, 1980a; Van Zyl, 1984b; Van Zyl & Van Huyssteen, 1988; Fourie, 1989). Malic acid was more sensitive to irrigation than tartaric acid (Van Zyl, 1984b).

Since the sugar content of grapes is the combined end result of dilution by the crop load, the sink-source relationship between foliage and fruit, the microclimate around the bunches and photosynthetic rate, the effect of irrigation on sugar content can vary considerably. Normally sugar content of grapes increased with water stress (Van Zyl, 1984b; Van Zyl & Van Huyssteen, 1988). However, in pots, in

Table 3 Summary of irrigation experiments in which the reproductive response of horticultural crops was determined.

CROP	REFERENCE	TREATMENTS		PLANT RESPONSE		BEST TREATMENT
		Growth stages involved (no)	Upper and lower boundaries of soil water status	Total yield	Fruit size	
Onions	Strydom, 1967	2	10%-65% TAW	✓	✓	40% TAW (SWP=-120 kPa)
Grapes	Claassen, 1969	-	Dryland - 75% TAW	ns	nd	
Tomatoes	Strydom & Van Eeden, 1969	-	10%-60% TAW	✓	nd	40%-50% TAW (SWP=-100 to -150 kPa
Cabbage	Strydom & Van Eeden, 1969	-	SWP=-100 to -400 kPa	ns	nd	
Green Peas	Strydom & Van Eeden, 1969	3	10%-40% TAW	✓	nd	40% TAW
Onions	Van Eeden & Myburg, 1971	2	10%-40% TAW	✓	✓	40% TAW
Grapes	Van Zyl & Weber, 1977	3	Dryland - 3 irrigations	✓	✓	2 irrigations
Citrus	Bredell & Barnard, 1977	-	3-14 day cycle (0.5-0.75 E_o)	ns	nd	
Bananas	Bredell *et al.*, 1978	-	1-7 day cycle (0.5-0.9 E_o)	✓	✓	drip; 90% E_o
Peaches	Haulik, 1979	-	0%-40% TAW	✓	✓	20% TAW
Potatoes	Mould & Rutherfoord, 1980	4	SWP=-30 to -70 kPa	✓	nd	SWP>-30 kPa
Grapes	Van Rooyen *et al.*, 1980a	2	10%-85% TAW	✓	✓	SWP=-5.3/-27.5 kPa
Potatoes	Cloete & Potgieter, 1981	-	0.5-1.25 E_o	✓	✓	E_o=4- mm
Green Peas	Olivier & Henrico, 1982	-	Gravimetric vs A-pan	ns	nd	
Grapes	Van Zyl, 1984a	5	25%-90% TAW	✓	✓	>50% TAW
Potatoes	Burgers & Nel, 1984	-	0.5-1.02 E_o	✓	✓	1.02 E_o
Avocado	Bower, 1985	-	SWP=-35 to -80 kPa	✓	nd	SWP>-55 kPa
Apples	Lötter *et al.*, 1985	4	25%-85% TAW	ns	✓	24/45/85/25% TAW in 4 stages respectively
Bananas	Robinson & Alberts, 1986	-	0.25 to 0.75 E_o	✓	✓	0.75 E_o
Carrots	Nortje & Henrico, 1986	-	20%-80% TAW	✓	ns	80% TAW
Cabbage	Nortje & Henrico, 1988	2	10%-70% TAW	✓	ns	30% TAW
Citrus	Du Plessis, 1988	-	Tensiometer vs Class A-pan	✓	✓	SWP=-50 kPa
Peaches	Tormann & Heyns, 1988	-	E_o=60 mm & 115 mm	ns	nd	
Guavas	Fourie, 1988	-	30%-80% TAW	ns	nd	
Granadilla	Staveley & Wolstenholme, 1990	-	SWP=-3 kPa to -50 kPa	✓	nd	SWP>-20 kPa
Grapes	Fourie, 1989	2	15% TAW-100% TAW	✓	✓	SWP=-30 to -35 kPa
Potatoes	Du Plessis, *et al.*, 1989	-	30%-80% TAW	✓	✓	80% TAW
Tomatoes	Fischer & Nel, 1990	4	Drip=2 daily & weekly	ns	✓	
Strawberries	Karsten, *et al.*, 1991	-	Drip=0.13-0.25 E_o; Microjets =0.25-0.50 E_o	✓	✓	Drip=0.25 E_o Microjets-0.50 E_o

lysimeters and in a field experiment with table grapes, the wettest treatments yielded the highest sugar content.

Grape colour (Fourie, 1989) and also the colour of red wine (Van Zyl, unpublished results) are favoured by water stress. Keeping quality of table grapes during cold storage was not affected by water regime (Van Rooyen, Weber & Levin, 1980a; Fourie, 1989). The first-mentioned authors concluded that a drier soil water regime before ripening and a wet regime during ripening will be beneficial to grapes. It is clear that differences regarding cultivars and localities and probably other factors too, influenced experimental results and the subsequent recommendations.

Plant physiology

Physiological processes underlying the many morphological responses to water stress, received no attention in irrigation trials prior to 1974. Since then it has become almost standard practice to determine at least leaf water potential (LWP) in irrigation experiments and often also transpiration rate, stomatal resistance or conductance and photosynthesis. This increased interest in plant physiology in relation to water stress not only reflects a different approach to irrigation research, but was also promoted through the availability of excellent measuring equipment. In general, plant physiological measurements were aimed at the following: a) collection of basic information such as the interrelationship between plant physiological factors, soil water status and climatological factors (Tormann, Van Schalkwyk & Steenkamp, 1974; Moreshet & Green, 1980; Meyer & Green, 1981;Robinson & Bower, 1987); b) explaining plant macro-response such as differences in evapotranspiration (Beukes, 1984b; Van Zyl, 1987; Fischer & Nel, 1990); c) determining the onset of plant water stress; d) asessing physiological parameters with a view to using them as indicators of plant water stress and for irrigation scheduling.

The latter two aspects are discussed in more detail. During progressive depletion of soil water, plant physiological measurements in bananas indicated the onset of water stress at around -20 to -25 kPa soil water potential (SWP) which corresponded to 80% TAW. Stomatal conductance seemed more sensitive to water stress than transpiration. In a similar approach Van Zyl (1987) found pre-dawn LWP the most sensitive indicator of water stress in grapevines. Onset of water stress occurred at a SWP of -64 kPa or 42% TAW. Pre-dawn LWP correlated highly with SWP ($r = 0.95$) and SWC ($r = -0.89$). In another experiment with table grapes (Fourie, 1989), plant physiological measurements showed the onset of water stress at -30 to -35 kPa SWP (41% TAW) irrespective of phenological stage.

Combinations of evaporative demand and SWP which created water stress in potatoes were determined with the aid of LWP, stomatal closure and also with visual stress symptoms (Rutherfoord & De Jager, 1975). A yield reduction of 3.2% and 3.7% per 13 hours stress during the bulking period were found when the measured plant parameters and the visual stress symptoms respectively, were used as stress indicators.

Canopy temperature as an indicator of plant water stress was evaluated on two horticultural crops viz., wine grapes (Van Zyl, 1986) and nectarines (Tormann, 1986). These researchers both used the temperature difference between reference well-watered canopies and dry canopies (sunlit in both cases) as stress indices. Mild water stress was indicated by temperature differences of 1.16-1.62°C and by 1.26°C in grapevines and nectarines respectively. A plant water stress index as described by Idso *et al.*, (1981) and Jackson *et al.*, (1981) was also calculated for nectarines. Mild stress was indicated by a value of 0.40 and severe stress by 0.75 (Tormann, 1986).

Although LWP measurements were recorded routinely in many irrigation studies, water potential of fruit was measured only in the case of avocado (Bower, 1985) and grapes (Van Zyl, 1987). Water potential gradients found between grapevine leaves and clusters, led the latter author to hypothesize that such water potential differences may be linked to the increased water consumption of higher crop loads.

Alternative Uses of Irrigation Systems

Fertigation

The application of fertilisers to horticultural crops through irrigation systems has become almost standard practice on many farms. Several articles discussed the principles involved, available equipment and fertilisers suitable for fertigation (Greeff, 1975a & 1975b; Conradie & Van Zyl, 1989). However, suprisingly few articles based on actual experimental results were found. In a recent very comprehensive study on nectarines, Fuller (1990) showed that choice of N source, irrigation regime and pulse stage can be successfully used to manipulate the redistribution of applied N in the soil profile using micro-sprinklers. Nitrate ions moved to greater depths than ammonium and retarding the pulse stage increased this difference.

Much more fertigation research on different crops, soils and irrigation systems seems to be needed to investigate problems such as the localised acidifying effect of fertigation under drippers.

Herbigation

In South Africa very few scientific investigations on the application of herbicides through irrigation systems were reported. In the first trial of this kind Bredell, Barnard & Vincent (1975) successfully controlled weeds in a young citrus orchard by applying the pre-emergence herbicide, simazine, through a micro-jet system. The herbicide was applied via a modified

fertiliser tank and the irrigation system operated at 200 kPa.

In a comprehensive study on grapevines, five pre-emergence herbicides were applied through a micro-jet system (Fourie, 1988). Tests showed that a pressure of 200 kPa and 280° micro-jets installed upright 450 mm above the soil surface, could achieve a co-efficient of uniformity (CU) of 90%. Herbicides were injected by an electrically driven diaphragm pump. Weeds were controlled effectively with no phytotoxicity signs in the crop.

Effective weed control was also achieved in potatoes with cyanazine applications through a centre-pivot system (CU > 90%)(Olivier, 1985). No visual phytotoxicity signs were noticed in the crop.

Evaporative cooling

High temperature together with low relative humidity can cause poor growth and production in tomatoes (Nortjé, 1984), stress in ginger (Anderson, Du Plessis, Scholtz & Niemand, 1990) and sunburn in apples (Kotze, Carreira, Beukes & Redelinghuys, 1988).

In two separate experiments evaporative cooling with overhead sprinklers and micro-jets was applied automatically when air temperature rose above threshold values.

In ginger overhead irrigation drastically decreased soil and plant temperature and resulted in a yield increase of 26 t ha^{-1} a^{-1}. However, the cooled plot used a total of 46% more water than the uncooled plot. The economic viability of evaporative cooling of ginger remains to be answered. Threshold temperatures were also chosen arbitrarily and should be investigated further.

Evaporative cooling decreased sunburn on Granny Smith and Golden Delicious apples by 50%. However, calyx-end russeting in Golden Delicious and poor colour development of Starking due to evaporative cooling, made this technique unsuitable for the first cultivar and put it in the balance for the second cultivar. In the case of Granny Smith evaporative cooling increased gross income by R4 000 ha^{-1} a^{-1}, making it an economically feasible practice. Total water consumption rose by 50% on cooled plots compared to the control.

The Future

Great progress has been made in irrigation research and development in South Africa during the past 25 years. However, future irrigation work will have to take the dual nature of farming in South Africa i.e. a sophisticated commercial sector and a developing small-holder sector, into account.

The first-mentioned sector requires irrigation scheduling techniques to automatically control the irrigation system according to real water needs. In this regard, sensors that can continuously and reliably measure soil, plant or meteorological indicators of water stress, should be aimed for. Equipment to measure diurnal swelling and shrinkage of plant organs as a function of plant water status, is now being tested in South Africa. This approach, together with the heat pulse method of determining sap flow in plants, can bring horticulture much closer to the long-awaited plant-based method of irrigation scheduling. The heat pulse method should, however, receive more research attention in horticultural tree crops. It is now technically feasible to use either of these two techniques to control irrigation systems.

The developing farmer has totally different needs with regard to irrigation scheduling and systems than his commercial counterpart. Recipe irrigation scheduling will probably again be in demand while the Class A-pan or even home-made pans may get a new lease on life among these farmers. Visible signs of water stress in the different crops, if properly calibrated, can also be of much benefit to the developing farming sector.

Developing farmers will not be able to afford expensive pressurised irrigation systems. Consequently research should again look at cheaper, simpler irrigation systems such as furrows, small basins filled with mulching material around trees or even at low pressure piping with large outlets, i.e. so-called bubbler irrigation.

Considering the commercial sector again, more research should be done on the application of sub-surface drip irrigation in horticulture. Despite poor initial results, subsurface wetting may have advantages in specific situations e.g. on soils with a low infiltration rate.

A serious knowledge gap regarding water consumption of young non-bearing fruit trees and plants with different crop loads and canopies exists. Similarly, crop growth models for the prediction of water use and yield received scant attention in horticulture. Future research should concentrate on these neglected areas.

Regulated deficit irrigation in its many forms has a place in horticulture, but should be experimentally tested in order to supply quantitative recommendations. Especially the application or relieving of water stress during periods when either vegetative or reproductive growth respectively is favoured, can produce optimum foliage/fruit ratios with the concurrent saving of water. In another approach to deficit irrigation, plants can be encouraged to exploit greater soil depths for water by applying suboptimal quantities of irrigation water. This aspect should also be studied in more detail for more crops.

Irrigation represents a multi-disciplinary research field par excellence, a fact which should be acknowledged and exploited in future. This fact has special relevance for the economic evaluation of irrigation research results since technically superior irrigation options may financially be disastrous.

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IRRIGATION RESEARCH AND DEVELOPMENT FOR FIELD CROPS: 25 YEARS OF PROGRESS

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Abstract

After standing accused, 25 years ago, of being an inefficient user of southern Africa's scarce resources, irrigated agriculture has risen to the challenge and attempted to improve efficiency considerably. This paper reviews aspects of irrigation research and development likely to have contributed to a trend towards greater efficiency in the irrigation of field crops. The direct measurement of potential water use of crops has been greatly facilitated by weighing lysimeter installations and the steady improvement of the neutron probe technique for soil water content measurement. Crop coefficients, used extensively for estimating potential crop water use from weather data, have been investigated and made more widely applicable. Exhaustive research has been done on the use of a wide range of plant variables as indicators of the onset and degree of crop water stress. Relationships which link both the onset of water stress and the degree of availability of soil water for crops to water and root density distributions in the soil profile and to potential water use (atmospheric evaporative demand) have been developed. Field experiments have provided valuable information on crop yields in relation to water use for a variety of conditions, including different levels of water stress. The development and use of crop growth models is serving to integrate results of often fragmented research. Appropriate models are seen as the most likely channels whereby results of such varied research can be transferred and usefully applied by planners and managers of irrigation projects and also by irrigation practioners.

Introduction

In 1967, during a South African National Irrigation Symposium, Du Plessis (1967) reviewed the policy of the then Department of Agricultural Technical Services with respect to the use of water by the agricultural sector. He pointed out that irrigation was responsible for consuming approximately 80% of South Africa's water resources and that the important urban, mining, industrial and power-generating sectors were, justifiably, beginning to demand increasing shares of the limited national water supply. With irrigation developing a reputation of being an inefficient user and possibly even a waster of water, further irrigation development would become increasingly difficult to justify unless much higher levels of irrigation efficiency could be achieved.

Du Plessis (1967) also severely criticised South African irrigation research. He considered investigations into water requirements of crops "so empirical that responsible organisations hesitate to accept the results as a firm basis for determining, with any certainty, crop water requirements under specific conditions and for calculating minimal and optimal water supply at different growth stages". Du Plessis urged investigators to adopt a more fundamental approach in which crop, soil, water and atmosphere could be addressed as interrelated components of a single system.

To what extent irrigation research and practice have succeeded, over the past 25 years, in responding to the challenge to become more effective is not easy to assess. Table 1 does, however, suggest that efficiency, in terms of land irrigated per unit volume of water, increased by approximately 18% between 1965 and 1990. With yields of irrigated crops also showing an upward trend, this increase would translate into an even larger percentage increase were efficiency expressed in terms of kg of product per m^3 of water. This considerable improvement undoubtedly derives from, *inter alia*, better cultivars and plant nutritional practices, in addition to irrigation-related factors.

Table 1 The estimated change in the area irrigated and irrigation water consumed from 1965 to 1990 in the Republic of South Africa.

	1965	1990	CHANGE
			%
Area under irrigation (10^6 ha)	[1]0.83	[2]1.29	+55
Annual water consumption (10^6 m^3)	[1]7 350	[3]9 690	+32
Area irrigated per unit of water (ha/10^3 m^3)	0.113	0.133	+18

Sources: [1] Du Plessis (1967)
[2] Unpublished irrigation land use analysis, Dept of Agricultural Development, 1990
[3] Dept of Water Affairs (1986)

The aim of this paper is to present an overview of some significant irrigation research activities in southern Africa which have contributed to improving effectivity of irrigation of field crops. Included are the estimation of potential water requirements of crops, recognition of the onset of crop water stress and establishment of relationships between crop yield and water stress.

Potential water requirements of crops

Despite the criticism by Du Plessis (1967) there were,

in 1967, already several researchers in southern Africa who, on the basis of the principle that potential water requirements of crops are determined by climate (Penman, 1948), had geared their research to establishing potential water use as a function of climate. Examples for cotton cited by De Wet (1967) were the work of Metelerkamp & Cacket in Zimbabwe (then Rhodesia) and Lea in Swaziland. In Natal, Thompson and colleagues had started similar research in support of the sugar industry (Thompson, 1967 a,b). Furthermore, intensive measurements of water use of vegetable crops with a view to deriving meteorologically-based estimates of water requirements of vegetables were reported by Strydom & Van Eeden (1967).

Measurement of potential crop water use

In obtaining measurements of potential crop water use via the soil water balance approach, early researchers were forced to rely heavily on gravimetric determination of soil water content involving laborious sampling programmes (Strydom & Van Eeden, 1967). Other techniques of measuring soil water status such as the use of gypsum blocks and tensiometers had also been attempted but their limited ranges and lack of any real superiority over the gravimetric technique in overcoming spatial sampling problems gained them little favour. By 1967 the neutron probe was only commencing to gain ground as an alternative means of routinely measuring soil water content (Thompson, 1967 a; De Bruyn, 1967; Bezuidenhout, 1967). Subsequently, regular improvements in portability, performance, calibration techniques and access tube installation methods have led to the neutron probe becoming a powerful irrigation research and management tool. Lysimetry in irrigation research in South Africa was pioneered by researchers at the Sugar Association Research Station, Mount Edgecombe (Thompson, 1986). Although drainage and hydraulic weighing lysimeters were initially used, these rapidly made way for mechanically, and later electronically, weighed lysimeters. Weighing lysimeters enable precise values of soil and crop evaporation to be obtained by solving the soil water balance equation for intervals as short as one day or even one hour. Besides the weighing lysimeters sited at Pongola for sugar research (Thompson, 1986), weighing lysimeter installations (some temporary, but most permanent) for field crop research were established on the Makatini flats (Hellman, 1976), Pietermaritzburg (Mottram & De Jager, 1974), Cedara (Mottram, 1985), Roodeplaat (Hutson, Green & Meyer, 1980), Bloemfontein (De Jager, Van Zyl, Kelbe & Singels, 1987) and Rietrivier (JJ Human, Univ. of the OFS, Bloemfontein. Personal communication, 1985).

The use of weighing lysimeters to measure potential crop water use has not, however, proved to be trouble-free. In a research environment there may, in the vicinity of the lysimeters, be intentionally stressed plots which result in height and leaf area index (LAI) discontinuities and induce a net horizontal exchange (advection) of energy. Meyer, Oosterhuis, Berliner, Green & Van der Merwe (1987) reported that, relative to potential evaporation, lysimetrically measured potential water use of wheat differed by 15-20% between two years, mainly as a result of differences in the soil water regimes of the surrounding plots. Even when lysimeter surrounds are irrigated to ensure crop water use at potential rates, suspicion has existed that lysimeter measurements may overestimate crop water use. Crop overhang (projected surface area of canopy marginally larger than lysimeter area) may sometimes be responsible (Pruitt & Lourence, 1985) but unavoidable differences in thermal and water regimes of lysimeter and field soils (Meyer *et al.*, 1987) have also been implicated. Thompson (1986) confirmed that potential water use of sugarcane measured with small (4 m^2) weighing lysimeters was consistently larger than that measured with a large (405 m^2) drainage lysimeter, even though the mean difference over several months was only 5%.

Micrometeorological methods of measuring potential (and actual) crop water use have not yet come into their own in South Africa, despite good results obtained by De Jager *et al.* (1987). With commercial Bowen ratio and eddy correlation systems becoming freely available and receiving attention from researchers at the Universities of the Orange Free State (W.H. van Zyl & J.M. de Jager, unpublished report to the WRC. Bloemfontein, 1991) and Natal (M.J. Savage, unpublished report to the WRC. Pietermaritzburg, 1991), a limited increase in the use of such equipment may be expected to take place.

Estimation of potential crop water use

Relationships found between field measurements of potential crop water use and various climatic variables and indices have enabled climate to be used as a predictor of crop water use, thereby extending the applicability of field measurements. The favoured climate index has consistently been some measure or estimate of evaporation. The most common of these has been Class A pan evaporation, although the Blaney-Criddle (Du Pisani, 1970) and, more recently, Linacre (Dent, Schulze & Angus, 1988) estimates of evaporation have also been advocated in the absence of data needed for the application of the more fundamental Penman approach. Locally a simple ratio, known as the crop factor or crop coefficient, has defined the working relationship between potential crop water use and pan evaporation.

Class A pan crop coefficients have, to date, fulfilled a pivotal role in the estimation of irrigation requirements of crops in South Africa. Directly or indirectly, they have formed the basis of three manuals

published for this purpose since 1970. Of these, two (Department of Agricultural Technical Services and Department of Water Affairs, 1973; Department of Agriculture and Water Supply, 1985) made direct use of available Class A pan data while the third (Dent *et al.*, 1988) used the Linacre formula to obtain a surrogate Class A pan data set representative of 712 homogeneous climate regions in South Africa.

The wide-spread use and simplicity of the Class A pan crop coefficient approach has tended to perpetuate its use with expansion of irrigation research and development into new regions and additional crops. In the process, inconsistencies have been revealed, resulting in calls for "more reliable" crop coefficients. Variability in empirically determined crop coefficients has derived either from inaccurate measurements or estimates of pan evaporation, variations in irrigation frequency or from climatic dependency. The latter has commonly, though erroneously, been assumed to be non-existent. Because of the sensitivity of Class A pan evaporation values to exposure (Bosman, 1990) the difficulties in obtaining truly representative evaporation measurements are becoming increasingly apparent. This should favour the advent of sound, less exposure-sensitive evaporation estimates, preferably based on the Penman-Monteith approach. As far as dependency of crop coefficients on irrigation frequency or climatic variation is concerned, a distinction needs to be drawn between early growth stages when crop canopy development is incomplete (LAI < 2.7) and later complete (full) canopy stages (Figure 1).

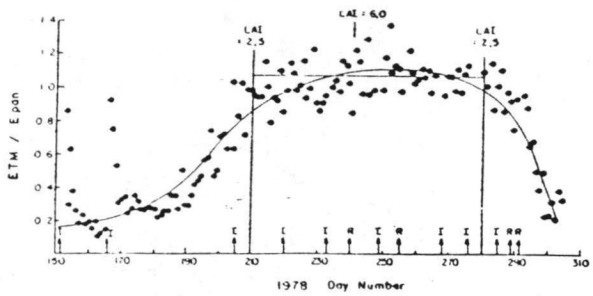


Figure 1 The ratio of lysimetrically measured potential water use of a wheat crop (ETM) to Class A pan evaporation (Epan), illustrating the possible variability in the crop coefficient during the season at different values of leaf area index (LAI). The timing of irrigation (I) and rainfall (R) events is indicated by the arrows. (After Meyer, Walker & Green, 1979).

During the incomplete canopy phase, crop coefficients will be sensitive to both the degree of vegetative cover and that proportion of the soil surface layer which is unshaded and thus predisposed to evaporative drying. During this phase crop coefficients are therefore dependent on LAI and the water content of the surface layer of the soil. The leaf growth or LAI submodel of the PUTU 9.86 wheat crop growth model (De Jager *et al.*, 1987) has expressed the relationship between leaf growth and temperature conditions based on data obtained in the semi-arid irrigation areas of South Africa. A refined leaf growth submodel having wider applicability (also to dryland growing conditions) has been incorporated in an updated (PUTU 989) version (Singels & De Jager, 1991b).

Relationships describing the nature of the dependence of crop coefficients on LAI and soil surface wetting events have been developed by De Jager *et al.* (1987) and further elucidated by Van Zyl, De Jager & Maree (1989). Implications, for practical irrigation scheduling, of the effects of LAI and soil surface wetting events on crop coefficients have been discussed by Burgers & Nel (1984).

Once full canopy has been achieved, relatively little of the previous sensitivity of crop coefficients to LAI and soil surface layer wetting remains. On the other hand, climatic dependence could become the main contributor to variability of crop coefficients if the energy balance of the transpiring crop and that of the standard evaporating surface respond differently to a range of prevailing climatic conditions. De Jager & Van Zyl (1989) and Van Zyl *et al.* (1989) have demonstrated theoretically and experimentally that, based on energy balance considerations, there would be considerable advantage in replacing the Class A evaporation pan with a short, freely transpiring gr surface as the standard for reference evaporation. The use of a freely transpiring vegetative surface(either lucerne or grass) is already common practice in the USA and elsewhere (Wright, 1985). Furthermore, since evaporation from a grass surface can be reliably estimated using the Penman-Monteith equation (Van Zyl & De Jager, 1987), direct measurement with, for example, a lysimeter is unnecessary.

The onset of crop water stress

As crop water stress sets in, the atmosphere relinquishes its control over the rate of water use. Water use is then increasingly controlled by the soil water in the root zone and the rooting distribution. This, together with the concomitant or crop yield reductions resulting from water stress, has caused researchers in South Africa to concentrate a considerable amount of attention upon the onset of water stress and relating it to soil and climatic factors.

Identifying and predicting the onset of crop water stress has, for example, been addressed in the case of container-grown maize, potatoes, groundnuts, wheat and cotton (De Jager & Mallett, 1972, Rutherfoord & De Jager, 1975; Human & De Bruyn, 1988), lysimeter-grown wheat, soybeans and maize (Meyer & Green, 1980a; Meyer & Green, 1980b; Mottram, 1985; Meyer *et al.*, 1987) and field grown maize, wheat, soybeans and cotton (Oosterhuis, 1982; Oosterhuis, Eastham & Walker, 1983; Walker, Oosterhuis &

Eastham, 1983; Eastham, Oosterhuis & Walker, 1984; Oosterhuis, 1984; Berliner, Oosterhuis & Green, 1984; Boedt & Laker, 1985; Mottram, 1985; Meyer *et al.*, 1987; Laker, Boedt & Hensley, 1987; Ceulemans, Impens, Laker, Vanassche & Mottram, 1988; Ceulemans, Laker & Vanassche, 1988; Vanassche & Laker, 1989).

In the above investigations, many measurable physiological variables have been tested with regard to their suitability as early stress indicators. Tested variables have included water potentials of non-transpiring leaves (uncovered leaves, predawn; covered leaves, midday) and fully transpiring leaves, components of leaf water potential (pressure and osmotic potentials), leaf diffusive conductance, photosynthesis, leaf expansion rate, canopy temperatures (using IR thermometry) and, in the case of soybeans, leaf angle. Daily changes, with soil drying, of the value of each indicator were typically followed and a clear change in the trend over time was taken to indicate the onset of water stress. In attempting to generalise the results of these investigations, it would appear that most indicators exhibit near-simultaneous responses to the onset of water stress. Such responses are easy to interpret if the onset of water stress is sudden and decisive, and more difficult to interpret if the onset is gradual or erratic. Also, while some indicators display greater sensitivity than others, the potential advantage of greater sensitivity can be offset by a greater variability between successive observations and therefore less certainty about when stress sets in.

Not surprisingly, there have been conflicting findings regarding the soil water status at which the onset of crop water stress becomes detectable. In South African literature, following the work of Hensley & De Jager (1982), this value of soil water content has also become widely recognised as the lower limit of Profile Available Water Capacity (PAWC), as opposed to the lower limit of Plant Available Water Capacity (PAW) which is synonymous with permanent wilting or death of the crop (Ratliff, Ritchie & Cassel, 1983). Both PAWC and PAW share the same upper limit, viz the water content reached in an initially saturated soil profile after two to three days of free drainage.

For convenience, the various findings relating to the onset of crop water stress and soil water status can be placed in two categories.

Findings in the first category suggest that the soil water deficit which corresponds to the onset of crop water stress (and therefore also PAWC) is a conservative quantity, knowledge of which may be usefully applied in irrigation management. Typical expressions of this are findings that 50-70% of PAW in the root zone can be depleted before water stress is observed (e.g. Meyer *et al.*, 1987) and that PAWC is reproducible for a given soil-crop combination, relatively climate-insensitive, and typically in the range of between 100 and 160 mm for a wide range of crop-soil combinations (e.g. Hensley & de Jager, 1982). Such results have generally been associated with lysimeter studies, field studies with deep soils fully irrigated to field capacity prior to crop establishment, and atmospheric evaporative conditions which have not been excessively severe.

The second category comprises findings that soil drying is accompanied by an increasing intensity of crop water stress, with no clearly defined point of onset which relates to a reproducible value of soil water content or PAWC. Examples are to be found in both container experiments (De Jager & Mallett, 1972) and field experiments (e.g. Boedt & Laker, 1985; Berliner and Oosterhuis, 1987). Such findings appear to be typical for conditions in which the growth of the root system is restricted, or where irrigation management aims to keep the lower part of the root zone dry or where severe atmospheric evaporative conditions tend to occur (Meyer *et al.*, 1987).

A quantitative method of reconciling various findings and of predicting the onset of crop water stress, taking into account certain soil, crop, climate and water management factors, has been developed by Botha, Bennie & Burger (1983) and Bennie, Coetzee, Van Antwerpen, Van Rensburg & Burger (1988) on the basis of an approach first suggested by Gardner (1960). The method involves computing the potential soil water supply rate (PWS) to the root system and comparing this with the climatically regulated potential crop water use rate, also termed the atmospheric evaporative demand (AED) by De Jager & Van Zyl (1989). In the unstressed situation, with PWS typically very much greater than AED, actual water use equals AED. At the onset of water stress, PWS = AED. As water stress intensifies, PWS becomes increasingly less than AED and actual water use is then restricted to PWS. The value of PWS is given by the following equation :

$$PWS = \Sigma F_i \ln(\theta_i/\theta_{ia})(\pi L_i)^{1/2}(\psi_i - \psi)z_i$$

where F_i is the soil-water conductance coefficient for layer i,

- θ_i and θ_{ia} are the actual and lower-limit volumetric water contents, respectively, of soil layer i,
- L_i is the root length density in soil layer i,
- ψ_i and ψ are the soil water potential of layer i and the crop leaf water potential, respectively, and
- z_i is the thickness of layer i.

This approach clearly demonstrates how the interplay between climate, the root length density distribution and soil water distribution through the profile determine the onset of crop water stress and the value

of PAWC. The practical use of the approach has been facilitated by the extensive data sets acquired for soil physical and hydraulic properties and for rooting characteristics in various irrigated soils (Bennie *et al.*, 1988).

Crop yield in relation to water stress

Water stress can obviously reduce crop yield through its effects on various yield components and may also have either a deleterious or beneficial effect on the quality of the product.

Irrigation projects (schemes) have traditionally been designed to provide a water-stress free soil environment for crops. However, as stated by Thompson (1978), economic realities could often dictate the need to consider some form of deficit irrigation as a more favourable option. This implies that water stress would need to be permitted, but at the same time carefully controlled and properly managed. Ideally, to make this possible, the effects of water stress on yield, yield components and quality must be known and predictable.

Several research projects have attempted to establish effects of water stress at various times during the growing season on the yield and quality of the product. In the main, the interpretation of results has more often than not been qualitative (Thompson, 1978), because of the complex nature of the cumulative effect of stress of varying degrees during a succession of growth stages and the uncertainty about stress hardening effects due to osmotic adjustment resulting from previous stress history (Oosterhuis *et al.*, 1983). Before 1975, the only quantitative reports on the effects of water stress on yield were for maize (De Jager, & Mallett 1972; Mallett, 1972) and potatoes (Rutherfoord & De Jager, 1975). For maize, stress in the period before silking was found, on average, to reduce grain yield by 3,2% per stress day and after silking by 4,2% per stress day. During the flowering period this factor increased to as much as 7% per stress day. For potatoes, stress caused a mean yield reduction of 3,2% per 13 hours of stress during the growing season. Since 1975, crop yield-water stress relationships have further been analysed using stress days (De Bruyn & De Jager, 1978, Spamer, Human & De Bruyn, 1980) and leaf water potential (Human & De Bruyn, 1988; De Kock, De Bruyn & Human, 1990; Nel & Berliner, 1990; Nel & Dijkhuis, 1991) as indices of the severity of crop water stress.

Because regular measurements of leaf water potential are rarely obtained routinely, Human & De Bruyn (1988) and Nel & Berliner (1990) developed graphic and regression models for estimating leaf water potential from values of soil water status and evaporation rate. Spamer *et al.* (1980) further used multiple correlation and regression analyses to reveal stages in the development of the wheat crop which were adversely affected by stress days, while Human & De Bruyn (1988) and De Kock *et al.* (1990) similarly identified stages of cotton growth during which low leaf water potentials were most prone to affect yield adversely. The approach used by Nel & Dijkhuis (1991) was to establish the relationship between wheat grain yield and the minimum leaf water potential adopted as the criterion for scheduling successive irrigations. While it is encouraging to note that all these approaches gave rise to strong statistical relationships, the effective use of such relationships in regression models will depend entirely on their seasonal stability and validity, as yet to be established, over a range of climatically different localities.

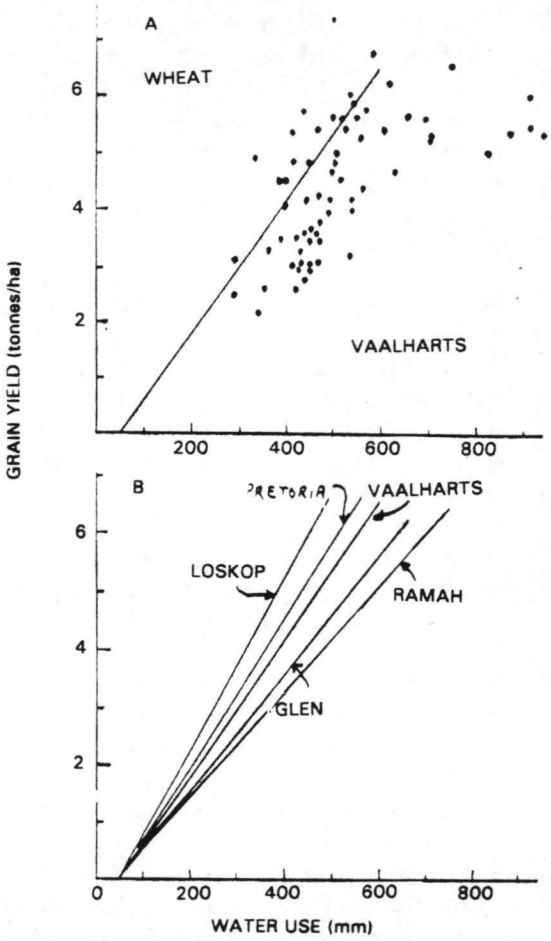


Figure 2 Crop water production functions for wheat. A. Scatter diagram comprising data for a single location, Vaalharts, obtained from numerous sources. The visually fitted straight line is intended to depict a realistic upper boundary curve. B. Upper boundary curves showing the differences in slope between different locations. (After Streutker, 1983a).

One of the simplest and most useful representations of the effect of water stress on crop yield is a simple graphical plot of yield versus actual water use, commonly termed the crop water production function.

Streutker (1983a, 1983b) compiled water production functions for each of a number of localities and crops, using historical crop yield and water use data from every available published and unpublished source (an example for wheat is shown in Figure 2). Subsequently, several other authors have added to the information for wheat (e.g. Figure 3), building up a clear though empirical picture of the expected maximum yield corresponding to any (sub-potential) level of crop water use at a given locality. In Figure 2a, for example, the line represents the upper threshold of crop yield obtainable for a given level of water use at Vaalharts. Figure 2b shows that threshold lines obtained at different localities have different slopes, probably reflecting differences in mean vapour pressure deficit between localities (Doorenbos & Kassam, 1979; Monteith, 1989). The diagnostic value of the water production function is obvious. For example, a data point located below and to the right of a threshold line is indicative of either water use inefficiency, deficient management or some crop disease or disorder. This situation could arise if water use data were inflated by excessive soil evaporation, undetected runoff or deep percolation losses, or if yield reductions due to below potential water use were aggravated by factors such as disease, nutritional imbalance or inappropriately timed irrigation.

Wherever particular care has been taken to minimise inefficiencies and disorders, a much tighter relationship than that shown in Figure 2 is obtained. The data shown in Figure 3, which derive from approximately a decade of field research with wheat at Roodeplaat (Berliner, Nel & Van der Merwe, 1990), illustrate this despite the fact that no attempt was made to normalise the data points with respect to vapour pressure deficit variations or to remove the effect of soil evaporation.

Greater attention to the effects of saturation deficit and soil evaporation on data used to compile water production functions would further enhance their reliability and usefulness and therefore needs to be encouraged. Interestingly, while the relationship between straw yield and water use in Figure 3 is apparently linear over the entire range, grain yield tends to level off at values of water use approaching the climate determined potential water use for the specific crop. Analogous responses to increasing water use in sugarcane (linear for cane yield; curvilinear for sucrose yield) were reported by Thompson (1976). This implies that water use efficiency for both wheat grain and sucrose production declines relative to that for biomass production at higher levels of crop water use, an observation which probably merits further investigation.

Because of their simplicity, water production functions unfortunately convey no information on how the timing and severity of water stress sequences during the season will affect final yield.

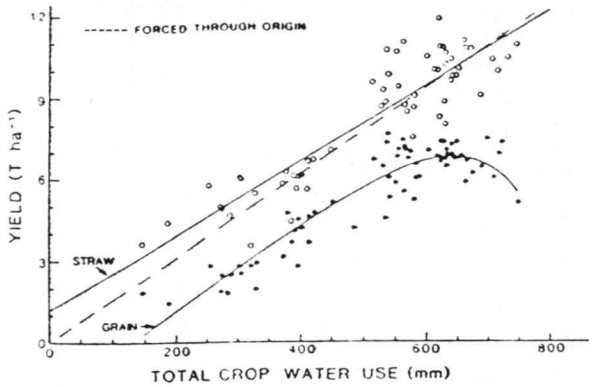


Figure 3 Crop water production function for wheat compiled from research results obtained over several years at the Roodeplaat Experiment Station. The open circles depict the linear relationship pertaining to straw yield and the solid circles the curvilinear relationship pertaining to grain yield. (After Berliner, Nel & Van der Merwe, 1990).

Irrigation planners are thus increasingly looking towards numerical crop growth models which operate on the basis of daily time steps, to provide this additional information. Model development for irrigation planning and management purposes has in South Africa achieved prominence, mainly during the past decade. The model PUTU 9.86 was developed for wheat under irrigation by De Jager *et al.* (1987) from the original PUTU maize model and a prototype model for irrigated wheat (PUTU 9; De Jager, Van Zyl, Bristow & Van Rooyen, 1982). PUTU 9.86 simulates the effect of soil drying between successive rainfall or irrigation events on water transfer in the soil-plant-atmosphere continuum, including crop water use and its soil evaporation component. This enables crop yield to be calculated on the assumption that actual yield (Y) is controlled both by the potential yield for water stress-free conditions (Y_m) and the relative water use deficits in successive growth stages, according to the following relationship of Doorenbos & Kassam (1979):

$$Y = Y_m [1 - \sum K_i(1 - E_i/E_{mi})],$$

where E_i and E_{mi} are values of actual and potential water use, respectively, and K_i is the weighting constant reflecting the crop's sensitivity to water stress in growth stage i. Other versions of PUTU estimate yield by using expressions relating water use deficits to physiological processes (such as photosynthesis and translocation) which affect grain production. Refinement of the PUTU models for wheat (PUTU 989; Singels & De Jager, 1991 a, b, c) is continuing and steps are being taken to adapt PUTU for other crops under irrigation.

Another major South African modelling initiative of

importance for irrigation concerns the ACRU agrohydrological modelling system (Schulze, 1989). ACRU contains routines for estimating yields of three irrigated crops (maize, wheat and sugarcane) and for maize allows a choice of yield estimation method. The most sophisticated of these options is based on the approach first proposed by Hanks (1974), in which actual yield (Y) is expressed as a fraction of the potential yield (Y_m) obtainable under conditions free of water stress, according to the equation :

$$Y/Y_m = (T_1/T_{m1})^{\alpha 1}(T_2/T_{m2})^{\alpha 2}(T_3/T_{m3})^{\alpha 3}$$

where T_i and T_{mi} are values of actual and potential plant evaporation (transpiration), respectively, and αi the weighting constant for each of the three growth stages, i. The growth stage boundaries can be determined either on the basis of heat unit accumulations or time (days) after planting. The partitioning of actual and potential water use into plant and soil components is necessary in this approach and is accomplished by the method proposed for the row crop model of Ritchie (1972).

Both PUTU and ACRU have been used in various irrigation planning and management tasks. Continued exposure of this nature is highly desirable and will undoubtedly lead to further refinement. While some experience has also been gained with prominent overseas models such as CERES and COTMOD, their usage in the irrigation context has up to now been minimal.

Research groups engaged primarily in modelling and those engaged in field research have in the past made their considerable progress in spite of a tendency to have been somewhat isolated from each other. There is now a realisation that further progress will require much closer interaction, commencing with the joint planning of research. The fruits of this approach are a better appraisal of sensitive areas still requiring investigation, a greater degree of critical evaluation of model performance and experimental results which have greater relevancy for the refinement of models.

Implications for irrigation practice

The gain in knowledge and understanding of the behaviour and role of water in the soil-crop-atmosphere continuum made in South Africa during the past 25 years has been unprecedented in this region. While there is some evidence that this progress has had a beneficial effect on the overall efficiency of irrigation, it is generally accepted that a long road still lies ahead before the knowledge gained is fully transformed into useful irrigation technology and is profitably applied in the planning and managing of the irrigation of field crops.

Much of the available information is still in a fragmented state, but with interaction between modelling and field research (especially on-farm field experimentation) gaining momentum, the integrating effect of models might very well reduce this fragmentation rather rapidly. Those models which are geared to the needs of irrigation planners and managers, while not sacrificing scientific soundness, are likely to be the most successful vehicles for converting research findings into technology which can be implemented. Models already discussed (PUTU, ACRU) are moving rapidly in this direction. In addition, the BEWAB model, at the heart of which is Bennie's procedure for computing water uptake from the soil profile (Bennie *et al.*, 1988), is an example of a model specifically designed for planning irrigation management strategies with specific crop yield objectives in mind.

As models also move in the direction of being able to accommodate goals, priorities and preferences (social and economic) of individual irrigators, they are very likely to find increasing application at farm level, either through the medium of user-friendly computer software or the services of specialist consultants. Channelled along this route, research results obtained over the past 25 years appear to be set to benefit on-farm irrigation management far more than did results channelled to irrigators in the form of ostensibly simple, do-it-yourself, irrigation scheduling schemes and procedures which were more often than not ignored by irrigators.

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RESEARCH ON CROP WATER STRESS AS A KEY TO INCREASED WATER USE EFFICIENCY

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Abstract

The most recent opinions of research workers on techniques for determining plant water stress and effect of stress on water use efficiency are reviewed. From this it becomes evident that although much information is available, no complete research programme is proposed that will lead to information on the amount of water required during the different growth stages of a specific crop which will result in the most efficient use of irrigation water. It is concluded that it should first of all be established what technique for determining plant water stress is most suitable for the specific crop. Thereafter it is necessary to define the exact duration of the water sensitive periods in the growth and development of the specific plant. The relative sensitivity of each period should be determined as well as the critical water stress level at which growth and yield are adversely affected. Water available for irrigation should be given preferentially during the most sensitive growth stages thus identified. Manipulation of amounts of water applied and the effects on growth and yield should then be investigated in order to increase water use efficiency.

Introduction

Limited water supplies are available to satisfy ever increasing demands for more food to be produced. It is therefore imperative that irrigation should be scheduled scientifically in order to increase yield per unit of water applied and at the same time to increase the quality of the product. A review of literature available that deals with the reaction of crops to different levels of water-stress during different growth phases will give a basis on which planning of irrigation scheduling can be done in such a way as to increase the production per unit of water applied and thereby increase the water use efficiency. From this study it should also become apparent where insufficient information is available and where priorities for future research should lie. Reginato (1990) identified three approaches to scientific irrigation scheduling as using the soil, the plant and the atmosphere. Each approach has its cadre of supporters, but it is important to look at the advantages and disadvantages of each, so that the user can decide which might best suit a speicific situation. In this process, it is desirable to investigate the complexity and ease of use of equipment utilised in each approach. Any technique for scheduling irrigation must have "early warning" capabilities, to alert the irrigator so that a decision can be made about when to irrigate for timely application of water.

Soil water status has been widely used to determine when irrigation must be applied (Campbell & Campbell, 1982). However, the need for irrigation depends on plant water status rather than that of the soil (Jones, 1984). Plant water status is not only dependent on soil water status but also on the evaporative demand of the atmosphere and plant characteristics such as root distribution and hydraulic conductance (Jones, Lakso & Syvertsen, 1985). An approach to scheduling that considers the crop water status should be advantageous since the crop responds to both the soil and the aerial environment, although this would be less clear in the presence of diseases or other plant injuries.

Crop demand for water depends on the evaporative conditions which vary from site to site. Attempts at estimating water demand are often based on meteorological measurements with account taken of soil and crop factors. Measurements are sometimes made of evaporation from an open water tank with a correction intended to make provision for differences in plant size and species. These methods generally estimate the water content of the soil and may be checked against measurements made with a tensiometer, neutron probe or the gravimetric technique. However, they do not take into account the differing abilities of plant roots to penetrate the soil an extract water nor do they predict the influence of temporary rapid increases in evaporative demand occurring during the course of each day (McBurney, 1988).

The ideal way of overcoming these limitations would be to monitor plant water stress directly by measuring plant water potential. At best this technique can only give spot measurements while plant water potential can change from minute to minute and measurements need to be continuous if a representative estimate of the crop water stress is to be obtained. McBurney (1988) pointed out that in any event it will never be possible to make measurements that cover more than a few of the possible combinations of crop, soil and evaporative conditions. Some means are needed for extending the results of a few experiments in order to make predictions over a wider range of conditions. One promising approach is to incorporate the information into mathematical models and use these for predictive purposes. Such models need to simulate, dynamically, the movement of water through the soil, plant and atmosphere so as to take account of the diurnal fluctuations in evaporative demand and temporal changes in soil water content and physiological properties. The challenge is to develop models to predict water stress within the crop for a range of soil, crop and evaporative conditions.

The aim of irrigation management is to control plant water status for the purpose of maximising or optimizing crop production while conserving water. Traditionally, irrigation is based on the consideration of soil water status and empirically determined crop water requirements based on weather related data. More emphasis should, however, be placed on the interaction of the plant with the atmosphere and consequent implications in terms of irrigation management.

Identifying plant water stress

Various methods have been proposed to identify plant water stress e.g. the use of physiological indicators, soil-plant-atmosphere models with appropriate measurements, and plant morphological indicators.

Evapotranspiration rate

Traditionally, plant water stress which significantly affects growth and yield was considered to occur when soil water is depleted to a certain level (eg. 50% of the plant available water in the soil). Since it is in most instances impractical to monitor soil water depletion on a daily basis, in order to anticipate when this critical level will be reached, resource was taken in calculating daily evapotranspiration (ET) from atmospheric and crop factors. Since these calculations at best depend on average atmospheric conditions prevailing during the specific growth stage of the crop, the crop canopy cover as well as the ability of the plant to regulate its evaporation rate according to the soil water uptake rate by stomata closure, they cannot be expected to give accurate results.

Hsiao (1990) discussed the interactions between the crop and the atmosphere in determining water use and plant water status and the implications for possible improvements of irrigation management. Reference or potential ET, (ET_o), is a measure of the capacity of the atmosphere to supply energy and assimilate water vapour. The crop coefficient (K_c), the ratio of crop ET to ET_o, accounts for the effects of crop characteristics and soil surface wetness on ET, and can be considered a description of the "wetness" and "roughness" of the field. Hsiao (1990) examined the dependence of ET and K_c on canopy cover and irrigation or rainfall frequency using a simulation model. He concluded that the control of transpiration by stomata may be overstated since this is usually observed in gas exchange chambers where the maintenance of constant leaf temperature eliminates energy supply as a limiting factor. Additionally, boundary layer conductance for crop canopies is smaller than that for individual leaves, lessening further the control of transpiration by epidermal (stomatal) conductance.

Evapotranspiration may be curbed under conditions of increased humidity as with crops cultivated under protection (Grange & Hand, 1987). This may lead to K_c values differing vastly from those determined in the open field.

Plant indicators

The soil-plant-atmosphere continuum is a concept which gives recognition to the fact that plant water status is not a unique function of soil water status, but is also dependent on transpiration rate and evaporative demand. This complicates the use of plant indicators for irrigation scheduling. The extent which the uptake rate of soil water is altered by transpiration rate and evaporative demand, should be considered.

The aim of the work by Sellés & Berger (1990) was to investigate which physiological indicators could be used as criteria for scheduling irrigation of peach trees. The indicators tested were pre-dawn leaf water potential, minimum daily stem and leaf water potential, daily average stomatal conductance and maximum daily growth and shrinkage of fruit and trunk. Special emphasis was placed on fruit and trunk measurements because they can be used for automatic regulation of irrigation in orchards, using drip, microsprinkler or any other pressurised system. The daily variation of trunk diameter (maximum daily growth and maximum daily shrinkage) and stem water potential were found to be the most responsive to water stress. The daily variation of fruit diameter was not as sensitive because the daily growth was affected too late in the season and maximum daily shrinkage is very dependent on fruit growth stage. Stomatal conductance was discarded since the stomata of the species tested were responsive to air humidity.

Oosterhuis, Le Maire & Le Maire (1987) investigated the relationship between pea leaf water potential and crop colour as water stress developed in the field. Pea leaflet water potential was measured by using a Scholander-type pressure chamber. The pressure chamber gave values similar to those of the screen-caged thermocouple psychrometer against which it was calibrated. The pressure chamber measured the decrease in water potential associated with the green-to-blue change in crop colour that occurs with the development of water stress. They concluded that crop colour change offers an easily identifiable indicator of the onset of water stress that could, with further testing, be used in crop water management.

It should, however, be stressed that any visual stress-indicator must be examined in association with leaf water potential values and crop growth and yield criteria to check whether these visual symptoms are manifested at the first onset of critical stress, or whether damage has already been done to the crop when observing them.

Stress indices using canopy temperature measurements

The use of canopy temperatures to detect water stress in plants is based upon the assumption that, as water

becomes limiting, transpiration is reduced and the plant temperature increases. Hand-held infrared thermometry, developed during the past decade, has extended the measurement of temperatures from individual leaves to entire plant canopies. Canopy temperatures are determined by the water status of the plants and by ambient meteorological conditions. The crop water stress index (CWSI) combines these factors and yields a measure of plant water stress.

Two approaches have been proposed, viz. an empirical approach by Idso, Jackson, Pinter, Reginato & Hatfield (1981), and a theoretical approach by Jackson, Idso, Reginato & Pinter (1981). Because it requires only three variables to be measured, the empirical approach has received much attention in the literature. It has, however, also received some criticism concerning its inability to account for canopy temperature changes due to radiation and windspeed. Bonanno & Mack (1983) used temperature differentials to schedule irrigations in snap beans. Midday canopy temperatures were measured with an infrared radiation thermometer, because the greatest differences between canopy and air temperatures occurred near solar noon. O'Toole, as cited by Oosterhuis (1983), found a poor agreement between actual and calculated crop foliage-to-air temperature differential (T_c-T_a) when net radiation, wind speed and vapour pressure differences occurred. Wind speed was found to be the primary factor causing erroneous estimation of the upper limit of T_c-T_a and hence the CWSI values.

The theoretical method of Jackson *et al.* (1981) is more complex in that it requires these two additional variables (net radiation and windspeed) to be measured, as well as an evaluation of the aerodynamic resistance. It thus accounts for differences in radiation and windspeed. Jackson, Kustas & Choudhury (1988) re-examined the theoretical approach and proposed a method for estimating an aerodynamic resistance applicable to a plant canopy. Their report concludes that the temperature of a plant canopy is determined by the water status of the canopy and by environmental factors such as net radiation, vapour pressure deficit, and windspeed. Using canopy temperatures as an index of the water status of a crop is not feasible unless the temperatures can be normalised for environmental variability, leaving only the water status as the determining factor.

The empirical approach utilises experimentally determined, fixed upper and lower temperature limits to normalise the observed temperatures for any level of vapour pressure deficit. The theoretical approach, for full cover canopies, allows the upper and lower limits to be determined by environmental conditions at the time of measurement, with only two parameters, the canopy resistance at potential evapotranspiration and the crop height, to be determined by field observations.

Jackson *et al.* (1988) found that in using CWSI to schedule irrigation, two major limitations became apparent. The first is that, although canopy temperatures can indicate stress, the degree of water stress is only quantified when compared to a non-stressed crop. The lack of fit to a 1:1 relationship between ET deficit and CWSI indicates the importance of a well-watered plot for comparison. Second, the CWSI, while quantifying water stress, does not indicate the amount of water required to eliminate stress or refill the root zone to field capacity. This information would have to come from soil water measurements and/or ET estimates from equations, such as the modified Penman equation (Ehrler, 1973).

The effects of water stress during different growth stages of various crops

Braunworth & Mack (1989) evaluated the relationships between the crop water stress index (CWSI), evapotranspiration (ET) and yield. CWSI values tended to be higher in plots which received less irrigation than in those that received greater amounts of water.

Hattendorf, Carlson, Halim & Buxton (1988) considered the relationship between yield of water-deficit stressed lucerne and the CWSI to be dynamic over the harvest period. Their investigation was conducted to define the yield-CWSI relationship(s), to test possible advantages of using the CWSI over the canopy-air temperature (T_c-T_a) differential, and to combine the yield-CWSI relationship with a growth function.

Water stress during different growth stages

Although it is generally accepted that the growth stage in which stress occurs has a definite effect on the growth and yield of a specific crop, De Bruyn & De Jager (1978) and De Kock, De Bruyn & Human (1990) indicated that water stress sensitivities of maize and cotton vary within a specific phenological development stage (Figures 1 & 2).

Hassan, Ogunlela & Sinha (1987) determined the yield and and growth responses of wheat to seeding rate and to moisture stress imposed at various growth stages, and also identified wheat growth stages that are most sensitive to soil moisture stress.

Withholding irrigation at any growth stage prior to anthesis had detrimental effects on most of the growth characters, whereas stress during crown root initiation (CRI) and jointing reduced most of the yield characteristics. Missing two consecutive irrigations at any given growth stage reduced grain yield more than did missing one irrigation; the greatest reductions in grain yield were 13 to 65% when one irrigation was missed at CRI and two consecutive irrigations were missed at jointing (the most sensitive growth stage), respectively. Moisture stress was also detrimental to number of grains, spike number, spike length, leaf area and number of tillers.

Grant, Jackson, Kiniry & Arkin (1989) determined

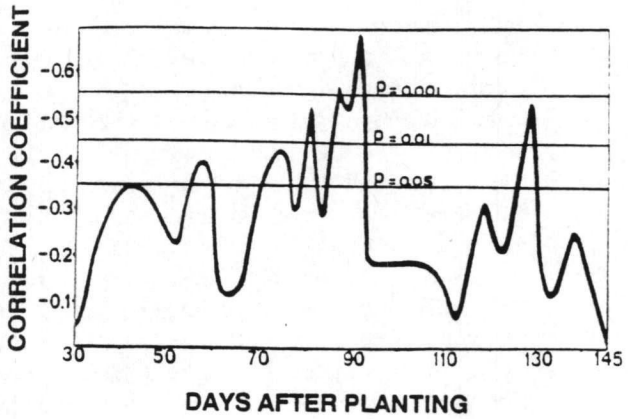


Figure 1 Drought sensitivity expressed by correlation co-efficients between number of moisture stress days and yield in maize plants. (De Bruyn & De Jager, 1978).

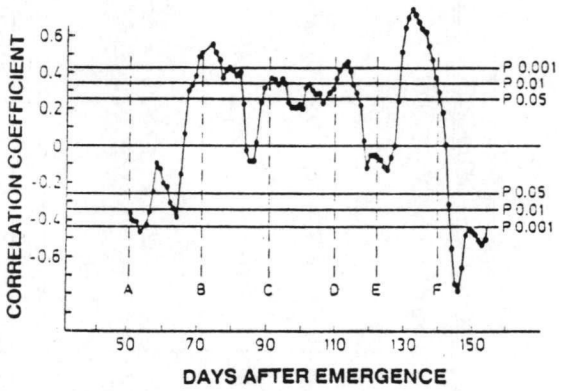


Figure 2 The effect of leaf water potential during the reproductive phase of the cotton plant on lint yields at Stages A) Square formation peaks; B) first flowers appear; C-D) flowering peaks; E) end of effective flowering period to produce bolls before onset of frost; F first bolls open (De Kock *et al.*, 1990).

the effects of water deficits during different growth stages on maize yield components. Individual plants were grown in containers in a glasshouse. For each treatment water was withheld until the accumulated water use in well-watered control containers was approximately twice the plant available water capacity in each container. Stress initiated prior to silking but relieved within two days after silking did not reduce kernel number, kernel weight, or plant yield. The fewest number of kernels, 45 % of the control, resulted from stress occurring during the seven day period after silking. Kernel weight was reduced by stress during the grain filling period, and the lowest weight, 51 % of the control, occurred for stress 12 to 16 days after silking.

Results of three years of research on cabbage crops by Nortje & Henrico (1988) yielded data on crop performance during summer months when the atmospheric evaporative demand is high, as well as during mild winter months. Yield and head mass of cabbages were enhanced by irrigating at frequent intervals during summer and winter. Severe soil water stress during the growth period prior to head formation was not detrimental to yield and quality. Regular irrigation from the time of head formation to maturation counteracted previous adverse effects of water stress on growth. Stress imposed during the period of head formation to maturity adversely influenced yield and quality. Weekly growth analysis indicated that the development of internal compactness of the heads was enhanced by dry water regimes. In the winter trials maturity was attained 10 days earlier in dry regimes than in wet regimes.

Duration and intensity of stress

The duration and intensity of the stress is of great importance since this affects the recuperative abilities of the crop after alleviation of stress. As can be expected, the responses to imposition and alleviation of stress differ considerably between crops as well as between different growth stages of the same crop. In the study by Human, Roux & De Bruyn (1990c) the effect of water stress on CO_2 uptake was measured at three different growth stages of wheat grown in Mitscherlich pots in a glasshouse experiment. Although water stress inhibited the CO_2 uptake rate of the entire plant, low stress levels briefly stimulated this process during the differentiation of the spikelet. Recovery of the CO_2 uptake rate of the whole plant deteriorated with increasing severity of stress and especially at later growth stages, while no recovery was evident on alleviating severe stress during seedfilling (Figure 3). The CO_2 uptake rate per unit of living leaf area generally decreased under stress, while the recovery after severe stress was considerably lower than after moderate stress. As with the whole plant, there was no recovery whatsoever of the CO_2 uptake rate per unit leaf area after the alleviation of severe stress during seed-filling.

Similarly, the effect of water stress on maize was investigated by Human, Du Preez & De Bruyn (1990a). In their experiment the effect of plant water stress on net photosynthesis and leaf growth was investigated in order to determine to what extent leaf water potential during vegetative growth and silking affects maize development (Figure 4). The CO_2 uptake rates per unit leaf area decreased to negative values under both moderate and severe stress conditions during the eighth leaf stage as well as during silking. During silking, the recovery of CO_2 uptake rate was much lower than during the eighth leaf stage. Leaf area decreased proportionally with increased stress but did not recover after alleviating stress on plants stressed during both the eighth leaf and silking stages. The effect of water stress on the dark respiration of maize was subsequently determined (Du Preez, Human & De Bruyn, 1989). On reaching a predetermined level of stress, CO_2 outflow rates were

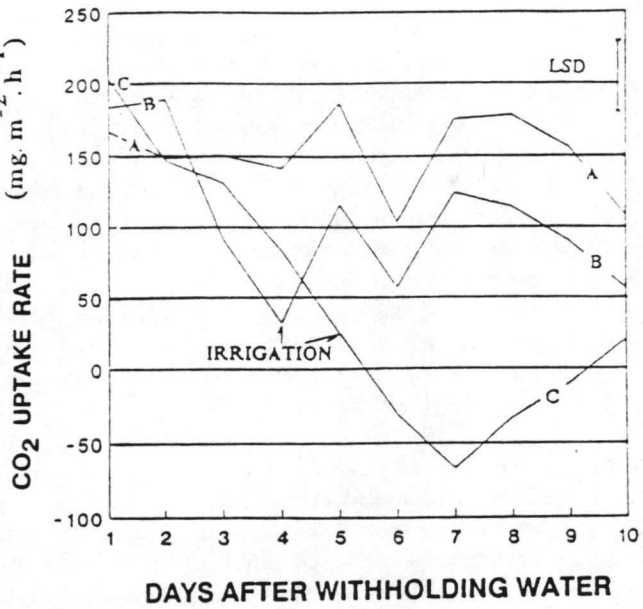


Figure 3 The effect of water stress during seed-filling of wheat on the CO_2uptake rates per unit living leaf area where: A - no stress was induced; B - moderate stress was induced; C - severe stress was induced (Human *et al.*, 1990(c)).

monitored at intervals during the night. Measured rates declined during the night but generally stabilised during the 4.5 h period preceding dawn. Results indicated that the nocturnal decline in dark respiration may have been influenced differently by water stress in the two cultivars and in the two growth stages considered.

Human, Du Toit, Bezuidenhout & De Bruyn (1990b) reported on the effect of plant water stress on net photosynthesis, leaf growth, yield and yield-related components of sunflower. Sunflower plants, grown

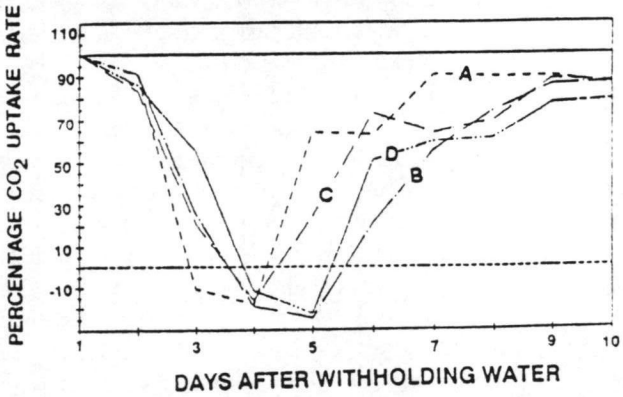


Figure 4 The effect of stress on the CO_2 absorption rate per unit living leaf area of maize as a percentage of that of unstressed plants where treatments A and B were moderately and severely stressed during both the eighth leaf stage as well as anthesis and silking and C and D were moderate and severely stressed only during anthesis and silking while moderate stress was alleviated 4 and severe stress 5 days after withholding water (Human *et al.*, 1990a).

under controlled temperature regimes, were stressed during budding, anthesis and seed filling. Leaf area of unstressed plants significantly exceeded that of plants under severe stress during all growth stages investigated. The CO_2 uptake rate per unit leaf area as well as the total uptake rate per plant, significantly diminished with stress, while this effect drastically increased during the reproductive phase of the plant (Figure 5). Although this resulted in significantly smaller heads and kernels, it did not affect the number of seeds borne in the inflorescence. Severe stress during anthesis and seed filling resulted in more empty kernels. Moderate and severe stress during budding significantly lowered both grain and oil yields while plants that experienced moderate stress during anthesis and seed filling significantly outyielded those under severe stress.

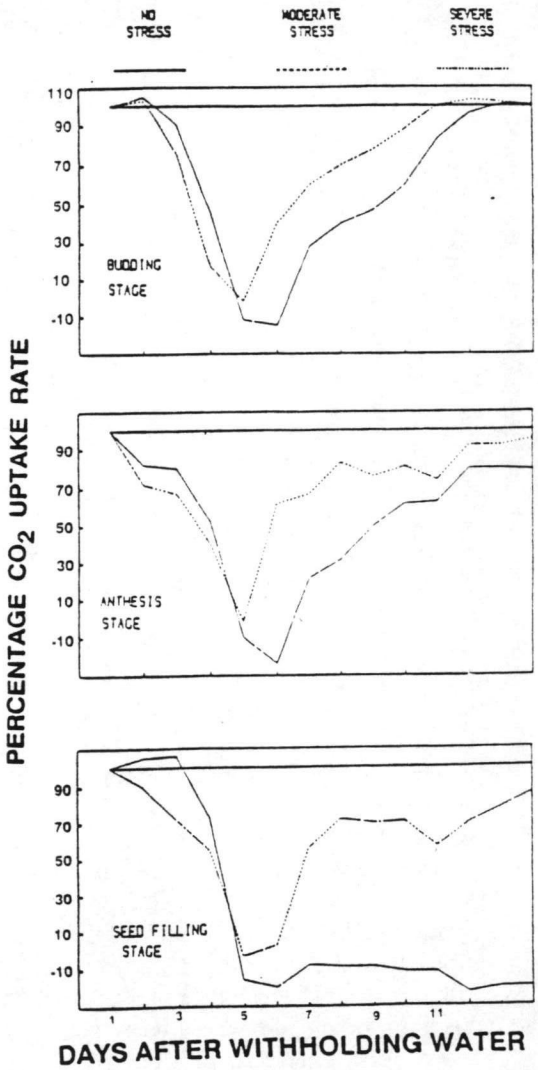


Figure 5 The CO_2 absorption rate per unit leaf area of sunflower during the build-up of and on recovery from different degrees of stress (moderate stress was alleviated on day 5 and severe stress on day 6) (Human *et al.*, 1990b).

Massacci, D'Ambrosio, Incarnato & Santarelli (1990) studied photosynthesis, stomatal conductance and water relations in response to withholding water in a maize crop under conditions of high atmospheric evaporative demand. Their aim was to probe environmental stress by gas exchange measurements in the field. In spite of dry soil, leaves kept fully turgid in all plants while stomatal conductance and photosynthesis decreased greatly in unirrigated plants. In order to identify daily stress effects under high transpiration, stomatal conductance measured after dawn was shown to be superior to leaf water parameters. Massacci *et al.* (1990) thus concluded that stomatal conductance measurements may be of use in irrigation scheduling of crops with critical water supplies. With the aid of a rainout shelter and different irrigation treatments, a range of soil and plant water deficits were imposed on cotton by Turner, Hearn, Begg & Constable (1986) in order to study the physiological and morphological responses to water stress as a step towards maximising yield per unit of available water. They found that as the soil water deficits increased, the leaves adjusted osmotically by 0.5 to 0.6 MPa at full turgor. The photosynthetic rate and leaf conductance at high quantum flux densities in the middle of the day decreased progressively as leaf water potential decreased from -1.9 MPa to -3.5 MPa. Leaf expansion was more sensitive to soil and leaf water deficits than was leaf photosynthesis. The daily rate of leaf expansion decreased when the pre-dawn leaf water potential decreased below -0.8 MPa. Water deficits reduced leaf and fruiting-site development, the number of floral buds and bolls retained, and eventually reduced the final yield, but the proportion of flowers that set bolls was not affected except where substantial soil water deficits developed during early flowering. Then large floral buds were retained at the expense of small floral buds. Turner *et al.* (1986) suggested that soil water deficits reduced the capacity of the crop to carry fruit as a result of lower rates of leaf photosynthesis.

Intervals between water applications

Not only do the intensity and the duration of the period of stress severely affect the physiological processes of the plant, but the length of apparently stress-free intervals between irrigations can also be of great importance. During these periods the plant can adapt and withstand succeeding water stress conditions to a greater extent.

Yield of irrigated cotton increases as the interval between water applications is decreased, even if the total amount of water applied is unchanged. Experiments were undertaken by Radin, Mauney & Kerridge (1989) to compare season-long water relations of high-frequency drip-irrigated cotton (one to two day intervals) to cotton irrigated at approximately two week intervals. Irrigation frequency had inconsistent effects on midday leaf water potential during vegetative growth. When the crop developed a heavy fruit load, however, the water potential of plants experiencing longer cycles was much lower than those of drip-irrigated plants, even with ample soil water remaining immediately prior to re-irrigation. Plant hydraulic conductance, estimated from regressions of single-leaf transpiration rate against leaf water potential, were high in both treatments early in the season. Hydraulic conductance decreased substantially during fruiting in plants subjected to long irrigation cycles but less so in frequently drip-irrigated plants. Late in the season, after fruit maturation and during plant regrowth, conductances were again high and similar in the two treatments. The results imply that during heavy fruiting, water stress, associated with long irrigation cycles, triggers deterioration of the root system. High-frequency drip irrigation, by preventing cyclical stress, apparently minimizes this deterioration during fruit filling.

Water use efficiency

Water use efficiency and nutrient requirements

Since relationships between water use and fertilizer needs are not well defined, Eck (1988) conducted field studies with winter wheat to determine the interacting effects of N fertilization and irrigation on N and P needs, wheat yields, and yield components. They found a definite relationship between water applied and nitrogen required for maximum yields.

Water stress-induced senescence is frequently alluded to, but interactive effects of water and nitrogen deficits on leaf longevity and on physiological changes associated with leaf aging have received little attention. Wolfe, Henderson, Hsiao & Alvino (1988) investigated these aspects in a field experiment with maize on a loam soil. They found that leaf photosynthetic capacity (PC) was correlated with percentage nitrogen during senescence in all treatments, but an occasional midday depression in PC, unrelated to leaf N status, was observed in severely water-stressed plants. Water stress intensified as stored soil water was gradually depleted, and the most rapid decline and earliest complete senescence of upper leaves occurred in the treatment where no irrigation was applied. These findings stress the importance of fertilization applications being in balance with the amount of irrigation water applied to provide for optimal growth and production of the crop.

In order to obtain a sound evaluation of the water use efficiency of a specific irrigation programme, it is important that the yield potential is not curbed by insufficient plant nutrients. Although some work has been done on nitrogen requirements under different irrigation levels, little is known about the effects of other macro and micro elements.

Water use in plants treated with growth regulators

The possibility cannot be ruled out that reducing the water requirements of a crop by limiting vegetative growth and hence lowering transpiration rate, may prove to be a cost effective means of increasing water use efficiency.

Atkinson (1986) pointed out that plant growth regulators directly affect nutrition as well as water relations by altering nutrient uptake or stomatal functioning. There can also be indirect effects resulting from changes in the growth pattern (e.g. changes in leaf area or leaf size, density and distribution of the root system). He reviewed the effects of paclobutrazol on tree crops and found that mainly leaf area and root length were inhibited. Leaf thickness increased due to increased length of palisade cells, resulting in increased cell wall area per unit leaf area which may reduce mesophyll resistance to water movement. Shoot extension is greatly reduced by paclobutrazol, although diameter may be unaffected. These changes will affect total nutrient requirements. Root growth in most instances was retarded but the shoot:root ratio also decreased. Treated plants may therefore have relatively more roots per shoot mass.

Leaf area reduction affects crop water use (Atkinson, 1986), as do the various resistances to water flow, of which canopy roughness effects, canopy diffusive resistance (also linked to leaf area) and resistance within the root system, are most important. These factors result in reduced water use by paclobutrazol-treated crops, while the water potential remains higher.

Plant growth regulators may affect nutrition both by reducing the size of the plant and hence total nutrient content, as well as by affecting nutrient uptake and consequently the concentrations thereof in the plant material. Nitrogen concentration differences were found to be due to reduced growth. Both phosphorus and potassium concentrations in leaves of treated plants were reduced, but paclobutrazol had no effect on leaf calcium content. Atkinson (1986) came to the conclusion that the application of plant growth regulators to fruit trees will affect their nutrient requirements.

Shanahan & Nielsen (1987) investigated the effect of growth retardants (anti-gibberellins) on the water use and yield of maize in an area where supplemental irrigation is required. Two anti-gibberellin, seed-applied, experimental plant growth regulators (PGRs), were used on maize grown under low and high levels of irrigation in a field study to determine the effect on vegetative growth, water use, water stress, grain yield, and yield components. Increasing application rates of the PGRs caused a significant reduction in early season plant height, leaf area index and dry matter accumulation, resulting in reduced early season evapotranspiration. The PGR treatments reduced plant water stress during silking and early grain fill, particularly under the low irrigation treatment. Reducing early season vegetative growth with the PGRs proved to be advantageous to productivity under water stress and counterproductive under nonlimiting water conditions.

The effects of an experimental antitranspirant on yield, quality and water use efficiency (WUE) of Russet Burbank potatoes were studied by Stark & Dwelle (1989). Potatoes were subjected to different levels of water stress by withholding irrigation for 12 to 21 day periods during tuber initiation or tuber bulking. The antitranspirant increased total yield of potatoes subjected to water deficits. However, treatment of well-watered potatoes reduced yield as a result of reduced tuber size. In nearly all cases, application of the antitranspirant increased the conservation of soil water, thereby improving water availability during the latter stages of the growing season. The WUE was generally improved where sub-optimal irrigation rates were applied.

Variation in water use efficiency and drought tolerance between different crops and cultivars

Apart from the fact that crops differ in their ability to withstand water stress conditions, differences in drought resistance between cultivars of the same species may also occur. Barker, Frank & Berdahl (1989) investigated this aspect by determining the water use efficiency (WUE) of different cultivars and clones of four forage grasses. Increases and decreases in forage yield were associated with total available water (soil water plus growing season precipitation) prior to harvest and effects of stress in one year on yield in subsequent years. There were no significant ($P<0.05$) differences in total water used before harvest.

Eck, Mathers & Musick (1987) considered drought-tolerant crops to be adaptable to areas where water is limited and where less water is applied by irrigation than is required for potential evapotranspiration and maximum yield. Their study was conducted to determine the effects of plant water stress at various growth stages on growth and yield of soybeans and to assess the adatability of the soybean plant to limited irrigation. They found soybeans amenable to limited irrigation under the stressful climate of the Southern High Plains, but their vulnerability to drought stress during seed development complicated management. Eck *et al.* (1987) considered soybeans to be more suited for limited irrigation than maize but less suited than grain sorghum, cotton or wheat.

Gordon-Werner & Dörffling (1988) studied root morphology, drought tolerance and heat tolerance of rye hybrids and cultivars and evaluated the use of membrane stability tests as a selection tool for drought and heat tolerance. Root length, surface area and lateral density were measured on plants at the three leaf stage. Plants which had the most extensive root

system tolerated drought the best and were also the most tolerant to sustained, though not to acute heat stress. There was no correlation between drought tolerance in potted plants and membrane stability following either heat or dehydration stress.

Larsson & Gôrny (1988) evaluated 11 oat cultivars varying in origin, in laboratory and field tests. Comparisons were made between drought resistance characteristics of juvenile plants and yield responses due to drought of crops grown in the field. By using automatic, movable rain shelters in combination with drip irrigation systems, both wetter and drier irrigation regimes could be applied in the field experiments. They found black oat cultivars to be more stable than white oat cultivars under water deficiency conditions, particularly on sandy soil. Modern white oat cultivars were found to be most drought sensitive. A drought resistance index (DRI) and the seminal root length (RL), as assessed at seedling stage, were strongly correlated with a field drought susceptibility index (S). It was suggested that DRI and RL could be used as selection criteria to increase drought resistance of oats.

Discussion

It appears that the concept of CWSI, as obtained from handheld infrared thermometry, has gained some ground against *in situ* measurements of leaf water potential by either psychrometers or the Scholander pressure chamber. Whatever method is to be used, it is most important that threshold values for every sensitive growth stage of a specific crop are established.

The determination of the exact duration of water sensitive growth stages has been sadly neglected by research workers. Most crops are extremely sensitive to water stress during flowering, while in others stress during seedfilling is even more detrimental to yields. Water sensitivity, however, is not necessarily restricted to the duration of a specific phenological growth stage. Sensitivity can commence or end before or after the onset of the phenological stage and even vary within an identified growth period. Where enhancing water use efficiency is the goal, it is important to establish, as the first step in a research programme, the exact duration of each sensitive period, as well as the relative water stress sensitivity between these identified sensitive periods.

De Bruyn & De Jager (1978) and De Kock *et al.* (1990) determined the relative water sensitivity of maize and cotton throughout their growing seasons on a day-to-day basis. This precluded mistakenly preselecting periods thought to be stress-sensitive during which the reaction of the plant to water stress was to be measured. The actual water sensitive periods could be accuraely defined for this purpose.

When the exact duration of the water sensitive period has been established, the effects of water stress on the physiological processes in the plant have to be determined in order to know in what way stress inhibits growth and yield. The effect of water stress on the CO_2 uptake has been measured by Human *et al.* (1990a, b & c) for maize, sunflower and wheat respectively. This was done as an indication of the effect of water stress on net photosynthesis, which is the main physiological process governing plant productivity. Their research was carried out under controlled conditions with plants grown in containers. Since it was found that the effect of the gradual build up of stress after withholding water and the extent to which the plants recovered after irrigation, was reflected in the CO_2-uptake rate, and since these patterns differed greatly during the different growth stages, the effect of plant water stress on various physiological reactions should further be tested in field grown crops.

Human & Pretorius (1991) measured the effect of plant water stress on the net photosynthesis, leaf temperature, stomatal conductance and transpiration rate during the life cycles of wheat and soybeans under field conditions. These results will provide scientific indicators of the need to irrigate in order to alleviate critical plant water stress before growth and yields are adversely affected.

The literature reviewed indicates that the effect of water stress on the growth and yield of the plant is determined by the magnitude of stress experienced and that the recuperative capabilities depend on the growth stage during which stress occurred as well as the duration of stress. There are also indications of conditioning to water stress where the plant has been subjected to mild stresses during earlier growth stages.

It is further evident that the duration of relative stress-free periods also determines the ability of the plant to recover from stress and produce optimally. This is a most complex issue which has a direct effect on the water use efficiency of a crop. The work done on conditioning to water stress is still in its infancy. There are merely indications that conditioning does in fact occur and most of these are based on work done in pot experiments where plant water stress builds up over a much shorter period than in the field. Since the duration of stress is a governing factor in conditioning, this aspect warrants close scrutiny for specific crops under field conditions.

Since there is sufficient evidence that the water use efficiency of different cultivars of the same species may vary considerably, there is justification to consider WUE in a breeding programme for drought tolerance. This will require experiments with different cultivars under field conditions, where water sensitivity is compared only during the most sensitive periods previously determined. The water use efficiency can thereafter be determined on the most drought tolerant cultivars or on members of certain groups of cultivars. This will eliminate unnecessary duplication in an effort to keep up with the constant

flood of new cultivars.

It appears that plant growth regulators probably have little beneficial effect on the water use efficiency of field crops. This aspect, therefore, may for the present be given a low priority, but cannot be totally ignored.

Nutrient requirements are closely associated with water use efficiency. While water use efficiencies should be determined under optimal nutrient levels, the actual fertilisation needs of a crop can be estimated when the required water application level has been established.

Some attention has been given to the effect of water application on the quality of horticultural products. Extremely little is known, however, of the effect on the quality of field crops. Quality is an aspect that is becoming more important but is, however, interrelated with cultivar and fertiliser as well as water applied. At this stage it is not clear what priority it should be given: should the cultivar with the best quality be selected whereafter the water use efficiency and nutrient levels are optimised or should the most drought tolerant cultivar be manipulated by water and nutrient applications to produce the best quality?

Conclusions

Irrigation scheduling based only on a pre-determined value of soil water status can hardly claim to be a scientific approach because it does not take atmospheric conditions into account and therefore ignores stress which may occur in the plant. Measurements of plant water stress are, however, variable due to constant fluctuations in meteorological conditions. Care should be taken, therefore, when interpreting these readings. With this precaution in mind, indices of plant water stress should be evaluated at the point when growth and yield are retarded to such an extent that water use efficiency is severely inhibited. These index values are not only crop and even cultivar specific, but vary according to the phenological growth stage of the plant. On alleviating stress, especially during earlier growth stages, the plant may not only recover and reach normal levels of its physiological processes, but will also be able to condition itself to withstand succeeding stress periods. On the other hand, prolonged and greater water stress will have a more severe effect on the plant, increasingly so during later growth stages. Conditioning to water stress is also determined by the duration of stress-free conditions between stressed periods. These aspects can best be studied where the effect of the magnitude, duration and frequency of water stress on the physiological processes of the plant are measured. Since net photosynthesis is directly related to growth and yield, the effects of stress conditions on the inhibition of the CO_2 uptake rate is of particular importance.

Much of the research that has been done on critical water stress levels was concentrated on pre-selected periods, defined according to the phenological development of the plant. The results thus obtained, however, give no indication of the exact duration of the water sensitive periods nor do they indicate the relative sensitivity of the different sensitive periods. They therefore give no indication as to when irrigation has to be applied in order to obtain the maximum beneficial effect. In this paper the conclusion is drawn that the relative sensitivity to water stress should first of all be determined on, if not a daily basis, then at least for each pentad over the entire growing season of a specific crop. The effect of water stress during these identified sensitive periods should then be determined by measuring the effect of magnitude and duration of stress on the physiological processes of the plant. Critical plant water stress levels, as determined for the specific technique, can thus be established for each sensitive growth stage.

Maximum water use efficiency can only be attained after the critical water stress levels have been established for each sensitive growth stage of a specific crop and the effect of water stress on the physiology of the plant has been studied. Water should be applied preferentially during the most sensitive periods for water stress and only when the critical water stress level is reached. In order to obtain the ultimate or most economical water use efficiency for a specific crop, various irrigation combinations should be tested, with results due to omitted irrigation applications being compared with those obtained when employing a complete irrigation programme. Care should, however, be taken that not only yield, but also quality of the crop harvested, is considered when deciding on the most suitable irrigation programme.

It is clear that the present knowledge of the water use efficiency of crops is extremely fragmented and restricted only to certain crops. Furthermore, little work has been done under field conditions, let alone on differences between cultivars of the same species. It appears that at present there are little more than mere indications as to the mechanisms affecting crop water use efficiency. These, nevertheless, enable one to properly plan research in this field and to initiate a logical programme of investigation in order to arrive at valid conclusions and recommendations to the irrigator and eventually attain the ideal which is to arrive at a reliable plant-based irrigation norm.

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CROP INDICATORS OF WATER STRESS FOR USE IN IRRIGATION SCHEDULING: AN OVERVIEW

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Abstract

In a crop production system plants are the most important component as they produce the yield. It is therefore appropriate to consider certain crop responses as indicators for irrigation scheduling. In the past both morphological and physiological indicators have been used. The usefulness of an indicator will depend upon its repeatability and ease of identification. To be considered practical, an indicator should respond before extensive reduction in economic yield occurs. Some indicators require sophisticated scientific equipment and others are simply visual observations of the crop. They include measurements of midday leaf water potential using a Scholander pressure chamber, soil water content using a neutron moisture meter, canopy temperature using an infra-red thermometer, stomatal resistance and leaf growth rate as well as leaf observations. A wheat crop irrigated according to leaf water potential, soil water depletion and canopy temperature is used as an example. The progressive approach is to include these parameters in computer models adapted for specific regional weather conditions. For effective irrigation, field observations of plant and soil conditions are required as frequently as possible. This task is simplified if a specific indicator has been identified as being useful. Management decisions can then be based on the crop indicator and irrigated accordingly.

Introduction

Optimal yields can be obtained by regular irrigation through the season so as to maintain the crop water status as a non-limiting factor. For irrigation scheduling, the timing and amount of water to apply need to be known. The amount of water to apply depends on the soil water depletion and the rooting depth of the crop, and the timing depends on the species, its daily water use and water stress tolerance. As the plant is interfaced to both the soil and the atmosphere, the plant itself provides the best integrator of the whole system and can therefore be used as an indicator of when irrigation is necessary.

As the economic yield of the crop is the primary aim of cultivation, it seems wise to allow the crop itself to be used as an indicator of the water requirements. A practical disadvantage is that the first effects of the yield-reducing water stress are not easily visible and water stress may already have affected the economic yield prior to detection. Therefore, a useful indicator is needed that can show a response or change during the initiation or onset of water stress.

Traditionally the wilting of leaves has been used to indicate the need for water application. It is also well known that wilting does not represent the beginning of the water stress period, but is in fact an advanced stage and indicates a severe water stress. Both morphological indicators, such as leaf rolling, surface wax, as well as physiological indicators, such as water potential, stomatal aperture, and carbon dioxide assimilation rates, have been proposed. The usefulness of an indicator will depend on its repeatability and ease of recognition (Oosterhuis, 1982) and it should respond before extensive reduction in economic yield occurs if it is to be considered as a practical indicator.

Physiological Indicators of Water Stress

It is well known that many physiological processes are affected by a limited water supply to the plant. Research has shown that as the severity of the water stress increases, so different processes are affected. Hsiao (1973) presented a table of generalized sensitivity of plant processes to water stress (Table 1).

Processes that have a response at high water potential are considered to be most sensitive to water stress: firstly cell growth, then at a biochemical level, cell-wall and protein synthesis followed by chlorophyll and nitrate reductase synthesis. As the stress further

Table 1 Generalized sensitivity to water stress of plant processes and parameters, where the length of the horizontal lines represents the range of stress levels at which the process is affected (From Hsiao, 1973 and Hsiao *et al.*, 1976).

Process or Parameter	Sensitivity to stress: very sensitive ⟵ insensitive; reduction in tissue water potential for effect: 0 — 1MPa — 2MPa
cell growth	------- - -
wall synthesis	---------
protein synthesis	---------
protochlorophyll formation	---------
nitrate reductase level	----------
ABA synthesis	- - ----------
stomatal opening	
-mesophytes	----------
-some xerophytes	---------- - - -
CO_2 assimilation	
-mesophytes	----------
-some xerophytes	---------- - - -
respiration	- - ----------
xylem conductance	- - ----------
proline accumulation	- - ----------
sugar level	----------

develops, the hormones are influenced, particularly ABA synthesis. Only after all these processes have been affected does stomatal aperture show detectable changes. The assimilation rate of leaves will also be affected after further water depletion.

It is useful to know the sensitive periods during the growth of the crop. Generally speaking the differentiation of vegetative to reproductive tissue is sensitive to water stress (Syvertsen, 1985). Of particular importance are the initiation of the floral and reproductive parts and the processes of pollination and fertilization which can lead to premature abortion of fruits and seeds if occurring during a stress period. Finally the yield will also be dependent on the water status of the plant during the seed filling stages.

A major disadvantage of the physiological indicators (and soil water measurements) is that they must be monitored on a frequent and routine basis. In addition, most of the procedures need expensive, specialised equipment and then the results must also be interpreted. The disadvantages make them impractical at a farm level and are partly responsible for the lack of applications.

Leaf water potential

Leaf water potential is soundly based on fundamental principles of thermodynamics, and is generally accepted as a good measure of plant water status. Leaf water potential is usually measured by a pressure chamber (Scholander, Hammel, Bradstreet & Hemmingsen, 1965) although detailed research measurements are made using thermocouple psychrometers (Wiebe, Campbell, Gardner, Rawlins, Cary & Brown, 1971). Pressure chamber measurements are easily made on a routine basis in the field at midday when evaporative demand is highest, and leaf water potential reaches its lowest (most negative) value. Certain precautions need to be observed during the measurement procedure (Turner & Long, 1980), such as covering the leaf prior to cutting to prevent excessive evaporation, and a slow increase of pressure in the chamber to allow adequate equilibration, etc. Under conditions of adequate water supply there will be a diurnal cycle of leaf water potential, decreasing from sunrise (approx. -0.3 MPa) to midday values which are both species and environment dependent. As the water deficit increases these midday values will decline to a lower level. The past history of the plant affects the leaf water potential values, and this influence is different for different species. A caution when using these values under severe drought conditions or repeated water stresses is that there is adaptation in the plant and the critical values will therefore change.

Growth

Cell growth is one of the first processes to be affected by water stress (Hsiao, 1973). Therefore, it is logical to use growth as an indicator of the onset of water stress. One of the major drawbacks is that unless the growth of an organ is in the linear phase, it is difficult to detect changes in growth rate. One way to overcome this problem is to maintain an "indicator plant" which always receives adequate water. The growth measurement from this plant can then be used a s a standard to assess the growth of the rest of the crop. This of course is not always possible. If the extent of uninhibited growth is known for a certain site from one year then it possibly could be used for future years also. Leaf growth has been used to detect onset of water stress in several crops (Meyer & Green, 1981; Walker, 1988) by measuring the leaf length. As the growth is dependent on turgor pressure within the cells, some researchers have attempted to measure turgor pressure. Unfortunately, there are many complications involved in such measurements, and several errors are introduced during the destructive sampling of growing organs (Boyer, 1988). Therefore turgor measurements derived from the difference between water and osmotic potential measurements are ill-advised, especially for growing tissue.

Stomatal Resistance

Stomata usually respond to water deficit at some threshold leaf water potential that is species-specific (Oosterhuis & Walker, 1987). This threshold is known to vary according to the previous history of water status of the plant (McCree, 1974). As stomata are light sensitive, stomatal resistance is more depen t on environmental factors, particularly the radiative load and wind speed. Stomatal resistance is measured with a porometer clipped onto an individual leaf and does not provide potential as a practical indicator.

Morphological Indicators of Water Stress

Water stress can have a marked effect on the structural and anatomical properties of a crop such as leaves changing their position or folding or rolling. The texture of the leaf surface may also change, due to increased hairs or wax deposits. Although the morphological changes are noticeable, they are not the first indication of stress, as they are all basically due to initial changes at a physiological level. Despite this, for practical proposes they should be heeded, and to prevent severe water stress and drought conditions developing.

Leaf Observations

Most of the modifications to the leaves are in an attempt to decrease the radiation load on the leaf and thus the severity of the stress. Although various crops have different leaf reactions to stress, most of are not immediate indicators of the onset of stress. They are still useful, because when the leaves show a response that means the situation is already critical needs to be attended to immediately. For example the

leaf angle of soyabeans is related to the water status of the plant (Oosterhuis, Walker & Eastham, 1985). Leaf colour is known to change as an adaptation to prolonged drought conditions. The radiation load can be decreased by increased pubescence or additional wax deposits. If the leaves are wilted then irrigation is certainly needed, although by that time the economic yield is sure to already have declined.

Some Currently Used Methods for Detecting Crop Water Stress

Useful indicators are those that are consistently sensitive to water deficit of a specific crop over a range of seasons and a wide variety of environmental conditions. Methods employing various indicators still have shortcomings, due to inadequacy in any one system, as will be shown in the wheat example that will follow.

Canopy Temperature

The measurement of canopy temperature using an infra-red thermometer has been used extensively in the USA for predicting irrigation of field crops (Idso, Jackson & Reginato, 1977). For good results standard indicator plants must be maintained well watered throughout the season as a point of reference. The stress indicator is then the difference between the two temperatures. Unfortunately there are also other problems associated with the use of canopy temperature, including the non-uniformity of the canopy, varying orientations and amount of exposed soil surface and changes in the crop surface due to growth stage (e.g. appearance of ears).

Crop Water Use

An estimate of crop water use can be made from evaporation pan measurements with the use of a crop factor which is species-specific. By measuring the soil water content using a neutron probe moisture meter (Van Bavel, Nielsen & Davidson, 1961), one can calculate the water loss from the soil. If measurements are also available neutron probe at field capacity, then the amount of water required to refill the soil profile can be calculated. The soil water content as such does not give an indication of plant water stress. However, if under the specific site conditions one knows that the plant shows stress symptoms at a certain water content or percentage depletion for a given evapotranspiration rate, then it can be used for irrigation timing. The depth to which the soil water measurements need to be made depends on the rooting depth of the particular crop.

Irrigation Models

Many of the above factors have been combined into computer models that can be used to predict the irrigation requirement of a crop. The level of sophistication of the model largely depends on the original designers and their objectives. The simulation models usually include the soil, plant and atmospheric components and work on a water balance model (e.g. CERES, PUTU). However, there are often shortcomings on the crop side. Other models may only include a prediction of irrigation from one or two of the components (e.g. BEWAB). For further details on the use of models of irrigation scheduling see other papers in these proceedings.

Wheat Crop Example

Triticum aestivum L. (cv. Zaragosa) was planted on 9 June 1986 at a plant population of 159 plants m^{-2} on a Hutton form of the Shorrocks soil series at Roodeplaat, NE of Pretoria, in South Africa (Nel, 1988). The treatments included a well-watered control plot which received water twice a week; a treatment irrigated when the soil water content reached 50% depletion of the plant available water as measured by the neutron probe; a treatment irrigated when the midday leaf water potential reached -1.2 MPa during the vegetative stage; and a treatment irrigated when the canopy temperature, measured by the infra-red thermometer, differed by 2°C from the control.

The fluctuation in the soil water content and leaf water potential, as measured by the pressure chamber technique, was determined for each of the treatments (Figure 1). It was observed that following the initiation of the treatments on day 223, the leaf water potential and soil water potential of all the treatments deviated from the control plot on day 236. Water was applied to all treatments on day 237. Following this the leaf water potential treatment was the first to be irrigated on day 252 and was followed by the other treatments on day 255. These treatments were then continued throughout the season (Nel, 1988). When the leaf water potential was used as the irrigation scheduling criterion the highest yield was obtained, namely 7.34 t ha^{-1} compared to 6.77, 6.61 and 6.96 t ha^{-1} respectively for the control, soil water content and canopy temperature treatments. This confirms that the use of a plant or crop indicator for irrigation timing, together with monitoring of the soil water content gave the best yield results. Lower wheat yields resulted on the other treatments that were irrigated by canopy temperature and soil water content methods.

Conclusion

There are a wide variety of reactions and responses to water stress among the various crop species. However, the question remains as to when to irrigate and with how much? Morphological plant indicators are not immediately helpful in indicating the onset of water stress, as they usually lag behind the changes in physiological processes. Therefore it is better to use the physiological based parameters as indicators. Leaf water potential as measured by the pressure chamber technique provides an easy method of detecting the

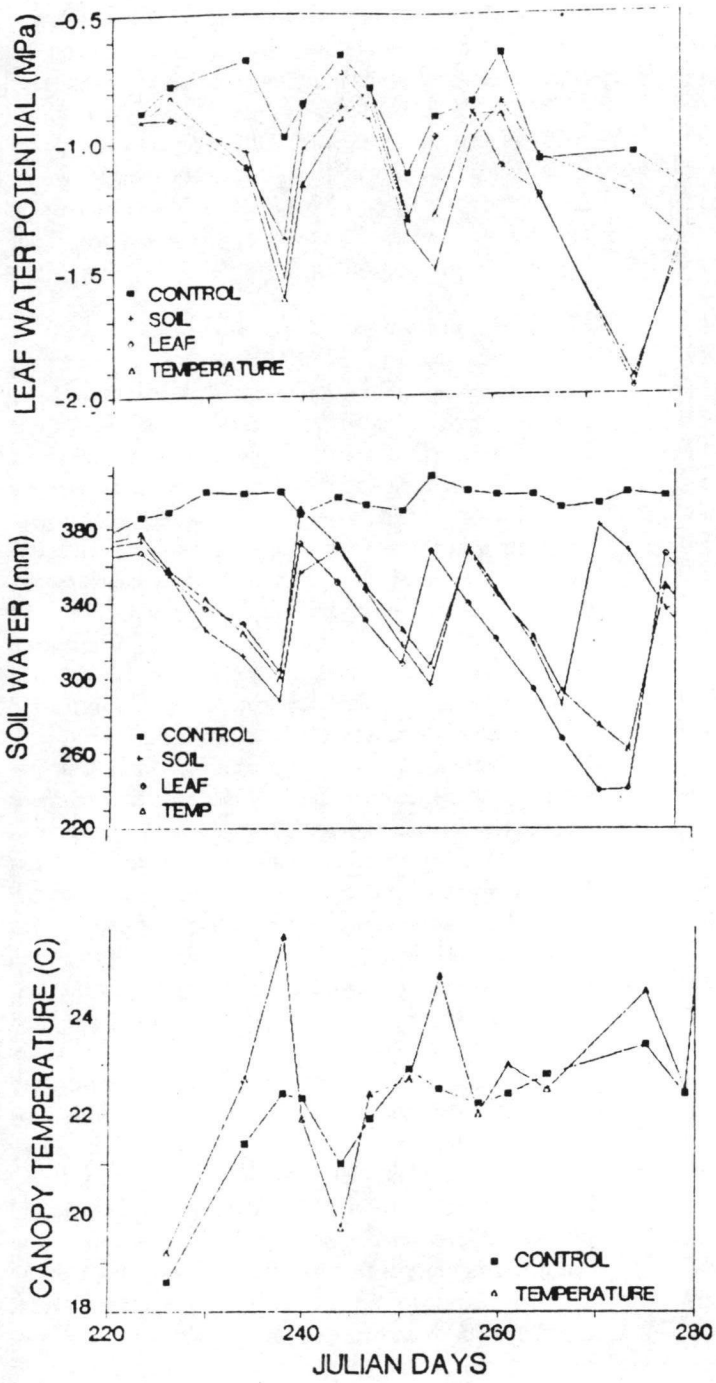


Figure 1 Data for a wheat crop grown at Roodeplaat. (a) Midday leaf water potential for the four treatments as indicated in the legend. (b) Soil water during the season. (c) Canopy temperature for the control treatment and that which was irrigated according to the temperature difference.

onset of stress, although this is impractical at a farm level. Leaf growth measurements also allow detection of the first signs of water stress, but are best conducted in conjunction with a well-watered control for comparison. Canopy temperatures as measured with an infra-red thermometer have been used at a farm level in the USA, but are most effective only when a well-watered comparison is available. However, at the present time in South Africa, to use plant based methods one has to invest in expensive equipment and diligently make measurements at least once a week. When using these methods, one still has to decide what degree of stress is to be allowed before irrigating. The amount of water to be applied can be calculated by two methods. Either, from a crop factor and accumulated pan evaporation since the last irrigation, or from the soil water depletion as measured by the neutron moisture meter. If the first indications of water stress are heeded and irrigation is applied, crop yields will not be reduced.

Plant indicators can be used to schedule irrigation, thereby increasing the efficiency with which the irrigation water is used. However, due to the impracticality of routine crop and soil monitoring at farm level, irrigation scheduling should rely on models with the following abilities: (a) the ability to accurately predict the crop water or stress status (eg leaf water potential, or ABA content); (b) the ability to accurately predict the soil water deficit; (c) to be run on a real time basis with actual current data as inputs (e.g. weather data from an automatic weather station); and (d) to have the predictions immediately and automatically available at the farm and in a format that the farmer can understand and apply to each section of the farm (ie user friendly).

When irrigation is timed according to crop indicators it allows the lowest possible irrigation frequency, and thus also the maximum opportunity for use of rainfall and a reduction in seasonal soil evaporation. Continued research is necessary to further develop the practical application of crop indicators and crop simulation models for use in irrigation scheduling.

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GROWTH AND YIELD OF TOBACCO UNDER A HIGH SOIL MOISTURE REGIME USING DRIP IRRIGATION

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Abstract

Flue cured tobacco (cv A4) was grown under drip irrigation at Rustenburg during 1987/88 to 1990/91 seasons with the aim of determining the yield potential of tobacco under optimum cultivation conditions, and relating plant growth to daily minimum and maximum temperature. The soil series was a Marikana that contains 48.5% clay and 400 mm m^{-1} water at field capacity. A dripper spacing of 120 by 80 cm wet the entire soil profile by means of lateral movement of irrigation water. Leaf area and number of leaves per plant were determined on a weekly basis. Cumulative degree days were calculated from daily minimum and maximum air temperatures and were used as measure of physiological time and as a driving force for leaf growth. An efficiency coefficient was calculated for leaf growth response to degree days. Leaf number and increase in leaf area were simulated using two season's data and yield estimated. Estimated yields correlated well ($R^2adj=0.918$) with the marketable yields of 3 790 and 4 600 kg ha^{-1} obtained during the two seasons.

Introduction

Drip irrigation technology has progressed exponentially during the past 15 years. Hall (1985) described advances in equipment, principles of chemigation and the application of drip irrigation technology to various crops. Despite this, production of flue cured tobacco under drip irrigation is practised by only a few farmers in the Republic of South Africa. Very few publications address this topic in connection with tobacco (Summer & Maw, 1987; Orphanos & Metochis, 1990). The advantages of drip irrigation in facilitating the efficient use of water is generally accepted (Fangmeier, Mezainis, Tucker & Husman, 1985). High yields of good quality tobacco leaf would, however, be required to justify the high capital cost of drip irrigation equipment and the greater maintenance and management inputs required of the farmer.

Growth processes in plants, including leaf initiation and expansion are temperature dependent (Wilkerson, Jones, Boote & Buol, 1989). Haroon, Long & Weybrew (1972) found day/night temperatures of 30/26°C to be near the optimum for tobacco but stem elongation was restricted at 34°C day temperatures and above. Temperatures below 26/22°C are detrimental to rapid growth. At 27/10°C leaf initiation and leaf expansion still progressed although at a slower rate (Hopkinson, 1967). Untimely flowering of some South African tobacco cultivars when exposed to 14/9°C reduced the number of leaves per plant and thus the yield potential (De Kock, 1987).

The purpose of this paper is to determine the yield potential of tobacco under drip irrigation at Rustenburg, and relate plant growth to daily minimum and maximum temperature.

Procedure

Flue cured tobacco cv A4 (bred by this Institute) was grown under drip irrigation at Rustenburg on a Marikana soil series during the 1987/88 to 1990/91 seasons. This soil contains 48.5% clay and, at field capacity, holds 400 m m^{-1} of water. During mid November (Table 1), seedlings were transplanted on to ridges spaced 120 cm apart, with the plants at 40 cm intervals along ridges. A dripper line was positioned on top of each ridge. Emitters with outlet flow rate of 2 L h^{-1} were spaced 80 cm apart. Two irrigation management procedures were compared, viz. daily irrigation where soil water content was maintained close to field capacity, versus irrigation at five day intervals. Immediately before an irrigation was due, the soil water deficit was calculated and soil water replenished in pulses at 12 hour intervals. The drier treatment received 75% of the total amount of water applied to the plots irrigated daily. The treatments were replicated eight times. Rainfall and high- frequency irrigation totalled between 952 mm and 1 245 mm during four seasons of experimentation (Table 1).

To provide optimum growing conditions, high fertilizer levels, as indicated in Table 1, were applied. The mineralisation rate of the red clay soil was high during 1987/88 and therefore only 25 kg N ha^{-1} was applied at planting. Nitrogen application was increased in the ensuing seasons. The tobacco crop was topped at 23 to 24 leaves $plant^{-1}$ after removal of four bottom primer leaves. Sucker growth was controlled chemically. The near optimum growing conditions in this trial provided the opportunity to relate potential growth and yield to climatic conditions.

Soil water content

Soil water content was measured daily with a neutron moisture meter (Hydroprobe 503DR; CPN Corp., California, USA) at 300 mm increments down to 2 100 mm soil depth.

Cumulative degree day (CDD) were obtained after using the triangulation method described by Sevacherian, Stern & Mueller (1977). Daily minimum (Tmin) and maximum (Tmax) air temperature

Table 1 Planting dates, soil analysis and fertilization of tobacco trails under drip irrigation at Rustenburg.

Seasons		1987/88	1988/89	1989/90	1990/90
Planting dates		16 Nov	23 Nov	24 Nov	24 Nov
Soil analysis	content[1]		Applied fertilisers		
Nitrogen kg ha^{-1}	486	12.2	30	45	72
Phosphorus kg ha^{-1}	133	150	142	150	123
Potassium kg ha^{-1}	1 250	120	120	120	120
Calcium kg ha^{-1}	8 150	300	300	300	200
Ca-source		Gypsum	Gypsum	Gypsum	Ca-acetate
Magnesium kg ha^{-1}	7 390				
Clay %	48.5				
pH (water)	6.30				
Rainfall (mm)		609	460	530	460
Irrigation (mm)		636	492	650	550
1st harvest date		22 Feb	15 Feb	26 Jan	21 Dec
Final harvest date		19 Apr	22 Apr	Hail[2]	13 Mch

[1] = Mean over 0 to 600 mm soil depth with bulk density 1.667 g cm^{-3} in November 1987

[2] = Crop was completely destroyed by hail after second priming

measured at the Institute's weather station were used taking 9°C as the lower base temperature and 35°C as the upper threshold. The triangulation method allows one to separate each day's contribution to the CDD into a before Tmax (a.m.) and after Tmax (p.m.) part. A better correlation between leaf growth and cumulative degree days was obtained by using 0.75 times a.m. and 0.25 times the p.m. degree days. CDD after planting served as physiological time.

Leaf number and size

Leaf areas at leaf positions (ie. leaf number) 4, 8, 12, 16, and 20 were measured weekly from the time each leaf began to exceed 212 cm² in size, this being the smallest measurable leaf size. The time taken from planting to reach this 212 cm² threshold, expressed in terms of CDD, was related to leaf number (Li) by means of a quadratic equation of the form;

$$CDD = a + bLi + cLi^2 \quad (1)$$

Leaf length and maximum width were measured and leaf area calculated as length x maximum width x 0.634 (Suggs, Beeman & Splinter, 1960). Leaf number per plant and leaf size were determined weekly on a sample of 10 plants per plot.

It was postulated that leaf expansion (Ad) from the time of the 212 cm² threshold onwards is dependent on degree days accumulated from that time (CDDd), the leaf area (Ab) at that time, and an efficiency coefficient (f) which conceptualises the efficiency with which CDDd is used in leaf growth. It seemed appropriate to weight each part of the day roughly in accordance with expected radiation energy loads, thus making each day's degree day contribution to CDDd equal to the a.m. contribution plus 0.5 of the p.m. contribution. Ad is given by:

$$Ad = Ab \times CDDd \times f \quad (2)$$

Leaf mass

Mature leaves were harvested by reaping two to four leaves at a time and then flue curing them. All pickings from the 87/88 harvest were separately graded and their mass determined. During 1988/89 and 1990/91 the four lugs and top leaves were separated from the bulk cutters and leaves. The change in leaf body Lm, as mass area^{-1}, at harvesting was calculated for each sequential leaf position during 1990/91 on five leaves per trial plot. The relationship between Lm and Li was determined statistically.

With the aid of equations (1) and (2), and measured daily contribution to CDDd, the growth of all leaves per plant was simulated. Total leaf area at harvesting, leaf mass cm^{-2} derived from Li, and the plant population employed (16 667 plants ha^{-1}) were used to estimate yield. The estimated yield was then compared with the harvested flue cured leaf yield to test the accuracy of the simulation.

Results and discussion

Soil water content

The trends in soil water content at depths of 300 and 600 mm in the soil profile for the two irrigation treatments are presented in Figure 1. During the entire season, irrigation at daily intervals resulted in only small deviations from field capacity, while irrigation at five day intervals together with rainfall also resulted in a high soil water content. Due to these high water regimes no significant differences existed between the measured parameters at the two

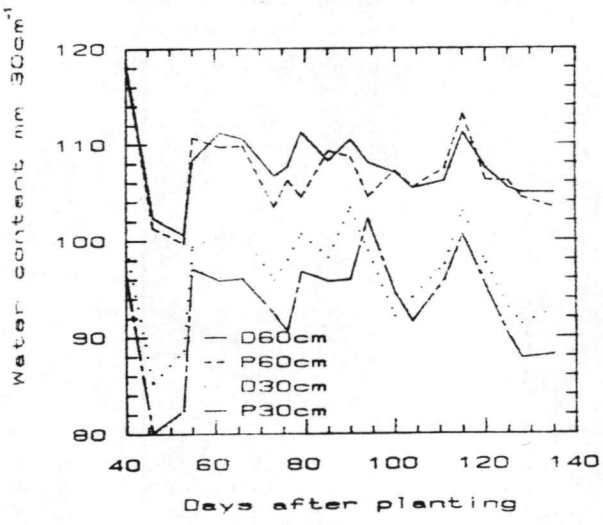


Figure 1 Soil water content in mm per 30 cm soil depth. D30 cm: measured at 0 to 300 mm depth, irrigated daily; D60 cm: measured at 300 to 600 mm depth, irrigated daily; P30 cm : measured at 0 to 300 mm depth, irrigated at pentade intervals; P60 cm: measured at 300 to 600 mm depth, irrigated at pentade intervals.

irrigation managements. Data from all plots were therefore used as replications.

Leaf number

The rate of leaf initiation of tobacco responded linearly to temperature according to Hopkinson (1967) and Haroon *et al.* (1972). This was largely confirmed by the fitting of equation (1) to our data. In the fitted form of the equation, viz.,

$$CDD = 140.57 + 9.42 \times Li + 0.1129 \times Li^2$$
$$(R^2adj. = 0.789;\ SE = 37.9;\ Df = 169)$$

the Li^2 term contributed very little to the interval (in CDD) required for a leaf at any stalk position to reach the minimum measurable size. Also, with 79% of variance explained, CDD, as defined, is a reasonably good predictor of leaf initiation and early expansion.

Leaf growth

The change in the efficiency of the growth response of tobacco leaves in all positions to CDDd during the season is given by equation (3) and illustrated in Figure 2:

$$f = 1.891 * 0.0225 * EXP(-0.0225 * CDDb)$$
$$(R^2adj = 0.829;\ SE = 4.0E\text{-}7;\ Df = 37) \qquad (3)$$

where, in this case, CDDb = cumulative degree days after any leaf has exceed 212 cm^2.

While it may seem logical to have used solar radiation either as an alternative driving force, or in addition to CDD to obtain good predictive capability for leaf growth, the high R^2 values obtained make this unnecessary. Papenfus (1967) also pointed out that low light levels already ensure maximum photosynthetic rate in tobacco and light intensity may contribute as

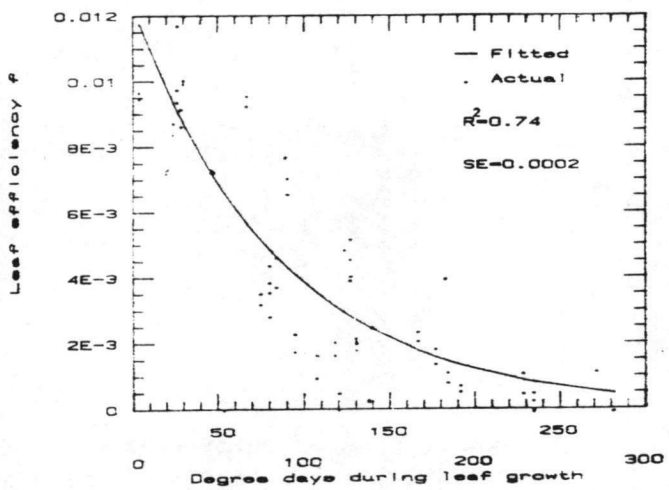


Figure 2 Efficiency (f) of the growth response of tobacco leaves to degree days during the growing season (see Equation 2).

little as 20% to the variation in assimilates.

Leaf mass

Figure 3 illustrates the increase in leaf mass per unit area (Lm) with advancing leaf position from the bottom to the top of the plant. Equation (4) descri this relationship.

$$Lm = 0.005867 + 0.0001661 * Li + 1.068E\text{-}5 * Li^2 \qquad (4)$$
$$(R^2 = 0.95;\ SE = 7E\text{-}4;\ DF = 19).$$

The bottom leaves were usually very thin, of poor quality and therefore removed as primers.

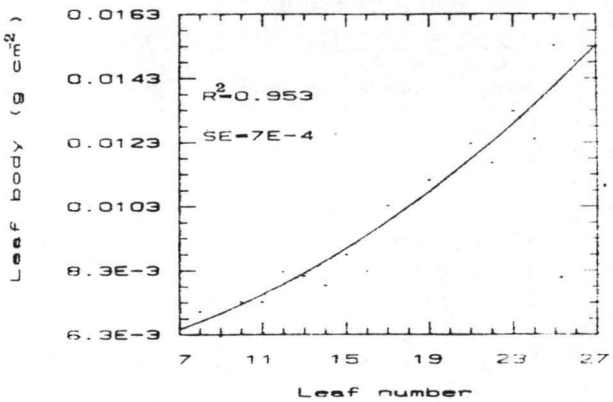


Figure 3 Change in leaf body (g cm^{-2}) from the bottom to top leaf positions.

Cured yield

Total flue cured yield did not differ significantly between the two irrigation frequencies due to the adequacy of irrigation, the good water holding capacity of the soil, and the complete lateral movement of water from the emitters (Barnard, Dippenaar & Venables, 1990). The mean marketable yields from the experiment for the 1987/88, 1988/89 and 1990/91 seasons were 3 790, 4 600 and 4 332 kg ha^{-1} respectively. This is in contrast to a mean yield for flue cured tobacco in the RSA of 1 569 kg ha^{-1} during the 1989/90 season (Anonymous, 1990). The winners of the Cavalla trophy for top production on average produced 2 500 kg ha^{-1} (Anonymous, 1986).

In our research, simulated cumulative leaf yield (kg ha^{-1}) over successive pickings (Ye), correlated well with the actually harvested cured leaf mass (Y) obtained in the 1987/88 and 1988/89 seasons ($R^2adj = 0.918$; $SE = 520.1$; $Df = 17$). Figure 4 illustrates this relationship, which is described by equation (5).

$$Y = 114 + 0.7977 * Ye \qquad (5)$$

A nonlinear regression (equation 6) gave a slightly improved fit ($R^2 = 0.994$; $SE = 156.74$; $Df = 16$):

$$Y = 219.44 + 0.1394 * Ye + 0.000399 * Ye^2 + 1.0E-7\ 1 * Ye^3 \quad (6)$$

The latter can be used to adjust a simulated leaf yield to ensure better correspondence with the anticipated actual yield.

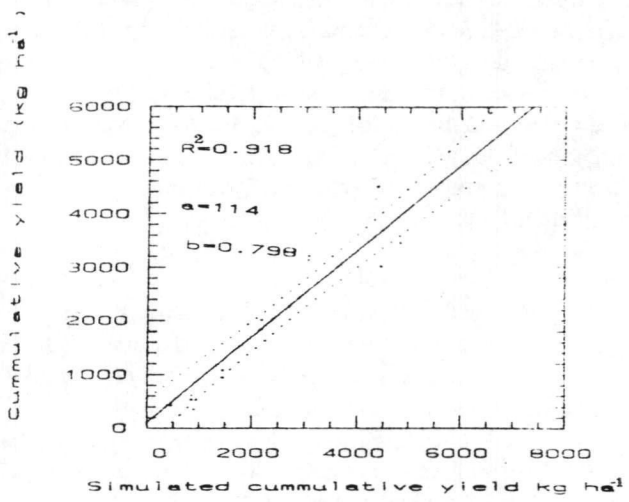


Figure 4 Comparison between simulated cumulated flue-cured tobacco yield, over several pickings, and harvested cumulative yield for two seasons, 1987/88 and 1988/89.

Conclusion

High yields in flue cured tobacco are possible under drip irrigation and good quality can be obtained. Cumulative degree days proved to be a reliable climatic parameter for predicting leaf number and increase in leaf area for the tobacco plant. The estimated leaf yields correlated well with the cured yields obtained in these trials. The proposed regression model should be valid for near optimum growing conditions at Rustenburg and may therefore be used to detect sub-optimal growth rates. The validity of the model would need to be checked at locations which differ from Rustenburg with respect to soil and climatic conditions.

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WATER USE AND YIELD OF IRRIGATED WHEAT

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Abstract

Certain agronomic practices, such as the amount of irrigation water applied, nitrogen fertilization and planting density, can have a considerable effect on grain yield of wheat cultivated under irrigation. The response of wheat, in terms of water use and grain yield, to three levels of irrigation, three rates of nitrogen fertilization (recommended = 150 kg Nha^{-1}, 50% lower and 50% higher than the recommended) and three planting densities (recommended = 100 kg seed ha^{-1}, 50% lower and 50% higher than the recommended) was investigated. Neither rate of nitrogen nor planting density had a significant effect on the quantity of water used during the growing season. Level of irrigation as well as nitrogen fertilization had a significant effect on grain yield, while planting density had no significant effect on yield. The increase in grain yield with a higher than recommended N-fertilization and planting density was negligible and not justified when the higher water use in obtaining this increase is considered.

Introduction

Agronomic practices, such as level of irrigation, fertilization and planting density, plays an important role in the cultivation of any crop under irrigation. The aim is always to obtain maximum grain yield with the minimum quantity of water used during the growing season. The response of crop plants to various combinations of irrigation and fertilizer levels has been the subject of several studies and the response function usually shows a positive interaction of irrigation and fertilizer (Singh & Kumar, 1981). Generally, response of wheat to irrigation is enhanced at higher levels of nitrogen (Shimshi & Kafkafi, 1978). Such response, however, depends upon the water availability at the critical stages of growth. Singh & Kumar (1981) concluded that N-fertilization may raise water consumption by wheat and barley to some extent, although not as much as yield.

The evaluation of the effect of water stress and nitrogen levels on yield is desirable in order to achieve a high water use efficiency (Singh & Kumar, 1981). Increase in water use and water use efficiency of wheat with increasing water availability was observed by Choudhury & Kumar (1980).

The aim of this study was to investigate the response of wheat, in terms of water use and grain yield, to three levels of irrigation, three rates of nitrogen fertilization and three planting densities.

Procedures

Wheat (cv. Gamtoos) was planted on 14 June 1989 at the Rietriver Research Station (29°07S, 24°36E). The soil was classified as a Mangano series of the Hutton form with a depth of 1 800 mm. The clay percentages for the 300, 600, 900, 1 200, 1 500 and 1 800 mm layers are 11.7; 14.7; 16.0; 15.1; 14.1 and 12.7, respectively. The phosphorus and potassium fertilization applied consisted of 50kg P and 25 kg K ha^{-1} respectively. The pH-values (KCl) for the 300, 600 and 900 mm layers were 5.7; 6.1 and 6.2, respectively.

The levels of irrigation (i) consisted of the following:

i0: Profile filled to field water capacity each time the soil water potential reached a value of -30 kPa at 30 cm soil depth. The soil water potential was measured by tensiometers.

i1: Profile filled to field water capacity each time the soil water potential reached a value of -80 kPa at 30 cm soil depth.

i2: Profile filled to field water capacity each time the soil water potential reached a value of -130 kPa at 30 cm soil depth.

The soil water potentials of i1 and i2 were obtained from a soil water retention curve after soil water content had been measured by a neutron soil water meter at 300 mm increments to a depth of 1 800 mm.

The three nitrogen levels (n) consisted of the following:

n0: 50% lower than the recommended level, i.e. 75 kg N ha^{-1}

n1: recommended level for the experimental site, i.e. 150 kg Nha (Anon, 1985).

n2: 50% higher than the recommended level, i.e. 225 kg N ha^{-1}

The three planting densities (d) consisted of the following:

d0: 50% lower than the recommended density, i.e. 50 kg seed ha^{-1}

d1: recommended density for the experimental site, i.e. 100 kg seed ha^{-1} (Anon, 1987)

d2: 50% higher than the recommended density i.e. 150 kg seed ha^{-1}

Analyses of variance were done on the total water applied (rain + irrigation + difference in profile water content at the beginning and end of the season) during the growing season and the grain yield obtained for the different irrigation and nitrogen levels and planting densities. No run-off occurred on the irrigation plots.

A multiplicative regression analysis, with grain yield the dependent and N-fertilization levels the independent variables, was used to predict grain yield for a specific N-fertilization ($Y = aX^{b}$).

Results and discussion

Water use

The quantifiable water use for the three irrigation levels, three nitrogen levels and three planting densities is shown in Table 1. The water use of the different treatments was low for the levels of grain yield obtained (Table 2). This can be ascribed to the existence of a water table, from which the crop obtained an unquantifiable quantity of water.

Table 1 Quantifiable water use (mm) by wheat for three irrigation levels (i), three nitrogen levels (n) and three planting densities (d) over the growing season.

	n0	n1	n2	Mean	
i0	287	346	320	318	
i1	229	235	248	237	LSDT (0.05) i=50.3
i2	206	164	225	198	LSDT (0.05) ixn=NS
Mean	241	248	264	251	
	d0	d1	d2	Mean	
i0	324	298	331	318	
i1	262	241	209	237	LSDT (0.05) ixd=NS
i2	178	191	226	198	
n0	253	219	250	241	
n1	261	261	223	248	LSDT (0.05) n=NS
n2	250	250	293	264	LSDT (0.05) nxd=NS
Mean	255	243	255	251	

LSDT (0.05) d = NS
CV = 24.4%
SE = 61.3

The results in Table 1 show that i0 (wet treatment) used significantly more water during the growing season than i1 (dry treatment) and i2 (stress treatment). Neither nitrogen nor planting density and none of the interactions had a significant effect on water used. Singh & Kumar (1981) found that wheat and barley at a more favourable soil water regime may use more water, resulting in an Et/Ep ratio of ≥ 1.0 during growth stage 2 (active tillering to flag leaf). They also observed that N-fertilization may raise water consumption by wheat and barley to some extent (9% and 8% respectively).

Grain yield

The grain yield for the three irrigation levels, three nitrogen levels and three planting densities are shown in Table 2.

From Table 2 it can be seen that i0 (wet treatment) gave a significantly higher grain yield than i2 (stress treatment) and n2 (225 kg N ha^{-1}) as well as n1 (150 kg N ha^{-1}) resulted in a significant higher grain yield than n0 (75 kg N ha^{-1}). Planting density had no significant effect on grain yield. Singh & Kumar (1981) also found an increase in grain yield with higher irrigation levels. In general they observed that N-fertilization may increase grain yield of wheat and barley considerably (90% and 100% respectively).

Table 2 Grain yield (kg ha^{-1}) of wheat for three irrigation levels (i), three nitrogen levels (n) and three planting densities (d).

	n0	n1	n2	Mean	
i0	5 057	6 625	6 494	6 058	
i1	4 427	6 293	6 303	5 674	LSDT (0.05) i=454.5
i2	4 903	5 508	6 060	5 490	LSDT (0.05) ixn=NS
Mean	4 795	6 142	6 286	5 741	
	d0	d1	d2	Mean	
i0	5 821	6 098	6 257	6 058	
i1	5 563	5 745	5 714	5 674	LSDT (0.05) ixd=NS
i2	5 053	5 602	5 817	5 490	
n0	4 711	4 915	4 761	4 795	
n1	5 715	6 163	6 548	6 142	LSDT (0.05) n=454.5
n2	6 011	6 367	6 480	6 286	LSDT (0.05) nxd=NS
Mean	5 479	5 815	5 929	5 741	

LSDT (0.05) d=NS
CV = 9.6%
SE = 553.1

The percentage less or more water used (quantifiable) and lower or higher grain yield than for n1 (recommended), at the other nitrogen levels, are shown in Figure 1. Figure 1 shows that the lowest level of N-fertilization (n0) used less water (3.%) than n1 (recommended), but the grain yield obtained from n0 was much lower (21.9%) than that of n1. The lowest level of nitrogen (75 kg ha^{-1}) was responsible for the much lower grain yield compared to the recommended level of nitrogen (150 kg ha^{-1}). The highest level of N-fertilization (n2) used 6.4 percent more water than n1, but the grain yield obtained was only 2.3 percent higher than that of the recommended (n1). This increase in grain yield with a higher than recommended N-fertilization level was negligible when the higher water use to obtain this increase is considered. A higher N-fertilization than 150 kg ha^{-1} will not be recommended in the vicinity of the experimental site for wheat under irrigation.

The percentage more water used (quantifiable) and lower or higher grain yield than for d1 (recommended), at the other planting densities, are shown in Figure 2. The lowest planting density (d0) used 4.7 percent more water than d1 (recommended), but the grain yield obtained was 5.8 percent lower than that of d1. The higher water use by d0 was not expected

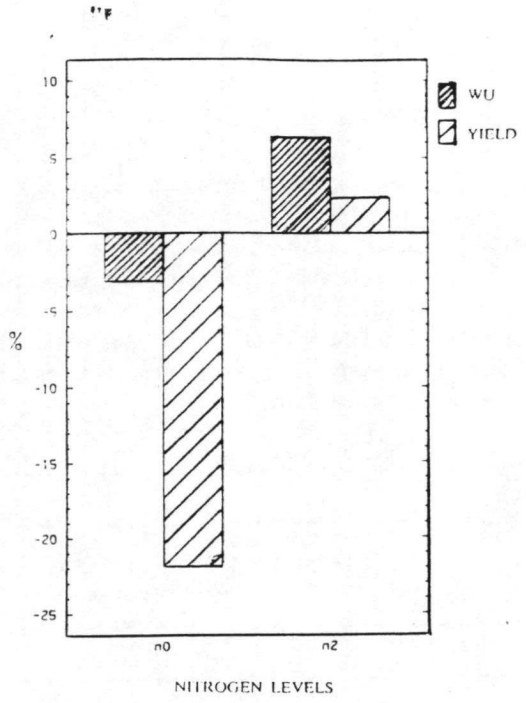


Figure 1 Percentage less or more quantifiable water used (mm) and lower or higher grain yield than for n1 (recommended) at other N levels for wheat as averaged over 3 irrigation levels and 3 planting densities.

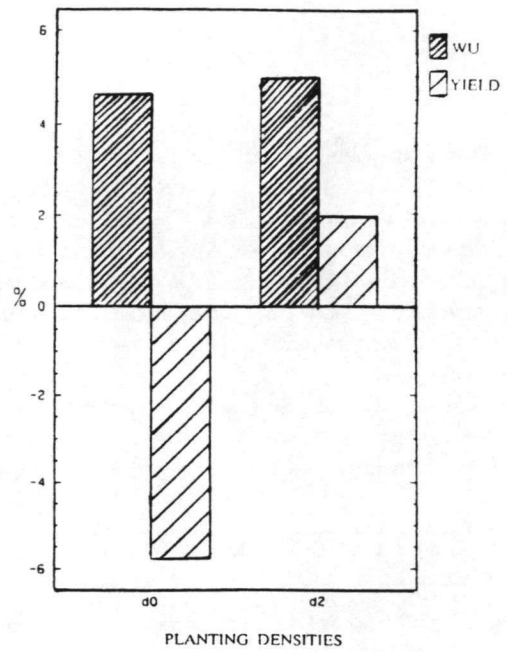


Figure 2 Percentage more quantifiable water used (mm) and lower or higher grain yield than for d1 (recommended, at other planting densities for wheat as averaged over 3 irrigation - and 3 nitrogen levels.

and cannot be explained. A lower grain yield by d0, compared to that of the recommended (d1), was expected. The highest planting density (d2) used 5.0 percent more water than d1, but the grain yield was only 1.9 percent higher than that of the recommended density (d1). This increase in grain yield with a higher than recommended planting density was negligible when the higher water use to obtain this increase is considered. A higher planting density than 100 kg seed ha^{-1} will not be recommended in the vicinity of the experimental site for wheat under irrigation.

The influence of N-fertilization (kg N ha^{-1}) at three irrigation levels and three planting densities on the grain yield of wheat are shown in Figure 3. The multiplicative regression equation, for the prediction of grain yield, for levels of N-fertilization is Y = 1 566.7 X^0.2615, where Y = grain yield in kg ha^{-1} and X = N-fertilization (kg N ha^{-1}). Only 50.3 percent of the variation in grain yield can be attributed to N-fertilization. Some other factors, probably water use among others, should be responsible for the rest of the variation in grain yield. The regression line is non-linear, which indicates that the increase in grain yield per unit nitrogen applied will be higher at low nitrogen applications. This is also shown in Table 2 where the difference in grain yield between n0 (75 kg N ha^{-1}) and n1 (150 kg N ha^{-1}) is 1 347 kg ha^{-1} while the difference between n1 and n2 (225 kg N ha^{-1}) is only 144 kg ha^{-1}. This is an increase of only 2.3 percent in grain yield from n1 to n2 as shown in Figure 1.

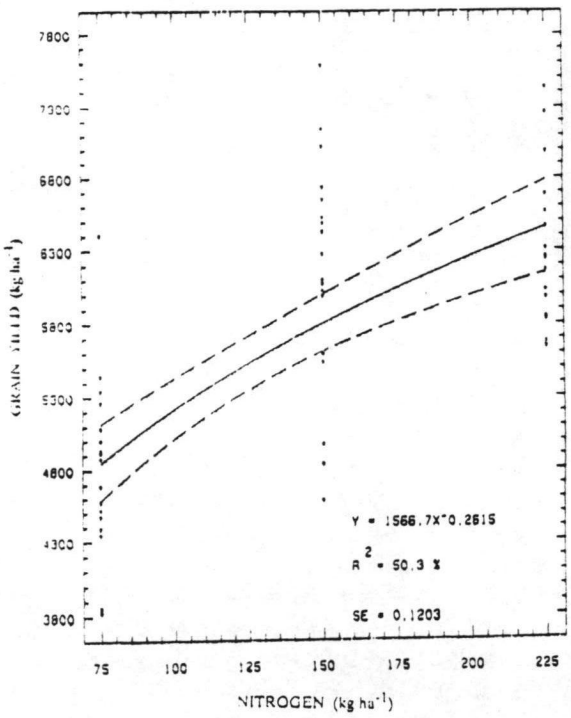


Figure 3 The influence of N-fertilization, at 3 irrigation levels and 3 planting densities, on grain yield of wheat.

Conclusions

Neither N-fertilization nor planting density had a significant effect on the quantity of quantifiable water used by wheat during the growing season. Grain y[illegible] was significantly affected by N-fertilization while

planting density had no significant effect. The increase in grain yield (2.3%) with a higher than recommended N-fertilization as well as higher than recommended planting density (1.9%) was negligible especially when the higher water use (6.4% and 5.0% respectively) to obtain this increase is considered. A higher N-fertilization and planting density than 150 kg N ha^{-1} and 100 kg seed ha^{-1} will not be recommended for wheat under irrigation in the vicinity of the experimental site. A non-linear regression curve for the prediction of grain yield response to N-fertilization, also indicates that the increase in grain yield per unit nitrogen will be lower at high than at low nitrogen applications.

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MEASURED AND SIMULATED PLANT STRESS CRITERIA FOR THE IRRIGATION OF SUGARCANE

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Abstract

Approximately 14% of the 380 000 ha of sugarcane grown in South Africa is irrigated. Irrigation designs and schedules are presently based on applying water when a simple water budget indicates a 50% soil water deficit. A more effic t means of scheduling irrigation was investigated by comparing stress factors for photosynthesis ($SWDF_1$) and for cell extension ($SWDF_2$) produced by a growth model, with plant extension rate (PER) and leaf conductance (g_l) determined in a rain shelter experiment near Mount Edgecombe, Natal. The water balance routine (taken from the CERES-Maize model) simulated realistically the water extraction patterns that were observed. The terms $SWDF_1$ and $SWDF_2$ corresponded with the observed onset of water stress but they failed to simulate the marked difference in the response of PER and g_l to subsequent stress. The model overestimated the effect of stress on g_l and consequently on sucrose yield particularly in the plant crop. However, $SWDF_2$ constituted a physically based criterion for applying irrigation when a loss in yield was imminent. Irrigation simulations using $SWDF_2$ and the 50% deficit criterion, demonstrated the possibility of saving irrigation water without sacrificing yield.

Introduction

Approximately 14% of the 380 000 ha of sugarcane grown in South Africa is irrigated. Most of the irrigation occurs north of the 28° parallel where rainfall is too low to support a viable crop. In the south, irrigation is applied in some of the dry river valleys and the viability of supplementary irrigation is often considered by growers in areas where rainfall is sufficient to support crops in most years. Irrigation designs and schedules are presently based on a simple water budget. Root zone soil water at potentials greater than -0.1 MPa, is regarded as freely available and irrigation is applied when this water has been depleted. The depletion level is usually simplified to 50% of the estimated total plant available water in the root zone. Potential evapotranspiration (E_o) of a crop with a complete canopy is equated to Class A pan evaporation (E_{pan}) and during the period of incomplete canopy, E_o is based on ratios E_o to E_{pan} which were determined in lysimeter experiments (Thompson, 1976).

The frequent occurrence of water stress in the south has led to the production of drought resistant varieties and to a limited amount of research on drought resistance mechanisms and stress criteria. Drought resistance in South African sugarcane varieties is achieved most successfully by avoidance rather than tolerance to stress although both mechanisms have been found to occur (Inman-Bamber, 1986). Osmotic potential at full turgor fell from -0.93 MPa in well watered plants to -1.45 MPa in severely stressed plants (Inman-Bamber & De Jager, 1986a). Comparable values are reported for Mauritian varieties (-1.0 to -1.6 MPa) by Roberts, Nayamuth, Batchelor & Soopramanien (1990) and for Hawaiian varieties (-1.05 to -1.55 MPa) by Koehler, Moore, Jones, Dela Cruz & Maretzki (1982). In one South African variety (N11), drought avoidance was conferred by a rapid reduction in green leaf area (Inman-Bamber & De Jager, 1986a) but the most resistant commercial variety (N12) avoided low leaf turgor by closing stomata at a relatively high leaf water potential (LWP = -1.2 MPa). Conversely a drought susceptible variety (N14) delayed stomatal closure until LWP decreased to 1.7 MPa. Plant extension rate (PER) in all varieties tested, was reduced when LWP decreased to less than -0.2 MPa and extension ceased when LWP deceased to -1.0 MPa (Inman-Bamber & De Jager, 1986b). In Hawaiian varieties stalk elongation declined rapidly when LWP fell below -0.5 MPa and it ceased w LWP declined to -1.3 MPa (Koehler *et al.*, 1982).

It is conceivable that the two stress criteria, PER and stomatal conductance (g_l), could be used to manage irrigation in such a way that stalk mass and sucrose con t are optimized. Plant extension could be allowed to proceed without water stress until a certain stalk size has been attained and then PER could be reduced without materially affecting $C0_2$ assimilation. The practice of withholding irrigation water during the maturation phase has been widely practised by growers without the knowledge of these stress criteria.

The CERES-Maize water balance routine (Jc & Kiniry, 1986) produces two soil water stress factors (SWDF) which may be useful in predicting PER and g_l since these are not likely to be measured by farmers. This routine has been linked to a carbon balance in a growth model called CANESIM which is being developed at the Experiment Station (Inman-Bamber, 1991). In this paper the SWDF indices are compared with PER, g_l and water use measurements in order to validate the model and to develop a more physically based method of scheduling irrigation than the method presently in use.

Materials and methods.

Details of the model which have been published elsewhere (Inman-Bamber 1991) may be summarized briefly as follows:

Rate of dry matter (DM) increment =

$dW/dt = (P_g - R_m.W).(1-R_{gr})$

where:

W = total dry mass of crop with roots (t ha^{-1})

dt = time interval (one day)
Pg = gross photosynthesis = 0.082 PAR.L_i.$SWDF_1$
PAR = photosynthetically active radiation
= 0.5 x solar daily radiant density (MJ m^{-2})
L_i = radiation interception = $1-e^{(-k.LAI)}$
k = extinction coefficient = 0.58 to 0.86
LAI = leaf area index
R_{gr} = growth respiration = 0.242 (g g^{-1})
Rm = maintenance respiration = 0.003 (g g^{-1})
The soil water stress factor for photosynthesis ($SWDF_1$ = O to 1) determined in the water balance routine, is the ratio of actual to potential transpiration (E_p/E_{op}).

Leaf area index is determined by predicting leaf tip appearance, leaf extension rate, final area of successive leaves, leaf senescence and tillering patterns. The soil water stress factor for cell expansion ($SWDF_2$) is used to restrict tillering, leaf appearance and extension during dry periods.

$$SWDF_2 = O.67 \cdot E_p/E_{op}$$

Predictions made by the model were compared with measurements made at midday on a plant and first ratoon crop of an experiment near Mount Edgecombe (29° 42' S, 31° 2' E) on a deep loamy sand (Hutton form, Clansthal series). The experiment consisted of three varieties, two irrigation regimes and four replications. A rain shelter (24.0 x 8.5 m) moved automatically over half the number of small plots (4.2 x 3.7 m) when it rained and moved away 30 minutes after rain ceased. The crop was planted on 31 August 1983 and plots in the sheltered area were denied rain and irrigation from 31 January 1984 to 5 July 1984 when harvesting was done. In the ratoon crop, irrigation in the sheltered area was controlled to keep soil deeper than 1.5 m in a dry state and water was withheld from 1 December 1984 to 22 January 1985 and from 1 March 1980 to 22 April 1980. Plots just outside the sheltered area were irrigated each week when necessary to avoid stress. Soil water content was monitored with a neutron probe (CPN, Ca. USA) which was calibrated for use near the soil surface (150 mm) and independently for use at greater depths (Inman-Bamber, 1986). Crop water stress was monitored with measurements of leaf water potential using a home made Scholander chamber, leaf resistance (Delta T Mk3 porometer, Cambridge, UK), and plant extension rate (PER). Crop growth was measured periodically by recording stalk dimensions and by taking samples to determine the dry matter and sucrose content of stalks.

Irrigation simulations were conducted with CANESIM using either the conventional 50% soil water depletion level or the $SWDF_2$ stress factor to signal an application of 60 mm irrigation. The water balance of the model was used for both irrigation criteria although a simple water budget is normally used to govern conventional irrigation scheduling. A minimum of 14 days between irrigations was allowed for the conventional schedule and 7 days for the schedule governed by the model's stress factor. The input files were constructed from measured physical properties of a deep structured clay (Shortlands form, Table 1) and the daily weather record from the Mount Edgecombe meteorological station. The root distribution coefficient (WR) for each layer (i) was derived as follows:

$$WR_i = e^{(-4Di/200)}$$

where Di is the depth of the centre of layer i (Jones & Kiniry, 1986).

Simulated crops started on 1 September each y from 1980 to 1990 and were allowed to develop for 365 days.

Results and discussion

Plant crop

During the first and third months (February and April) of the protracted stress which was applied to the p t crop, simulated and measured root water extraction patterns were similar (Figure 1). Measured water extractions during March and May were considerably less than the amounts predicted by the model's soil water balance. This may not reflect badly on the soil water balance model because of the difficulty in measuring small changes in water content in a deep soil with the neutron probe. Although mean water content was based on measurements from 24 access tubes and the average standard error was only 2% of the mean, the changes in water content per layer in this deep profile were often of the same order as the standard error.

The observed and simulated results both indicated that a considerable amount of water was extracted from depths close to 3 m. This water seemingly prevented LWP and g_l decreasing to extreme levels and resulted in only a small reduction in sucrose yield (10.7 and 11.8 t ha^{-1} for stressed and irrigated plots, respectively).

The soil water balance model indicated stress as a reduction in $SWDF_1$ at approximately the same time that g_l of stressed plants deviated from that of unstressed plants but $SWDF_1$ approached zero when g_l of stressed plants was only half that of irrigated plants (Figure 2). The 80 to 90% reduction in photosynthesis conveyed by $SWDF_1$ at this stage was too severe. CANESIM consequently underestimated the sucrose yield of the stressed crop by a considerable amount. A yield of 57 t ha^{-1} was predicted by the model compared to 10.7 t ha^{-1} measured in stressed plots. The irrigated crop was accurately simulated by CANESIM which predicted a yield of 11.7 t ha^{-1} compared to a measured yield of 11.8 t ha^{-1}.

Ratoon crop

In the ratoon crop, the good agreement betv observed and simulated soil water content in the sheltered area, indicated that the model's water balance

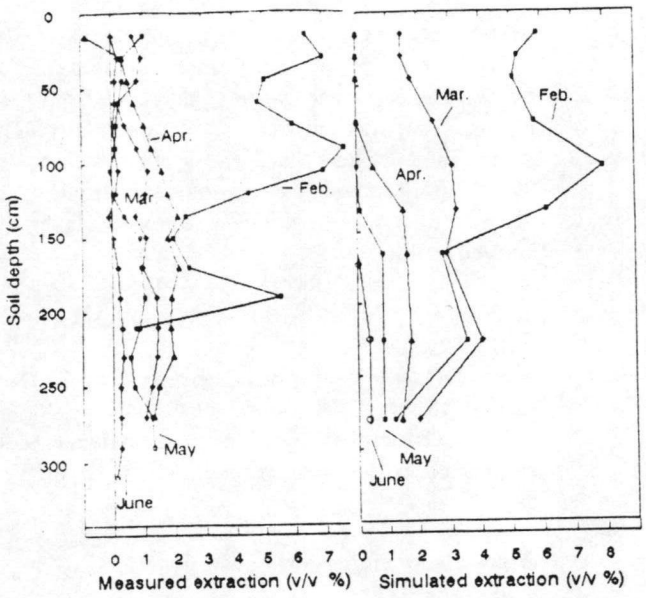


Figure 1 Simulated and measured water extraction during successive months after precipitation and irrigation water was denied to the plant crop for 1983/1984

was realistic (Figure 3). In both stress periods, PER declined rapidly when $SWDF_1$ decreased at the onset of stress and reached zero shortly before or after $SWDF_1$ became zero (Figure 4).

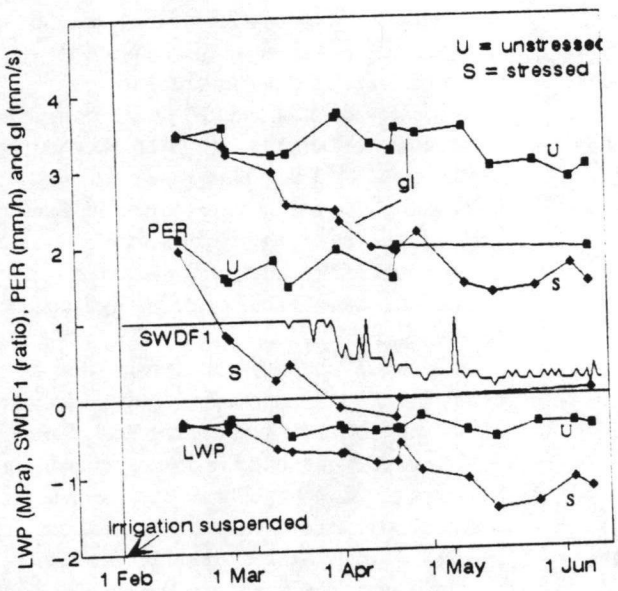


Figure 2 Simulated and measured stress indices during the plant crop

Leaf conductance (g_l) decreased rapidly to about 1 mm s^{-1} and then more gradually to about 0.3 m s^{-1}. A decline in g_l with crop age has been observed in sugarcane (Meinzer & Grantz, 1987) and this may account for the reduction in g_l of the irrigated crop in Figure 4.

Diurnal g_l measurements on 1 and 2 April showed that

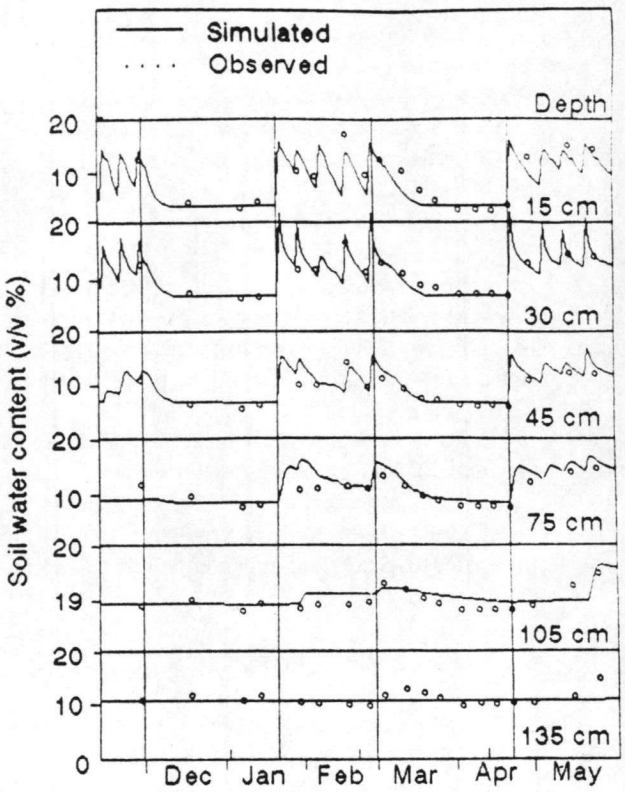


Figure 3 Simulated and measured soil water content of the soil profile under the rain shelter during the ratoon crop

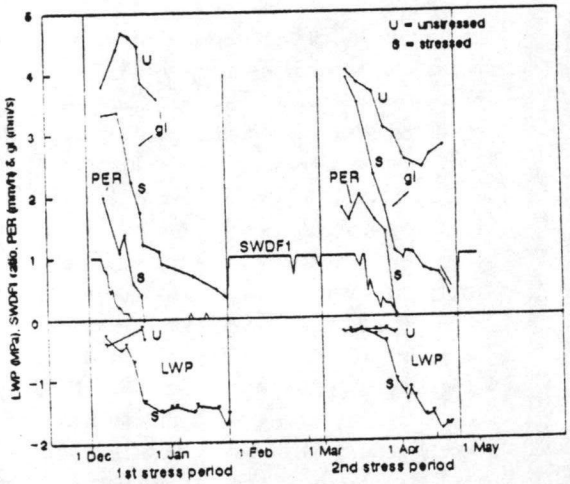


Figure 4 Simulated and measured stress indices of the ratoon crop

g_l returned to 2.5 mm s^{-1} at about 8h00 after being as low as 0.5 mm s^{-1} at 13h00 the previous day (In - Bamber & De Jager, 1986b). No recovery in PER was detected during this period. It is thus evident that some CO_2 assimilation occurred when LWP was approaching -2.0 MPa.

The degree of stress imposed in the ratoon crop was

much more severe than that imposed on the plant crop and yields were reduced substantially (Figure 5). Fresh cane growth stopped during the second stress period as would be expected from PER measurements but dry cane mass and sucrose yield continued to accumulate. The model overestimated the accumulation of stalk DM and sucrose when $SWDF_1$ =1 and it failed to simulate the observed growth after $SWDF_1$ reached zero.

By definition $SWDF_1$ should equal the ratio of transpiration by the stressed crop (E_p) to transpiration by the irrigated crop (E_{op}), provided the leaf area indices (LAI) of both crops were similar. During the stress periods, LAI of the stressed crop varied between 0.8 and 2.3 and LAI of the irrigated crop exceeded 2.5, and $SWDF_1$ should therefore have been greater than E_p/E_{op}. The soil component of the water use data that provided an approximation of Ep/Eop, was probably small because of the complete canopy of the irrigated crop and the dry soil surface of the stressed plots. Contrary to expectations, the water use ratio for stressed and unstressed crops was considerably greater than $SWDF_1$ during the periods of stress (Figure 6). This departure from reality corresponded with the difference between simulated and observed growth in Figure 5.

Although $SWDF_1$ was supposed to correspond with changes in g_l and $SWDF_2$ with changes in PER, the two water deficit factors differed little as stress indices. The rationale for $SWDF_1$ is broadly correct but some of the assumptions about the root system may not apply directly to sugarcane. Despite these errors $SWDF_2$ may be regarded as a conservative stress criterion for the

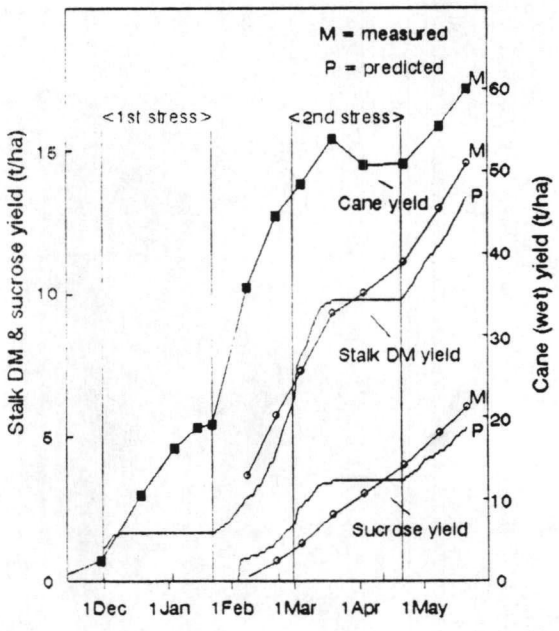


Figure 5 Measured growth of cane yield (wet mass) and simulated and measured growth of stalk DM and sucrose yields of stressed sugarcane during the ratoon crop

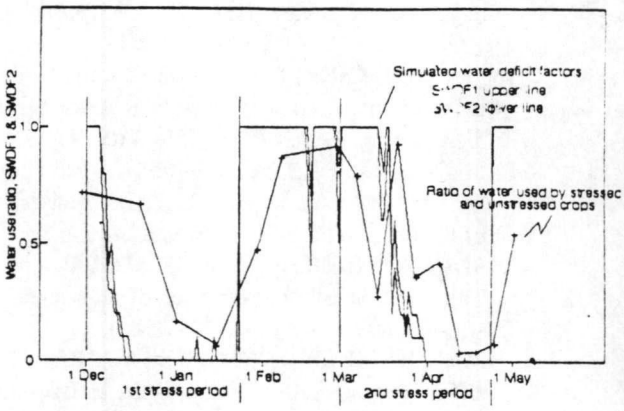


Figure 6 Simulated stress indices and the ratio of water used by stressed and unstressed ratoon crops

application of irrigation. The foregoing evidence indicates that sucrose yield would not be reduced if water was applied when $SWDF_2$ started to decline.

Irrigation simulation.

The simulations indicated that an irrigation schedule based on a conventional depletion criterion on a Shortlands clay on the north coast would result in a mean sugar yield of 16.4 t/ha. This is 0.5 t ha more than the mean yield predicted for a crop which was irrigated only when water stress was imminent according to the assumptions in the CANESIM model. The annual application of irrigation was 492 mm for the conventional schedule and 378 mm for the schedule regulated by $SWDF_2$.

Rainfall efficiency was improved from 72 to 82% by the use of the physiologically based stress criteria. Ellis & Lankford (1990) saved 140 mm irrigation without sacrificing sucrose yield by withholding irrigation water during tillering and ripening phases. Sucrose yield was reduced from 14.6 to only 14.1 t ha by withholding 250 mm irrigation during winter in an experiment by Inman-Bamber (1982).

Conclusions

The observations supported assumptions in the model regarding soil water extraction and flow. The assumptions of the carbon balance were also suppo
The soil water deficit factors did not distinguish adequately between stresses sensed by the cell exte n and gas exchange processes. While $SWDF_2$ may respond too abruptly to truly represent stress affecting suc accumulation, it is a useful criterion for irrigation scheduling and it represents a substantial advancement on the previous method for determining when to irri e.

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PRELIMINARY RESULTS ON THE RESPONSE OF APPLE TREES TO SOIL WATER REGIME

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Abstract

The effects of seasonal variation in soil water regime on the growth, yield and plant physiological response of apple trees were investigated in a field trial on the Elgin Experiment Farm. Water stress imposed during a particular phenological development phase affected the response of the tree during subsequent phases. Irrespective of soil water regime during phase 3, tree growth tended to be lower with a 60% or 40% regime in phase 2. Furthermore, with an 80% soil water regime during phase 1, both wet (80%) and dry (40%) regimes during phase 2 resulted in decreased yield. The decreased yield due to the wet soil water regime could possibly be ascribed to competition from increased vegetative growth. The rate of fruit growth during phase 3 could be decreased by either the direct effect of water stress or indirectly when water stress during previous phases resulted in decreased vegetative growth. However, weather conditions during this season were exceptionally mild and the degree of water stress imposed is expected to be less than would be normally the case. Furthermore, trees in the full bearing phase will have to be studied before final recommendations can be made.

Introduction

Commercial production of apples in the South Western Cape with its hot and rain-free summers is only possible under irrigation. The South African apple industry is largely dependent on the export market where fruit quality is of vital importance. Furthermore, soils in the major apple production areas are either coarse textured or gravelly and shallow which places great demands on irrigation management. The average production of apples in South Africa can be estimated at 28 t ha^{-1}, but experimental and some commercial orchards often reach production levels of 100 t ha^{-1}. Although factors such as soil preparation, quality of plant material, plant and training system, fertilization and management all contribute towards this low production, it is well known that irrigation scheduling is poorly understood and practised by apple producers.

A considerable amount of research has been conducted world wide on the effect of irrigation on growth, yield and fruit quality of apple trees. However, in most of these studies a high soil water regime was compared with either no or limited irrigation under humid summer rainfall conditions and the results obtained have limited usefulness under local conditions. Few studies of the response of apple trees to soil water regimes have been carried out under semi-arid conditions. Assaf, Bravdo & Levin (1974), Guelfat' Reich *et el.* (1974) and Assaf, Leven & Bravdo (1975) in Israel compared wet, dry and combined irrigation regimes. Beukes & Weber (1982) in South Africa studied the effect of soil water regime during different phenological growth phases on the response of apple trees. The soil water regime under study was imposed during a particular growth phase with optimum soil water conditions being maintained during the rest of the growing season. Although these studies yielded useful guidelines regarding the response of apple trees to soil water regime, it should be borne in mind that the phenological development of deciduous fruit trees is a continuous process and that conditions during one developmental phase can affect the response of the tree and/or fruit during subsequent phases (Fereres & Goldhamer, 1990). Furthermore, in both the studies by Assaf *et al.* (1974) and Beukes & Weber (1982), fruit thinning was not carried out with the result that treatments which resulted in heavy fruit set also resulted in small and therefore unmarketable fruit. Average fruit masses reported by Assaf *et al.* (1974) ranged from 80 to 110 g $fruit^{-1}$. Such small fruit would be unacceptable in South Africa because they could not be exported. In the present study, factorial combinations of soil water regimes were applied during different phenological stages of development and fruit were thinned in order to ensure optimum production levels in different treatment combinations. The objective was to evaluate the effect of seasonal water supply on the performance of apple trees.

Material and methods

An apple orchard with Golden Delicious trees on Merton 793 rootstock was established in 1985 on the Elgin Experiment Farm. Experimental plots consisted of four trees separated by Granny Smith guard trees as pollinators and trees were spaced 4.5 m x 2.5 m. The soil used contains 65% gravel with 21% clay and 23% silt in the <2 mm fraction. Soil water characterization was carried out on disturbed samples in the laboratory by pressure extraction between 10 and 1 500 kPa. The total available water holding capacity of the soil, corrected for stone content, was 63.8 mm m^{-1}. For the first four years after planting no differential treatments were applied. Treatments consisted of a factorial combination of three soil water regimes (viz. 80%, 60% and 40%, i.e. the residual available soil water percentage in the 0-600 mm soil layer at which

irrigation was applied to replenish soil water to field capacity) during four phenological phases:

1. cell division (the first 50 days after full bloom);
2. cell enlargement and vegetative growth (a period of approximately 60 days following the previous phase until four weeks before harvest);
3. ripening;
4. post harvest.

During phases 1 and 4 only the 80% and 60% regimes were applied. In four additional treatments, a 20% soil water regime was applied in each of the growth phases followed or preceded by a 60% regime in the remaining phases. The experiment was laid out as a randomised block design with three replicates. Irrigation was applied by microjet and each treatment combination was irrigated separately. Soil water content was monitored by neutron probe and tensiometers. Standard liming and fertilization programmes were applied and soil fertility levels were monitored by analyses of soil samples every second year and leaf samples annually.

Fruit was thinned to one cluster after normal fruit drop had taken place and before 40 days after full bloom. The effect of treatments on the plant physiological response of the tree was observed during the different phenological stages and after transition from one stage to the next. Photosynthesis, transpiration and stomatal behaviour was measured with an ADC Model LCA-3 Photosynthesis/Transpiration meter and leaf water potential with an Arimad Pressure Chamber. Osmotic potential of the cell sap was determined after freezing in liquid nitrogen with a Wescor Model 5 500 Vapour Pressure Osmometer on the same leaf used for determining leaf water potential. Diurnal trends were obtained from measurements made from 04:00 to 16:00 on the same tree. Fruit growth was monitored by measuring the diameter of labelled fruit at weekly intervals with a Cranston Gauge. Fruit was harvested at optimum maturity and total mass and number were recorded per tree. Fruit samples were stored in the regular atmosphere for 3 months at -0.5°C before evaluation of fruit quality and mineral composition. Susceptibility of fruit to bruising was evaluated at harvest by dropping a 28 mm diameter metal cylinder with a mass of 15 g from a height of 150 and 300 mm on the cheeks of the apple. The diameter and depth of the bruise was measured after keeping the fruit for 7 days at 20°C. Results reported were obtained during the second season of differentialtreatment and were subjected to analyses of variance (Snedecor & Cochran, 1980).

Results and discussion

Soil water characteristics and irrigation

A typical soil water characteristic curve and matric potentials associated with soil water regimes applied are shown in Figure 1. Soil matric potential at which irrigation was applied ranged from -26 kPa to -375 kPa

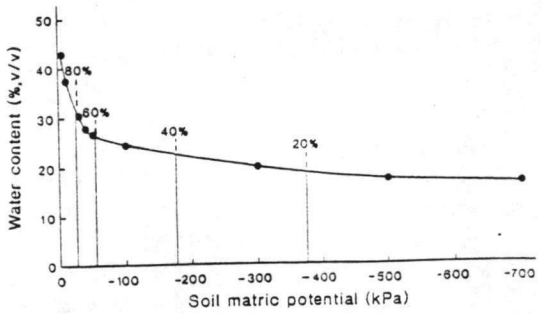


Figure 1 Soil water characteristic curve indicating matric potentials associated with different soil water regimes.

for the different treatments. Precipitation, Class-A evaporation and mean irrigation cycle length during the 1990/91 season are summarized in Table 1. Considerable precipitation was recorded during growth phases 1 and 2, but intensities greater than 10 mm d^{-1} were only recorded during two days and one day, respectively, and probably did not have a great effect on irrigation treatments. The irrigation treatments imposed during the different phenological growth stages resulted in large differences in irrigation cycle length and rain had little effect during phase 3 (1990/91) (Table 1). However, atmospheric evaporative demand, as indicated by pan evaporation, was 10% to 20% lower during growth phases 2 and 3 of

Table 1 Precipitation, class A pan evoration and irrigation cycle length during the 1990/91 season.

Growth phase	Duration (d)	Precipitation (d)	Precipitation (mm)	Ep[z] (mmd^{-1}) (1990/91)	Ep[z] (mmd^{-1}) Long term	Mean irrigation cycle length (d) 80%	60%	40%	20%
4	32	4	7	4.2	4.1	4.6	9.0	21.5	36.0
1	43	10	76	5.6	5.4	3.6	8.7	15.8	31.9
2	58	10	38	6.0	6.7	2.8	6.2	11.1	18.6
3	27	4	9	4.5	5.8	3.6	7.8	14.1	23.5

2 Class-A Pan evaporation

this season compared with long term averages. Therefore, levels of water stress to which these treeswere subjected were probably lower than would be the case during a normal season. Furthermore, the maximum yields obtained were only 15.5 ha^{-1}, whereas the yield potential of thisorchard at full bearing would probably be in excess of 70 ton ha^{-1}. The present results must therefore be regarded as preliminary.

Growth

Tree growth as indicated by annual increase in trunk circumference was significantly affected by soil water regime during growth phases 1 and 2 as well as the interaction between soil water regimes during phases 1 and 3 and phases 2 and 3. With an 80% (wet) soil water regime during phase 1, the soil water regime during phase 3 had no significant effect on tree growth (Table 2). On the other hand, with a 60% (medium) regime during phase 1, tree growth was significantly decreased if a 40% (dry) regime was imposed during phase 3. The interaction between growth phases 2 and 3 (Table 3) indicated that best growth was obtained with an 80% regime in phase 2 and either an 80% or a 60% regime in phase 3. Irrespective of soil water regime during phase 3, tree growth tended to be lower, often significantly so, with a 60% or 40% regime in phase 2.

Table 2 Effect of soil water regime during the cell division (1) and ripening (3) phases of growth on the annual increase in trunk circumference (mm) of Golden Delicious apple trees.

Phase 1	Phase 3		
	80%	60%	40%
80%	36	36	37
60%	32	33	26

LSD (P=0.05) Phase 1 x Phase 3 : 4

It is known that both shoot extension growth and trunk thickening of apple trees are very sensitive to water deficit (Landsberg & Jones, 1981; Lötter, Beukes & Weber, 1985; Fereres & Goldhamer, 1990) and shoot extension is probably the first process to be affected by water stress (Uriu & Magness, 1967). The cumulative effect of water stress on vegetative growth in deciduous fruit trees is a reduction is tree size and therefore yield potential. However, in full bearing trees vegetative growth in only needed in order to maintain and renew reproductive bearing wood and excessive growth which results in large leaf to fruit ratios can be detrimental to fruit quality (Van

Table 3 Effect of soil water regime during the cell enlargement (2) and ripening (3) phases of growth on the annual increase in trunk circumference (mm) of Golden Delicious apple trees.

Phase 2	Phase 3		
	80%	60%	40%
80%	38	38	31
60%	30	32	34
40%	33	33	29

LSD (P=0.05) Phase 2 x Phase 3 : 5

Schreven, 1961). The present results indicate that although the greatest part of the annual vegetative growth takes place during phase 2, the increase in trunk circumference was greatly affected by soil water regime during phase 1 and to a lesser extent during phase 3.

Yield and fruit size

With an 80% soil water regime during phase 1, significantly higher yields were obtained when a 60% regime was imposed during phase 2, irrespective of the soil water regime during phase 3 (Table 4), whereas both the 80% and 40% regimes during phase 2 resulted in significantly decreased yield. However, when a 60% soil water regime was imposed during phase 1, the regime during phases 2 and 3 had little effect on yield. Apart from the effect of soil water regime on tree size discussed previously, a number of other yield determining processes can be affected by water stress (Fereres & Goldhamer, 1990). Flower bud initiation and development in deciduous fruit trees during summer and autumn can be prevented by severe water stress, but are either not affected (Landsberg & Jones, 1981) or enhanced (Chalmers, Mitchell & Jerie, 1985) by moderate stress. Fruit set on apple trees is increased as tree water supply improves (Landsberg & Jones, 1981), but severe water stress can result in fruit drop (Uriu & Magness, 1967). However, it must be borne in mind that severe water stress is unlikely to develop in apple orchards in the western Cape during autumn and spring due to rain and low atmospheric evaporative demand. From previous studies the decreased yields under an 80% soil water regime during both phases 1 and 2 (Table 4) were not expected, but competition from increased vegetative aerial growth may offer an explanation. Since a large portion of the annual root growth takes place during this phase, it could be due to changes in ratios of plant growth substances because of a smaller root system under a wet irrigation treatment (Assaf *et al.*, 1974; Levin, Assaf & Bravdo, 1980). However,

Table 4 Effect of soil water regime during the cell division (1), cell enlargement (2) and ripening (3) phases of growth on yield (kg tree^{-1}) of Golden Delicious apple trees.

Phase 1	Phase 2	Phase 3		
		80%	60%	40%
80%	80%	10.3	9.8	12.8
	60%	17.4	16.8	16.8
	40%	10.3	12.6	12.8
60%	80%	12.7	14.9	15.6
	60%	16.7	14.8	15.6
	40%	15.0	14.6	13.6

LSD (P=0.05) Phase 1 x 2 x 3 : 3.9

large differences in the size of the root system are not expected during this, the second year of differential treatment, since trees were irrigated identically during the first 4 years after planting.

Average fruit size was not significantly affected by the factorial combination of the three soil water regimes, probably due to the effect of fruit thinning.

Rate of fruit growth

The rate of fruit growth was not significantly affected by any combination of 80%, 60% and 40% soil water regimes. However, when a 20% regime was imposed during either phase 2 or 3, the rate of fruit growth was decreased significantly during phase 3 and this resulted in significantly decreased yield (Table 5). Decreased rate of fruit growth during phase 3 is probably due to a direct effect of water stress. Fruit growth during phase 2 was not significantly affected by water stress during the same phase, a result similar to those of Lötter *et al.* (1985). The fact that severe water stress during phase 2 only resulted in a decreased rate of fruit growth during phase 3 is probably due to the effect of water stress on vegetative growth as indicated by the small increase in trunk circumference (Table 5(c)), which could have resulted in decreased leaf:fruit ratio. Decreased vegetative growth would decrease the amount of photosynthates available for fruit growth.

Fruit quality

The susceptibility of fruit to bruising by mechanical impact was not significantly affected by irrigation regime. Other quality parameters will only be evaluated after 3 months in cold storage.

Table 5 Effect of the sequence of soil water regimes during the cell enlargement (2) and ripening (3) phases of growth on (a) the rate of increase in fruit diameter during these phases, (b) yield and (c) annual increase in trunk circumference of Golden Delicious apple trees.

(a) Rate of increase in fruit diameter (mm d^{-1})

Growth phase	Soil water regime (%) (Phase 2 - Phase 3)					LSD (5%)
	20-60	40-60	60-60	60-40	60-20	
2	0.372	0.410	0.386	0.428	0.403	0.057
3	0.183	0.294	0.266	0.255	0.156	0.028

(b) Yield (Kg tree^{-1})

	7.8	11.8	15.0	13.6	8.2	2.9

(c) Annual increase in trunk circumference (mm)

	24	29	34	32	35	7

Plant physiological response

Although plant physiological responses of the trees were observed throughout the season, results are only presented for two dates, viz. noon observation on January 30th, 1991 and diurnal observations on February 12th, 1991 in order to illustrate the effect of soil water stress on tree performance. Soil matric potentials were derived from the soil characteristic curve (Figure 1), using neutron probe observations. The effect of soil water regime on plant physiological response of apple trees at noon is shown in Table 6. All treatments were at their driest point before

Table 6 Effect of soil water regime on the plant physiological response of Goden Delicious apple t (30 January 1991).

Soil water regime (%)	Soil water content (m^3m^{-3})	Soil matric potential (kPa)	Leaf water potential (MPa)	Osmotic potential (MPa)	Turgor (MPa)	Stomatal conductance (μMol $m^{-2}s^{-1}$)	Rate of photo-synthesis (mg $CO_2m^{-2}s^{-1}$)	Rate of tran-spiration (mg $H_2Om^{-2}s^{-1}$)
80	0.284	-30	-1.87	-2.65	0.78	0.35	0.58	158
80	0.247	-90	-1.82	-2.55	0.73	0.28	0.53	145
80	0.210	-215	-2.01	-2.49	0.48	0.11	0.22	82

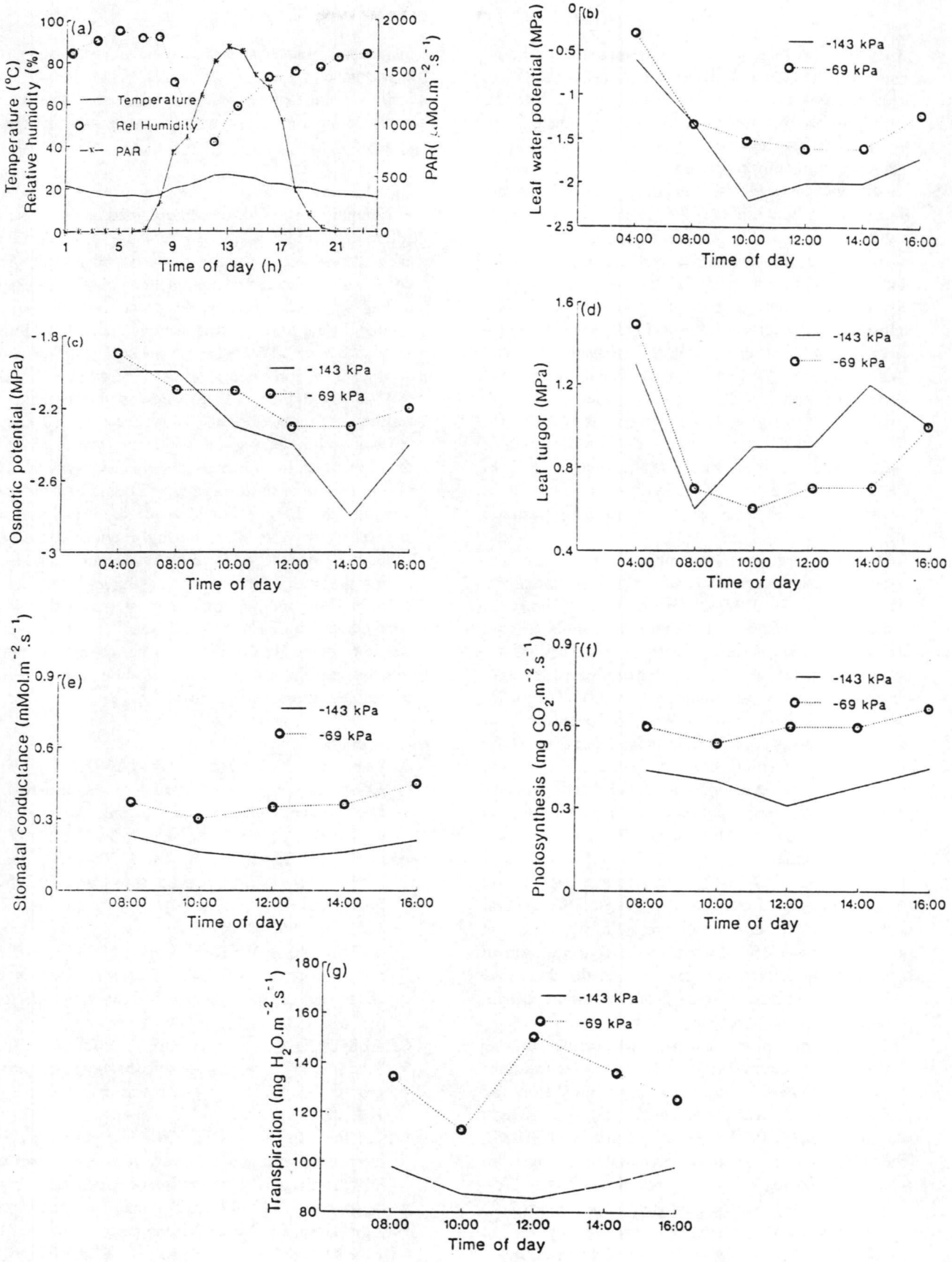


Figure 2 Diurnal variation in meteorological parameters and plant physiological response of Golden Delicious apple trees at two soil matric potentials on February 12th, 1991.

irrigation. Although soil water potential differed markedly between the different treatments there was little difference between leaf water potentials. It had been previously observed that these parameters are often not closely related in fruit trees (Jones, 1983). There was little difference in turgor potential, stomatal conductance as well as rates of photosynthesis and transpiration between the 80% and 60% soil water regimes. However, in comparison with the 80% soil water regime, the 40% regime resulted in a substantial decrease in turgor potential as well as stomatal conductance and rates of photosynthesis and transpiration. Clearly, stomatal response is more directly related to turgor than to leaf water potential (Jones, Lakso & Syvertsen, 1985). The large decrease in rate of photosynthesis during water stress will greatly affect tree growth and metabolites available for fruit growth and can explain the decreased growth of the tree and fruit discussed previously as a result of the direct effects on expansion growth as well as indirect effects on other metabolic processes (Jones *et al.*, 1985).

Diurnal variation in meteorological observations and response of apple trees at two soil matric potentials, viz. -69 and -143 kPa, are shown in Figure 2. Although leaf water and osmotic potentials (Figure 2(b) and (c)) did not differ greatly at 04:00 and 08:00, large differences became apparent from 10:00 until observations were terminated at 16:00. Turgor of leaves from trees at the lower matric potential were lower at 04:00 and 08:00 than those from trees at the higher matric potential, but from 10:00 to 16:00 these differences were reversed. The higher turgor pressure at lower soil matric potential is probably due to closure of stomata (Figure 2(e)) and decreased transpiration rates (Figure 2(g)). The effectiveness of stomatal control of leaf water status of apple was demonstrated by Jones *et al.* (1983). The general decrease of the relative water content of plant tissue at midday, and the consequent passive concentration of solutes in the cells which gave rise to the decreased cell osmotic potential (Figure 2(c)), occurs in all fruit trees (Jones *et al.*, 1985).

In addition, there is also an active diurnal photosynthate accumulation in fruit tree leaves since translocation rates, at least in apple, are quite slow and probably do not equal photosynthetic rates in the light period (Priestley, 1973 as cited by Jones *et al.*, 1985). The large decrease in osmotic potential for leaves from trees at the lower soil matric potential (Figure 2(c)) despite decreased rate of photosynthesis (Figure 2(f)) is probably an indication of a greater decrease in translocation with increased degree of water stress.

The trees from this trial are still bearing quite light crops. With heavier fruit loads in subsequent seasons, photosynthetic demand and plant physiological responses are expected to become greater. Fruit of apple trees are hydraulically well isolated from the main transpiration stream and have large hydraulic capacitances (landsberg & Jones, 1981). Heavy fruit loads are therefore expected to increase the effect of water stress on leaves and thus the photosynthesis system.

Conclusions

Preliminary results have been obtained of the effect of soil water regime on the performance of apple trees. Water stress imposed during a particular phenological development phase affected the response of the tree during subsequent phases. Irrespective of soil water regime during phase 3, tree growth tended to be lower with a 60% or 40% regime in phase 2. Furthermore, with an 80% soil water regime during phase 1, both wet (80%) and dry (40%) regimes during phase 2 resulted in decreased yield. The decreased yield due to the wet soil water regime could possibly be ascribed to competition from increased vegetative growth. The rate of fruit growth during phase 3 could be decreased by either the direct effect of water stress or indirectly as a result of water stress during previous decreasing vegetative growth. However, weather conditions during the season of observations were exceptionally mild and the degree of water stress imposed by atmospheric conditions is expected to be less than would be normally the case. Furthermore, trees in the full bearing phase will have to be studied before final recommendations can be made.

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WATER USE AND YIELD OF WHEAT AS INFLUENCED BY DIFFERENT SOIL WATER REGIMES

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Abstract

When a crop is cultivated under irrigation, there is always the possibility that a restriction in the supply of water may occur during any growth stage of the crop. It is therefore important to know what the response in growth and yield of a crop will be should water stress occur during different growth stages. The effects of five soil water regimes, four of which induced water stress during different growth stages of the crop, on the grain yield and water use of wheat planted on two dates, were investigated. Water stress during the whole growing period as well as during the reproductive period resulted in a significant reduction in grain yield. The reduction in grain yield was more drastic for the late compared to the normal planting date. Water stress during the vegetative stage caused no significant reduction in grain yield in the case of both planting dates. No significant differences in water use efficiency between soil water regimes were obtained irrespective of planting date.

Introduction

Water for irrigation purposes will become less available and more expensive in future. It is of the utmost importance that yield per unit water used be as high as possible. Too much or too little water during specific growth stages does not only cause water to be wasted, but may also reduce yield. It is therefore important that irrigation water be applied as effectively as possible, at the right stage and in the correct quantities (Hillel, 1987). Water stress during critical growth stages is one of the primary causes world wide of reduced crop production (Scott, Ferguson & Wood, 1987). It has been emphasised by many researchers that if sufficient water is available in the soil for normal vegetative development, no increase in yield will be obtained by additional irrigation during this growth stage (Heatherly, 1988). Knowledge of the water requirements during the different growth stages of crops is very important. These requirements can be satisfied by irrigation if they are known. In this study the effects of five soil water regimes, four of which induced water stress during different growth stages, on the grain yield and water use of wheat were investigated for two planting dates.

Procedures

Wheat was planted on 13 June 1989 (early planting) and 12 July 1989 (late planting) at a seeding rate of 100 kg ha^{-1} at the Rietrivier Research Station (29°07S, 24°36E). The soil was classified as a Mangano series of the Hutton form with a depth of 1 800 mm. The clay percentage of the 300, 600, 900, 1 200, 1 500 and 1 800 mm layers was 11.7; 14.7; 16.0; 15.1; 14.1 and 12.7, respectively. The wheat received a fertilizer application of 75 kg N, 50 kg P and 25 kg K ha^{-1} at planting and a top dressing of 75 kg N ha^{-1} four weeks after planting. The cultivar used was Gamtoos. Individual plots were 10 m long and 5.6 m wide, of which 8 m x 4 m per plot was harvested. Irrigation water was applied to the plots by means of microjets to achieve even distribution of the water. Because of the high output of the jets, the irrigation can be considered as simulated flood irrigation. The trial was laid out in a 5 x 5 latin square design.

The five soil water regimes consisted of filling the profile to field water capacity whenever the soil water potential of 300 mm soil depth reached a value of:

A) -30 kPa;
B) -80 kPa;
C) -130 kPa;
D) -30 kPa; during the vegetative stage and -130 kPa during the reproductive stage
E) -130 kPa during the vegetative stage and -30 kPa during the reproductive stage.

The soil water potential of -30 kPa was indicated by tensiometers. Soil water corresponding to -80 and -130 kPa were obtained from a soil water retention curve and attainment of these soil water contents indicated by measurements with a neutron soil water meter at 300 mm increments to a depth of 1 800 mm.

Analyses of variance were done on the water consumption (rain + irrigation + difference in profile water content at the beginning and end of the season) during the growing season, the grain yield obtained and the water use efficiency (yield water use) for each of the five soil water regimes and two planting dates. A linear regression analysis, with yield the dependent and water use the independent variables, was used to predict grain yield for a specific amount of water consumed.

Results and Discussion

The water use, grain yield and water use efficiency for the five soil water regimes and two planting dates are shown in Table 1.

The results in Table 1 show that, for the early planting date, A (no stress) used significantly more water during the growing season than C (severe stress), while a significantly higher grain yield was

Table 1 Water use (mm), grain yield (kg ha^{-1}) and water use efficiency (kg ha^{-1} mm^{-1}) for five soil water regimes at two planting dates.

Treatment	Early planting			Late planting		
	Water use	Grain yield	Water use efficiency	Water use	Grain yield	Water use efficiency
A (no stress)	622	5976	9.69	643	6018	9.51
B (mild stress)	471	4356	9.25	402	3111	7.69
C (severe stress)	392	3897	10.03	354	2639	7.30
D (reproductive stress)	504	4561	9.11	427	2962	6.53
E (vegetative stress)	516	5426	10.48	511	4660	8.87
Mean	501	4843	9.71	467	3878	7.98
LSD_T	184	1534	NS	200	2609	NS
CV%	18.2	15.7	9.6	21.2	33.4	24.5

obtained from A than from B (mild stress) and C. For the late planting date, A used significantly more water and gave a significantly higher yield than B, C and D (reproductive stress). Previously published research showed that increased water use of wheat, as a result of regular water supply, increased leaf water potentials and in consequence total yields and grain yield (Singh & Kumar, 1981). In the present study, water use, grain yield and water use efficiency of all treatments, with the exception of A, were higher for the early than for the late planting. It was previously reported that both water use and yield of late seeded wheat were markedly reduced as compared to timeously seeded wheat (Singh & Kumar, 1981) although the delay in planting adversely affected grain yield more than it did water use.

Lower water use efficiencies were recorded when wheat and barley were irrigated frequently since yield did not increase in proportion to water use (Singh & Kumar, 1981). No significant differences in water use efficiency between the different soil water regimes were obtained for either of the two planting dates. This means that those treatments which received the most water during the growing season gave the highest grain yield. Singh & Kumar (1981) obtained water use efficiency values of 12.0 and 9.6 kg ha^{-1} mm^{-1} for wheat growth under severe stress after timely and late seeding, respectively.

The treatment differences compared to A (no stress) with regard to water use, grain yield and water use efficiency are shown in Figure 1 for the early and Figure 2 for the late planting dates. For the early planting date severe stress (-130 kPa) during the whole growing period (C) had the largest depressing effect on yield followed by mild stress (-80 kPa) during the whole growing period (B), severe stress (-130 kPa) during the reproductive stage (D) and severe stress (-130 kPa) during the vegetative stage (E). It seems as if water stress during the vegetative stage was a contributory factor to drought hardening. Certain crops that have been exposed to mild water stress during earlier stages of growth become drought hardened, such that they can better withstand subsequent drought than if they had not previously been stressed (Oosterhuis, 1983). Although the difference in water use between severe stress during the reproductive stage (D) and severe stress during the vegetative stage (E) was small (19% and 17% less than A, respectively) the difference in grain yield between the two was much larger (24% and 9% less than A, respectively). This was also reflected in the water use efficiency (D = 6% lower and E = 8.2% higher than A).

At the late planting date severe stress (-130 kPa) during the whole growing season (C) had the largest depressing effect on yield followed by severe stress during the reproductive stage (D), mild stress during the whole growing period (B) and severe stress during the vegetative stage (E).

It is also clear that, as in the case of the normal planting date, water stress during the reproductive stage is more detrimental than during the vegetative stage (D = 56% and E = 23% lower grain yield than A). This was also reflected in the water use efficiency (D = 31% and E = 7% lower than A). Although severe stress during the vegetative stage (E) gave the smallest reduction in yield, it seems as if all stress treatments during the late planting had a more detrimental effect on yield compared to the normal planting date.

The influence of water use corresponding to the different soil water regimes on the grain yield of wheat for the early and late planting dates, is shown in Figures 3 and 4, respectively.

The regression equation for the prediction of grain

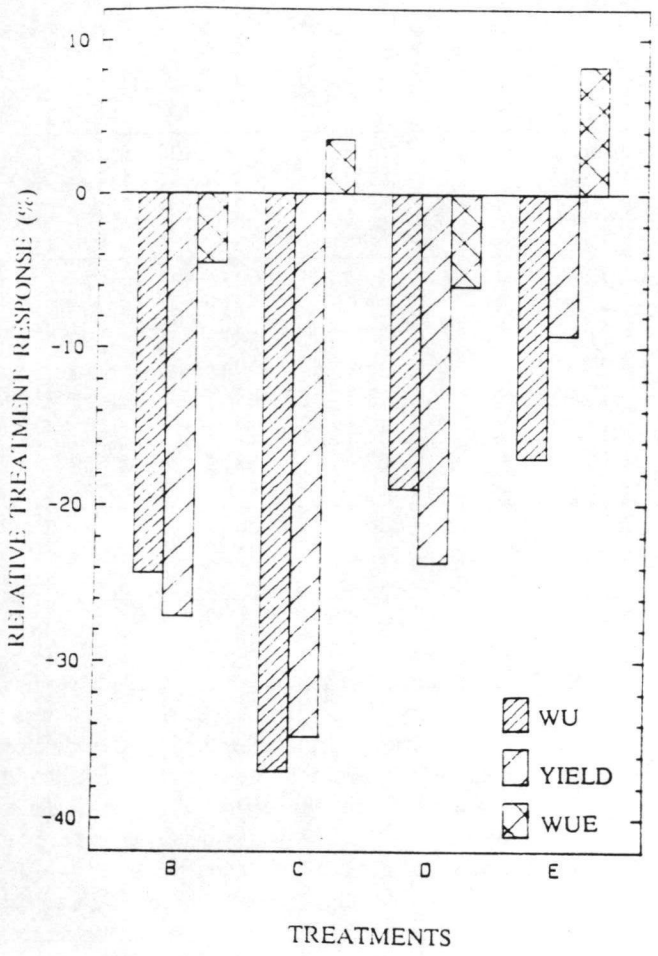


Figure 1 Treatment differences compared to A with regard to water use (WU) (mm), grain yield (kg ha^{-1}) and water use efficiency (WUE) (kg ha^{-1} mm^{-1}) for early planted wheat.

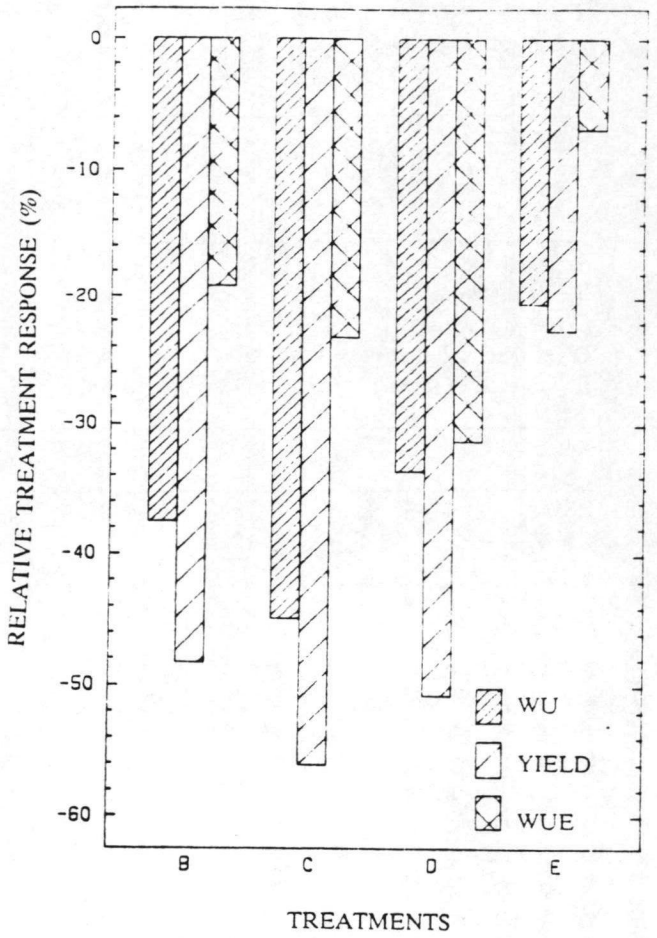


Figure 2 Treatment differences compared to A with regard to water use (WU) (mm), grain yield (kg ha^{-1}) and water use efficiency (WUE) (kg ha^{-1} mm^{-1}) for late planted wheat.

yield, for the early planting date is $Y=539.91 + 8.5913X$ (Figure 3) and for the late planting date is $Y=-1557.3 + 11.629X$ (Figure 4), where Y = grain yield in kg ha^{-1} and X = water use (mm). In the case of the early planting date 78.1% and in the case of the late planting date 86.2% of the variation in grain yield can be attributed to water use.

Conclusions

Soil water stress during any of the growth stages of wheat will cause a reduction in grain yield and the reduction will be more detrimental at a late planting date compared to a normal planting date. Soil water stress during the reproductive stage of wheat causes a greater reduction in grain yield than soil water stress during the vegetative stage. The reduction in yield due to soil water stress during the vegetative stage, especially for an early or normal planting date, was relatively small. Stress during the vegetative stage also gave a smaller reduction in yield than a mild stress during the whole growing period.

If a water shortage is expected or when saving of water is the objective, moderate soil water stress (≥-80 kPa) during the crop's vegetative stage and well-watered conditions (≥-30 kPa) during the reproductive stage appears to be the best option for satisfactory grain yields and high water use efficiency.

At a low water use (350 mm) the difference between predicted grain yield for normal and late planted wheat is large (1 034 kg ha^{-1}). Wheat planted at the nor time uses smaller quantities of applied water more efficiently than late planted wheat. The difference in predicted grain yield between timeously and late planted wheat decreases as the water use increases up to a point (690 mm) where the same yield is predicted for both plantings. Additional research, over a wider range of soil water regimes, will be required.

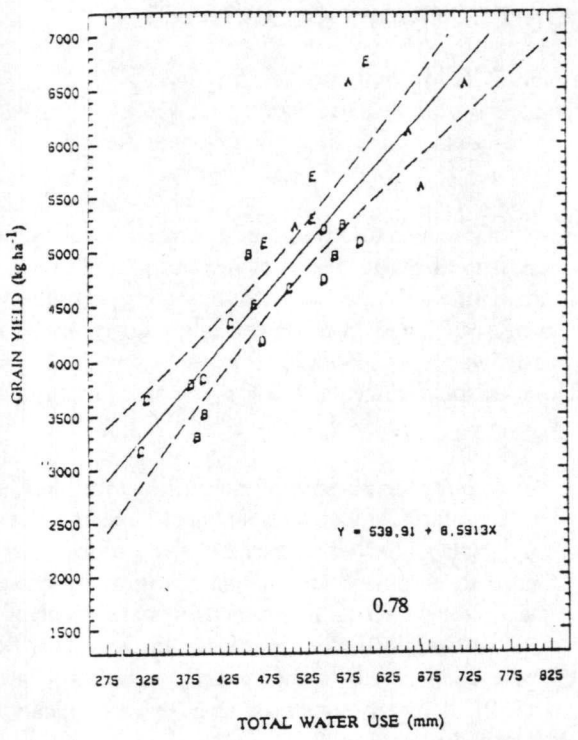


Figure 3 The influence of water use (mm) corresponding to five soil water regimes on grain yield (kg ha^{-1}) of early planted wheat.

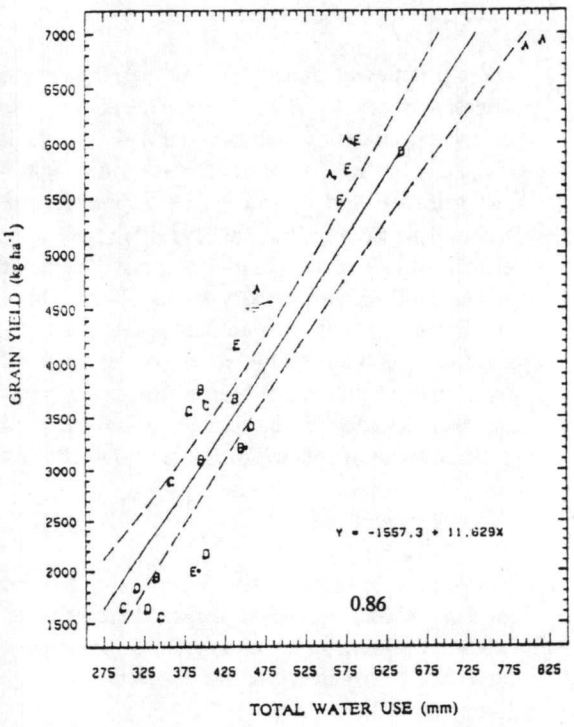


Figure 4 The influence of water use (mm) corresponding to five soil water regimes on grain yield (kg ha^{-1}) of late planted wheat.

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EVAPORATION MEASUREMENT COMPARISONS AND ADVECTIVE INFLUENCES USING BOWEN RATIO, LYSIMETRIC AND EDDY CORRELATION METHODS

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Abstract
A study in Natal involving Bowen ratio and eddy correlation aerodynamic measurements and lysimetric measurements, showed good comparison between Bowen ratio and lysimetric measurements for the measurement period of the data. Eddy correlation measurements underestimated the evaporation significantly compared to the other techniques. The influence of advection on Bowen ratio evaporation measurements, calculated from Bowen ratio and lysimeter data, appeared to be relatively insignificant but variable. The total daily evaporation amounts for two Bowen ratio systems compared favourably with each other and the lysimeter evaporation measurements, but less so for 20 min intervals.

Introduction

In irrigated agriculture, information on total evaporation is important in selecting cropping strategies, designing irrigation systems and irrigation scheduling. Methods for evaporation measurement include soil based, plant (heat pulse, sap flow, porometry) and aerodynamic techniques. Aerodynamic measurements have the following advantages over the other methods mentioned: 1) measurement of leaf area index (*LAI*) is not necessary; 2) the techniques are portable compared to fixed lysimetric measurements; and 3) hourly or sub-hourly measurements are possible compared to the daily measurements obtained using the neutron probe, for example.

However, aerodynamic measurements of sensible and latent heat at the canopy surface, have fetch limitations (Brittin & Heilman, 1989) and may be affected by advection (Lang, 1973; Blad, Verma & Rosenberg, 1977; Brakke, Verma & Rosenberg, 1978; Bertela, 1989). Furthermore, certain assumptions, that may be necessary for the theoretical development of a measurement system, may not actually apply.

In this study, evaporation was measured above a mixed grassland community and a maize crop at various locations in Natal using Bowen ratio (Tanner, 1960; Tanner & Fuchs, 1969; Tanner, Greene & Bingham, 1987) and eddy correlation techniques (Swinbank, 1951; Tanner, Tanner, Dugas, Campbell & Bland, 1985). These simultaneously measurements, which appear to be the first reporting of such measurements for Southern Africa, were supplemented with lysimeter measurements. From the data collected, we were able to determine the influence of advection on the Bowen ratio evaporation measurements.

Theoretical considerations

When considering sensor placement, advection and fetch influences on measurements above a vegetated surface, there are a few constraints that exist in the case of aerodynamic methods: vertical distance between sensors should be such as to allow the detection of large enough profile differences in the measured parameter; sensors placed above a vegetated surface for the purpose of monitoring sensible F_h (also often referred to as H) and latent heat flux densities L_vF_w (also referred to as LE) at the canopy surface, need to be placed at a height z within the boundary layer for which both flux densities are constant with vertical height; and the measurement height for Bowen ratio and eddy correlation sensors is critical (Pasquill, 1972). A list of terms used in this paper appears as Appendix.

Bowen ratio theory

According to Fick's Law of Diffusion, the latent heat energy flux density L_vF_w (Wm^{-2}) is given, in finite difference form, by:

$$L_vF_w=(\rho c_p/\gamma)K_w(\bar{e}_2-\bar{e}_1)/(z_2-z_1) \quad (1)$$

where ρ is the air density (kg m^{-3}), c_p the specific heat capacity of dry air (J $kg^{-1}K^{-1}$) at constant pressure, γ the psychrometric constant (66 Pa K^{-1} at sea level at 9°C), K_w the exchange coefficient (m^2 s^{-1}) for latent heat transfer, and $\bar{e}_2$ and $\bar{e}_1$ the time-averaged water vapour pressures (Pa) at heights z_2 and z_1 (m) respectively. The sign convention used here for latent heat and other flux density terms (except for the net irradiance I_{net}) is that an amount leaving the surface is positive and that being received is negative. The psychometric constant γ (at atmospheric pressure p) may be calculated from γ_o, the psychrometric constant at sea-level atmospheric pressure p_o ($\approx$ 101.3 kPa):

$$\gamma=\gamma_o p/p_o \quad (2)$$

Subsequent to this initial work, the psychometric constant γ was corrected for air temperature, water vapour pressure and atmospheric pressure. T corrections do not affect the conclusions of the work here.

Similarly, the sensible heat energy flux density F_h (W m^{-2}) is given, in finite difference form, by:

$$F_h=(\rho c_p K_h)(\bar{T}_2-\bar{T}_1)/(z_2-z_1) \quad (3)$$

where K_h is the exchange coefficient for sensible heat energy transfer ($m^2 s^{-1}$) and
$\hat{T}_2$ and $\hat{T}_1$ are the time-averaged air temperatures at heights z_2 and z_1 respectively.

Following Bowen (1926), we consider the Bowen ratio β:

$$\beta = F_h / L_v F_w = (\gamma K_h / K_w)(\hat{T}_2 - \hat{T}_1)/(\hat{e}_2 - \hat{e}_1) \quad (4)$$

Generally, the exchange coefficients K_h and K_w are unknown. However, Rider (1954) showed that the K_h/K_w ratio is not too far from unity under a variety of conditions. Similarity holds when convective conditions are fully forced, that is, for which the Richardson number Ri satisfies the condition: $-0.01 \leq Ri \leq 0.01$ (Thom, 1975). It is now generally accepted that the Similarity Principle holds good under neutral conditions, as opposed to stable or unstable conditions (Dyer, 1974). Assuming this principle holds, then substituting $K_h/K_w = 1$ into Equation 4, we get:

$$\beta = F_h / L_v F_w = \gamma(\hat{T}_2 - \hat{T}_1)/(\hat{e}_2 - \hat{e}_1) \quad (5)$$

Hence β can be determined from a measurement of air temperature and water vapour pressure at two levels (above canopy surface) in the atmosphere.

The aerodynamic approach used thus far only enables the $F_h/L_v F_w$ ratio to be determined but not the individual flux density terms. To do this, we need to invoke the surface energy balance. Assuming that photosynthetic and physical heat energy storage amounts in the canopy are small and neglecting advection, the surface energy balance is given by:

$$I_{net} = L_v F_w + F_h + F_s \quad (6)$$

where I_{net} = the net irradiance above the canopy and
F_s = the soil heat flux density.

Substituting $F_h = \beta L_v F_w$ (from Equation 5) into Equation 6 and solving for $L_v F_w$, we get:

$$L_v F_w = (I_{net} - F_s)/(1 + \beta) \quad (7)$$

where we note that $L_v F_w$ is indeterminate if $\beta = -1$ (that is, $F_h = -L_v F_w$ or, in other words, F_h and $L_v F_w$ are equal in magnitude but opposite in direction). Similarly, since $F_h = \beta L_v F_w$ (from Equation 5), and using Equation 7, we get:

$$F_h = \beta (I_{net} - F_s)/(1 + \beta) \quad (8)$$

If advection heat flux density A is not negligible, then Equation 6 becomes:

$$I_{net} = (L_v F_w)_{BR} + (F_h)_{BR} + F_s + A_w + A_h \quad (9)$$

where the subscript BR indicates measurements using the Bowen ratio technique, $A = A_W + A_h$ is the energy flux density removed from the system ($A > 0$ W m^{-2}) or advected horizontally into the system ($A < 0$ W m^{-2}), and A_w and A_h represent the latent and sensible heat flux densities advected, respectively. It can be shown that, approximately:

$$A = (1 + \beta)\, A_w = (1 + \beta)[(L_v F_w)_o - (L_v F_w)_{BR}] \quad (10)$$

where $(L_v F_w)_o$ = the actual evaporation flux density at the canopy surface (Savage *et al.*, in preparation). We assume that $(L_v F_w)_o$ is obtained from lysimetric measurements.

Lysimeter measurements

The evaporation measurements least affected by advection, theoretically, are lysimeter latent heat flux density measurements $(L_v F_w)_o$ and calculated lysimeter sensible heat flux density $(F_h)_o$ values where the latter is given by:

$$(F_h)_o = I_{net} - (L_v F_w)_o - F_s \quad (11)$$

These values, $(L_v F_w)_o$ and $(F_h)_o$, are advection free for at the lysimeter surface, windspeed V = 0 m s^{-1} so that advection flux density $A = 0$ W m^{-2}. The Bowen ratio method for the determination of $(L_v F_w)_{BR}$ and $(F_h)_{BR}$, which includes advective effects, may be compared with the respective $(L_v F_w)_o$ (using Equation 10) and $(F_h)_o$ lysimeter values, the latter calculated from Equation 11.

Eddy correlation

Ideally, eddy correlation sonic anemometer measurements of vertical windspeed fluctuation should be at a height that allows one eddy between the unit's separation distance d. If the sensor is too close to the canopy surface, more than one eddy may be sensed. Also, sonic reflections from vegetation may affect measurements. The first problem underestimates vertical windspeed fluctuation and there may be an overestimate for the second. Theoretically, for a sonic anemometer with source and detector tubes a distance d apart, the minimum operating height for flux density measurements is $6\pi d$ (Kaimal, 1969). The eddy correlation technique (Swinbank, 1951) is an absolute technique for the measurement of surface evaporation with sensors placed above the canopy.

Materials and Methods

Two independent (separate) Bowen ratio systems were used to determine surface evaporation, the sensors of the systems being placed about 0.8 m apart. Net irradiance and soil heat flux density data were

collected using separate sensors connected to separate dataloggers. Two net radiometers (one Middleton and one Fritschen type available from REBS, four soil heat flux plates (Middleton type) and eight soil temperature sensors were used to measure net irradiance I_{net} (W m^{-2}), soil heat flux density F_s (W m^{-2}) and soil temperature T_{soil} (°C) respectively and used to calculate the Bowen ratio latent heat flux density $L_v F_w$ (W m^{-2}, Equation 7) for each system.

Lysimeter data enabled the surface latent heat flux density $(L_v F_w)_o$ to be measured directly. The construction details of the lysimeter are discussed elsewhere (Everson *et al.*, in preparation): the surface area of the lysimeter is 1 m^2 and contained 1 m^3 of undisturbed soil with the weighing design allowing a depth resolution of 0.1 mm. An automatic drainage system operates at its base to extract soil water at a 0.1 kPa suction pressure.

Two net radiometers were placed 1.0 m above ground on a north-south axis with the radiometer support on the south side to avoid shading of the ground surface by the supports (Savage, 1988). The soil heat flux plates were buried at a depth of 80 mm, on a north-south axis together with a liberal length of wire to reduce the influence of heat conduction along the surface exposed wires to the sensor. Four soil temperature sensors (type E thermocouples mounted in tubes and similar in design to other temperature sensors described by Savage (1980) were buried at depths of 20 mm and 60 mm below the soil surface. These sensors were connected in parallel to produce a spatially averaged soil temperature measurement for the two depths for two different positions. Soil water content in the 80 mm layer was gravimetrically measured every week.

In each of the Bowen ratio systems, a single cooled dewpoint hygrometer was employed to measure the dewpoint T_{dp} (°C) of air drawn in from 1.0 m or 1.8 m above ground. For each system, air temperature at 1.0 m and the air temperature difference between 1.0 and 1.8 m was measured using two bare type E thermocouples each with a parallel combination of 76 μm diameter thermocouples. This combination would function even if one of the thermocouples were damaged.

All sensors were connected to a Campbell 21X datalogger, one datalogger being used for each of the Bowen ratio systems. A frequent measurement period of 1 s for dewpoint and air temperatures was employed and 10 s for all other sensors. The dewpoint temperature was averaged for a period of 80 s (after a mirror stabilization time of 20 s first), converted to water vapour pressure and then the datalogger switched a solenoid to sample the other level. Every 20 minutes the datalogger converted an average of the input storage values to final storage. Weekly, the data were transferred to computer and the Bowen ratio energy components calculated for each 20 min period from 08h00 to 18h00. The datalogger was programmed to switch off the cooled dewpoint mirror system between 18h00 and 06h00 the next day in order to conserve battery power and extend the life of the pump of the cooled mirror system.

Due to the effect of dew wetting all sensors during the night, and because the Bowen ratio $\beta = (F_h)_{BR}/(L_v F_w)_{BR}$ tends to -1 around sunrise and sunset causing $(L_v F_w)_{BR}$ (Equation 7) to be indeterminate (sometimes even in the absence of dew), only measurements between 08h00 and 18h00 were used for comparison with other techniques or calculations. This problem was not experienced with lysimetric or eddy correlation evaporation measurements. However, eddy correlation measurements were never obtained under condensation or dew conditions for fear of damaging the sonic anemometer and krypton hygrometer sensors. For this reason, the eddy correlation data are sparse compared to the other techniques. Details of the eddy correlation measurement system are discussed more fully by Monnik, Savage & Everson (1995).

Results and Discussion

Bowen ratio estimates

The $(L_v F_w)_{BR}$ comparisons between the two systems were good (Figure 1; Table 1). Hence either:

- both systems compare but are not accurately indicating the actual surface evaporation;
- or both systems compare but do accurately indicate the actual surface evaporation.

The slight bias in the 20 min latent heat flux density $(L_v F_w)_{BR}$ values (Figure 1, Table 1) and hence in sensible heat flux density F_h (data not shown) between the two systems is mainly due to the net irradiance differences between the two net radiometers (Figure 2). However, these differences do not explain some of the scatter of the data (Table 1) of Figure 1. The response of both systems to the changing microclimate is excellent (Figure 3), the response being indicated by a change in evaporation $(L_v F_w)_{BR}$ owing to a sudden change in net irradiance I_{net}.

While there is some variability in the 20 min Bowen ratio $(L_v F_w)_{BR}$ data between the two systems, these differences are negated when calculating daily total evaporation (Table 2); the maximum percentage difference between the two systems for the five-day period was less than 8 % but the percentage differences averaged less than 3 %.

Lysimeter evaporation

Bowen ratio evaporation estimates compare favourably with lysimetric estimates (Figure 4, left hand y-axis in W m^{-2}, the right hand axis being in mm), indicating that they are measuring actual surface evaporation (Table 1). Since the lysimeter is less affected by advection influences, it appears that advection is not playing a role to the extent that the Bowen ratio estimates are in error. As was the case with the two

Table 1 Statistical data[1] associated with the 20 min comparisons between evaporation estimates $(L_vF_w)_{BR}$ in W m^{-2} (Equation 7) from two Bowen ratio systems, at Cathedral Peak Catchment VI, between lysimeter evaporation heat flux density $(L_vF_w)_o$ and Bowen ratio evaporation (calendar day 11 to 14, 1991) and between eddy correlation and UNP Bowen ratio evaporation for the 08h00 to 18h00 time period.

Site and statistical information	CSIR Bowen *vs* UNP Bowen	CSIR Bowen *vs* lysimeter	Eddy correlation *vs* UNP Bowen
Calendar day, year	95 to 100, 1990	12 to 14, 1991	42 to 43, 1991
Slope	0,977	0,911	0,449[3]
SE_{slope}	0,0283	0,0467	0,1410
Intercept (W m^{-2})	16,315[2]	54,592[2]	65,280
$SE_{intercept}$ (W m^{-2})	6,152	20,671	58,883
Number of data points	149	75	26
r^2	0,890	0,839	0,297
$S_{y.x}$ (W m^{-2})	33,766	56,348	52,465
100 * root mean square systematic error/total mean square error	37,8	32,8	65,0
100 * root mean square unsystematic error/total mean square error	62,2	67,2	35,0
Total root mean square error (W m^{-2})	258,60	424,17	208,7

[1]In each case, the technique mentioned first has been used to generate the dependent evaporation data set and the second technique used to generate the independent evaporation data set.

[2]We reject the null hypothesis that the intercept is 0 W m^{-2}, at the 95 % level of statistical significance.

[3]We reject the null hypothesis that the slope is 1, at the 95 % level of statistical significance.

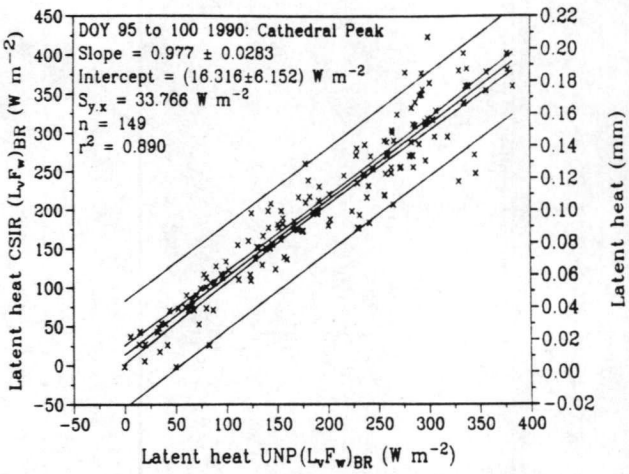


Figure 1 Comparison between the heat flux density $(L_vF_w)_{BR}$ (W m^{-2}, Equation 7) (left hand y-axis) or in mm (right hand y-axis) for calendar day 95 to 100 inclusive (1990) for the 20 min data between 08h00 and 18h00 for UNP and CSIR Bowen ratio systems. The narrow confidence belts are for the mean and the wide for a single predicted value.

Table 2 Total daily of evaporation[1] (mm) using two Bowen ratio systems for six days (calendar day 95 to 100 inclusive) in April 1990 for the 08h00 to 18h00 time period for Cathedral Peak Catchment VI

System/method	Total daily evaporation (mm) for various days						Six day total (mm)
	95	96	97	98	99	100	
Bowen ratio UNP	3,2	2,4	2,8	2,7	3,0	1,0	15,0
Bowen ratio CSIR	3,4	2,4	2,9	2,6	2,9	1,1	15,3

[1]All values were calculated to two decimals and rounded off to one decimal

Bowen ratio systems, the response of both the lysimeter and Bowen ratio systems to the changing microclimate is good (Figure 4). Calculated equilibrium (Priestley & Taylor, 1972) evaporation (not shown in this paper) also compares favourably with Bowen ratio estimates of evaporation for this time of year.

Effect of advection on Bowen ratio evaporation measurements

Prime facie evidence of advection has been obtained by comparing latent heat flux density L_vF_w and I_{net} - F_s: if $L_vF_w > I_{net} - F_s$, then sensible heat flux density F_h has been drawn from the air and consumed in evaporation (Rosenberg, Blad & Verma, 1983). This inequality implies a negative Bowen ratio β (see Equation 7). We have not noticed a negative β value for our data sets (except during dew and rainfall events) and therefore have had to use other methods for determining the significance or otherwise of advection. The role of advection was investigated by comparing Bowen ratio evaporation with equilibrium and lysimeter evaporation. From the definition of equilibrium evaporation (*viz.*, weak flow of humid air over a wet canopy), it is clear that if Bowen ratio estimates are significantly larger than equilibrium evaporation, then the probability exists that advection is significant, or the canopy cannot be considered to be wet, or advection is both significant and the canopy dry.

The Bowen ratio estimates of evaporation compared favourably with equilibrium evaporation except for times in winter when the canopy was extremely dry, with Bowen ratio estimates significantly less than equilibrium evaporation (Savage *et al.*, in preparation). This evidence indicates then that advection seldom played a role and that the Bowen

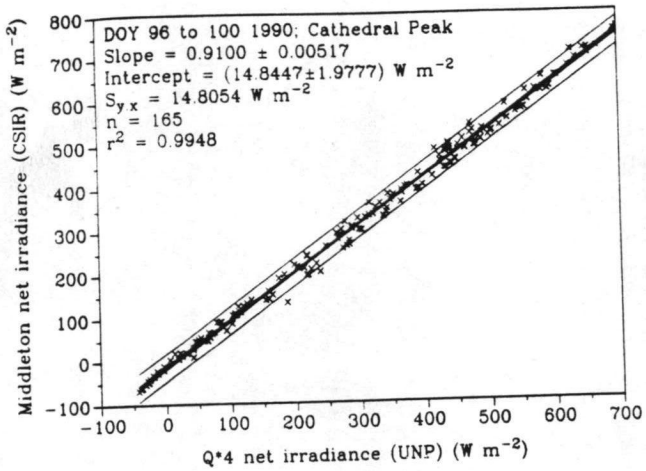


Figure 2 Comparison of the REBS Q*4 net radiometer (x-axis) with the Middleton net radiometer net irradiance I_{net} (W m^{-2}) for 20 min data (calendar day 95 to 100 inclusive) indicates a consistent bias. The narrow confidence belts are for the mean and the wide for a single predicted value.

ratio estimates indicated actual evaporation. Assuming no error in lysimeter and Bowen ratio evaporation measurements, the advection flux density A (W m^{-2}) was calculated (Equation 10) for three consecutive days for which Bowen ratio and lysimeter data were available (Figure 4). For calendar day 13 and 14 (Table 3), $A > 0$ W m^{-2} indicating heat energy was being removed by advection during these times. For calendar day 12, A was generally negative indicating heat energy was being advected into the area. For this three day period, the magnitude of A never exceeded 203 W m^{-2} (Table 3). The data shown in Table 3 further indicate that the role of advection is small for this three day period. However, it is clear from Figure 4 and the standard deviation of A compared to the mean $\bar{A}$ (Table 3), that advective influences are variable. The Bowen ratio (right hand y-axis of Figure 4), between the midday hours, averaged between 0.3 and 0.4, indicating high evaporation conditions.

Table 3 Mean $\bar{A}$, standard deviation SD_A, maximum and minimum of the 20 min advection heat flux density A vlaues (Wm^{-2}, Equation 11) for three consecutive days (calendar day 12, 13 and 14, 1991) for the 08h00 to 18h00 time period for Cathedral Peak Catchment

Day of year	$\bar{A}$ (W m^{-2})	SD_A (W m^{-2})	Maximum A (W m^{-2})	Minimum A (W m^{-2})
12	-6	78	133	-203
13	32	68	150	-97
14	35	69	187	-97

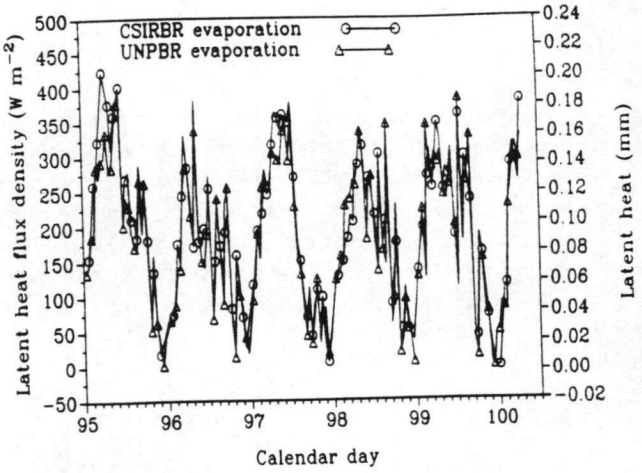


Figure 3 Diurnal variation in Bowen ratio $(L_vF_w)_{BR}$ (W m^{-2}, Equation 7) latent heat flux densities for the UNPBR and SCIRBR systems, for calendar day 95 to 100 inclusive (1990) for 20 min data between the times 08h00 and 18h00. The calendar day indication on the x-axis indicates the first measurement time for that day (08h00).

Eddy correlation evaporation

Unlike the Bowen ratio and lysimetric techniques, the eddy correlation is an absolute technique not requiring the use of the energy balance (Equation 6) for the determination of L_vF_w and F_h. However, the technique appears to underestimate evaporation (Table 1). The reasons for this underestimation will not be discussed here (Savage *et al.*, in preparation).

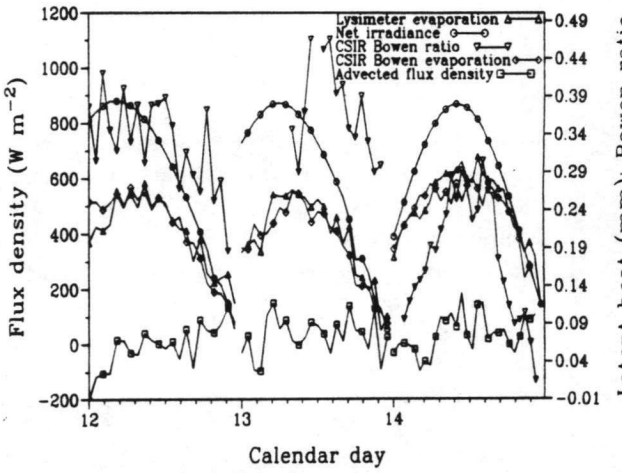


Figure 4 Diurnal variation in net irradiance I_{net} (W m^{-2}), left hand y-axis; mm, right hand y-axis), advection heat flux density A (W m^{-2}), lysimeter evaporation flux density $(L_vF_w)_o$ (W m^{-2}, left hand y-axis; mm, right hand y-axis), Bowen ratio $(L_vF_w)_{BR}$ (Equation 7) latent heat flux densities (W m^{-2}, left hand y-axis; mm, right hand y-axis), and the Bowen ratio β (Equation 5, right hand y-axis only) for calendar day 12 to 14 (1991) inclusive for 20 min data between the times 08h00 and 18h00. The calendar day indication on the x-axis indicates the first measurement time for that day (08h00).

Conclusion

Bowen ratio evaporation (daily total) compares adequately with lysimeter evaporation indicating a lack of advective influences for our data set. The Bowen ratio technique has proved to be a reliable technique for measuring evaporation requiring routine maintenance two to five times per month. The eddy correlation technique appears to significantly underestimate evaporation. The reasons for the underestimation deserve urgent attention. Bowen ratio and lysimetric estimates of evaporation were found to compare favourably. While 20 min evaporation estimates for the techniques (excluding eddy correlation) were reasonably comparable, daily totals were very good. Advection flux density estimates were shown to be relatively small and variable (for 20 min periods). This aspect requires more attention and data. Our research paves the way to a more routine use of the more portable Bowen ratio evaporation techniques for the estimation of actual evaporation.

Acknowledgements

Financial and/or infrastructure support for our work from Forestek, Foundation for Research Development, University of Natal, University of Natal Research Fund and the Water Research Commission is gratefully acknowledged. The assistance provided by Mr Karl Monnik (Agrometeorology Section, Cedara) with the eddy correlation equipment is also acknowledged.

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Appendix: List of Terms

Advected heat energy flux density A (W m^{-2})
Air temperature (time averaged) $\bar{T}_1$ at level 1 (°C)
Air temperature (time averaged) $\bar{T}_2$ at level 2 (°C)
Atmospheric pressure p (kPa)
Atmospheric pressure at sea-level p_o (kPa)

Bowen ratio $\beta = F_h/L_vFw$

Density of air ρ (kg m^{-3})

Dewpoint temperature of air T_{dp} (°C)

Exchange coefficient for latent heat K_w (m^2 s^{-1})

Exchange coefficient for sensible heat K_h (m^2 s^{-1})

Height above soil surface z_1 (m)

Height above soil surface z_2 (m)

Latent heat flux density L_vF_w or $(L_vF_w)_{BR}$ as measured using the Bowen ratio technique (W m^{-2})

Latent heat flux density $(L_vF_w)_o$ as measured using the lysimetric technique (W m^{-2})

Net irradiance I_{net} (W m^{-2})

Psychrometric constant γ (Pa K^{-1})

Sensible heat energy flux density F_h or $(F_h)_{BR}$ as measured using the Bowen ratio technique (W m^{-2})

Sensible heat flux density $(F_h)_o$ as measured using the lysimetric technique (W m^{-2})

Soil heat flux density F_s (W m^{-2})

Soil temperature (average for depths 20 and 60 mm below the soil surface) T_{soil} (°C)

Specific heat capacity of air at constant pressure c_p (J kg^{-1} K^{-1})

Water vapour pressure (time averaged) $\bar{e}_1$ at level 1 (kPa)

Water vapour pressure (time averaged) $\bar{e}_2$ at level 2 (kPa)

Wind speed in the horizontal plane $\bar{V}$ (m s^{-1})

COMPARISON OF EDDY CORRELATION ESTIMATES OF EVAPORATION WITH BOWEN RATIO AND EQUILIBRIUM EVAPORATION

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Abstract

The eddy correlation technique, an absolute aerodynamic evaporation measuring technique, was routinely used for a five-month period to obtain real-time evaporation measurements above maize and a mixed grassland community in Natal. For the maize data, the eddy correlation evaporation estimate was consistently lower than Bowen ratio and equilibrium evaporation estimates of actual evaporation. The eddy correlation evaporation estimates responded quickly to sudden changes in net irradiance. The underestimate in eddy correlation evaporation was independently confirmed by comparing the sum of eddy correlation measured latent and sensible heat flux densities with the difference between net irradiance and soil heat flux density. The ratio between these quantities was always less than unity, indicating an underestimation in eddy correlation evaporation and/or sensible heat. The eddy correlation technique is a potentially useful technique for portable and absolute evaporation measurement.

Introduction

The water budget of the crop root zone is often used for making irrigation scheduling decisions. With this approach, irrigation and rainfall are the primary additions to soil water, and evaporation is the major process removing water from the root zone. Methods for estimating evaporation include soil, plant and atmospheric methods. Despite twenty years of intense investigation, the problem of predicting evaporation when soil water supplies are limiting remains a large one for physical ecology (Denmead, 1984).

The eddy correlation technique (ECT) involves the direct measurement of sensible and latent heat atmospheric gradients or fluxes within the surface boundary layer. The technique is based on the assumption that the flux density of an entity is related to the mean of the product of the fluctuation of vertical windspeed and the fluctuation of the entity (typically air temperature or water vapour density). A necessary requirement is that for a sufficiently long period of time the quantities of ascending and descending air are equal.

Swinbank (1951) first introduced the method for measuring the vertical flux density of heat. His theory was subsequently applied to latent heat and CO_2. Application of eddy correlation theory results in the following equations:

$$F_h = \rho_a c_p \overline{w'T'} \quad (1)$$

$$L_v F_w = L_v \overline{w'q'} \quad (2)$$

where F_h is the sensible heat flux density (W m^{-2}), ρ_a is the density of dry air (kg m^{-3}), w′ is the instantaneous fluctuation of vertical wind speed (m s^{-1}), T' is the instantaneous fluctuation of air temperature (°C), L_vF_w is the latent heat flux density (W m^{-2}), c_p is the specific heat capacity of dry air at constant pressure (J kg^{-1} °C^{-1}), q' is the instantaneous fluctuation in water vapour density in the vertical direction (kg m^{-3}) and the overbars indicate time average values (typically 10 to 30 minutes). The ECT measurements (Equations 1 and 2) are in theory absolute so that net irradiance (I_{net}) is not required for measurement of evaporation. However, invoking the shortened energy balance

$$I_{net} = L_vF_w + F_h + F_{soil} \quad (3)$$

(where L_vF_w and F_h are measured using ECT and where F_{soil} is soil heat flux density) and defining closure C

$$C = \frac{L_vF_w + F_h}{I_{net} - F_{soil}} \quad (4)$$

provides a method for checking the validity of ECT measurements.

Tanner, Tanner, Dugas, Campbell & Bland (1985) evaluated six eddy correlation systems. They found that the turbulent flux measurements tend to underestimate the fluxes. Their six systems gave energy balance closure C (Equation 4) of between 0.69 to 1.02. Tanner (1988) found that the closure term in the energy balance equation was uncharacteristically close to unity when comparing two ECT systems with two EBBR (energy balance Bowen ratio) systems.

A relatively inexpensive sonic anemometer suitable for eddy correlation technique measurements has been developed (Campbell & Unsworth, 1979). The fluctuation in w' is important as it is correlated with both fluctuations in air temperature and water vapour density. Their sonic anemometer had good directional characteristics, excellent frequency response and a linear response to wind speed. The 0.1 m pathlength allows for a measurement height of 1 m above crop canopies. Biltoft & Gaynor (1987) found the thermal

time constant to be considerably less than the 20 minutes suggested by Tanner (1984, quoted by Biltoft & Gaynor, 1987).

Campbell & Tanner (1985) designed an ultraviolet krypton hygrometer for measurement of water vapour densities. Included among its positive characteristics are its high sensitivity, short measurement path and its low power consumption.

Kaimal (1975) stated that the minimum height for eddy correlation sensors is:

$$z_{min} = 6\pi d \quad (5)$$

where z_{min} is the minimum sensor height above ground and d is the sensor resolution. This indicates that for a CA27 sonic anemometer (Campbell Scientific, Logan, UT, USA) with a 0.1 m path length, the minimum sensor height is 1.9 m. Height of the ECT sensors recorded in the literature range from 0.9 m above wheat stubble (Tanner, 1988) to 2.2 m above a cotton crop (Barnes, Karl, Kunkel & Stone, 1990). It is therefore apparent that there is currently no standard regarding the placement height of eddy correlation sensors.

Our aim was to measure evaporation from maize using the eddy correlation technique, a technique that is portable, non-destructive and absolute and 1) to compare these measurements with EBBR measurements, 2) test for closure, and 3) compare them with equilibrium evaporation under certain conditions. Finally, some of the ECT assumptions and the sensors were to be examined for their adequacy.

Materials and Methods

A model CA27 sonic anemometer based on the design of Campbell & Unsworth (1979) was used. Care was taken to prevent the transducers from getting wet by dew or sudden thunderstorms. The ECT system was never left to stand outdoors overnight; usually measurements were made on single days between 10h00 and 15h00.

Air temperature fluctuations were measured using a 13 μm fine-wire Type E thermocouple (model 127, Campbell Scientific, Logan, UT, USA). The thermocouple was placed 20 to 30 mm from the sonic anemometer path. Water vapour density fluctuations were measured with a model KH20 ultraviolet adsorption hygrometer (Campbell Scientific, Logan, UT, USA). The KH20 windows were cleaned every two hours by lightly rubbing the windows using cotton buds previously dipped in distilled water. The purpose of this was to remove the scaling of the source tube window due to disassociation of atmospheric constituents by the ultra-violet photons. Two calibration curves were supplied with the KH20 hygrometer, one for the wet range and the other for the dry vapour range. These two data sets were combined into a single quadratic relationship.

The soil heat flux density (F_{soil}) was estimated as the sum of the measured soil heat flux density at a depth of 100 mm (F_{plate}) and the calculated change in heat storage for the 100 mm above a pair of soil heat flux plates (F_{stored}). The component F_{stored} had to be processed at a later stage as the bulk density and soil water content was required but unknown at the time of field data collection. This was the only component of the energy balance (that is, excluding energy used in photosynthesis and advected energy) that could not be calculated on a real time basis.

Additional micrometeorological measurements collected included net irradiance (Q*6 net radiometer, REBS Inc., Seattle, WA, USA), air temperature, water vapour pressure (PC207 probe, Campbell Scientific, Logan, UT, USA), wind speed and wind direction.

The CA27 sonic anemometer, the 127 thermocouple and the KH20 hygrometer were placed at a height of 1.9 m above the crop canopy in accordance with the recommendations of Kaimal (1975). However, logistical problems were experienced when the ma reached its full height.

All equipment was powered by two 12 V lead acid batteries. One battery powered the ECT sensors the second powered the micrologger. A 21X (Campbell Scientific, Logan, UT, USA) micrologger was used to supply the necessary excitation voltages to the sensors and to record all measurements. The 21X micrologger was programmed to convert all voltage measurements to their S.I. equivalent using their calibration data. This meant the measured energy flux densities were available on a real time basis, enabling the relative magnitude of the various components of the energy balance to be checked *in situ*. A simplified flow chart of the micrologger program is shown (Figure 1). We chose an averaging period of 10 minutes as this would reduce errors caused by an insufficiently long thermal time constant for the thermocouple reference junction.

The calibration data for the KH20 krypton hygrometer for both wet and dry water vapour ranges were combined into a single quadratic relationship. This relationship formed part of the micrologger program and has helped towards the use of real t measurements in the field.

Sites

The experiments were conducted at two sites. The ECT systems were compared with two EBBR systems and a lysimeter which are permanently placed at Catchment VI, Cathedral Peak. The site consists of a mixed grassland community and has a moderate slope and the dominant breeze is upslope (from the north). The ECT system was placed 3 m from the EBBR systems.

The second set of measurements were performed on a maize crop at the Cedara Agricultural Development

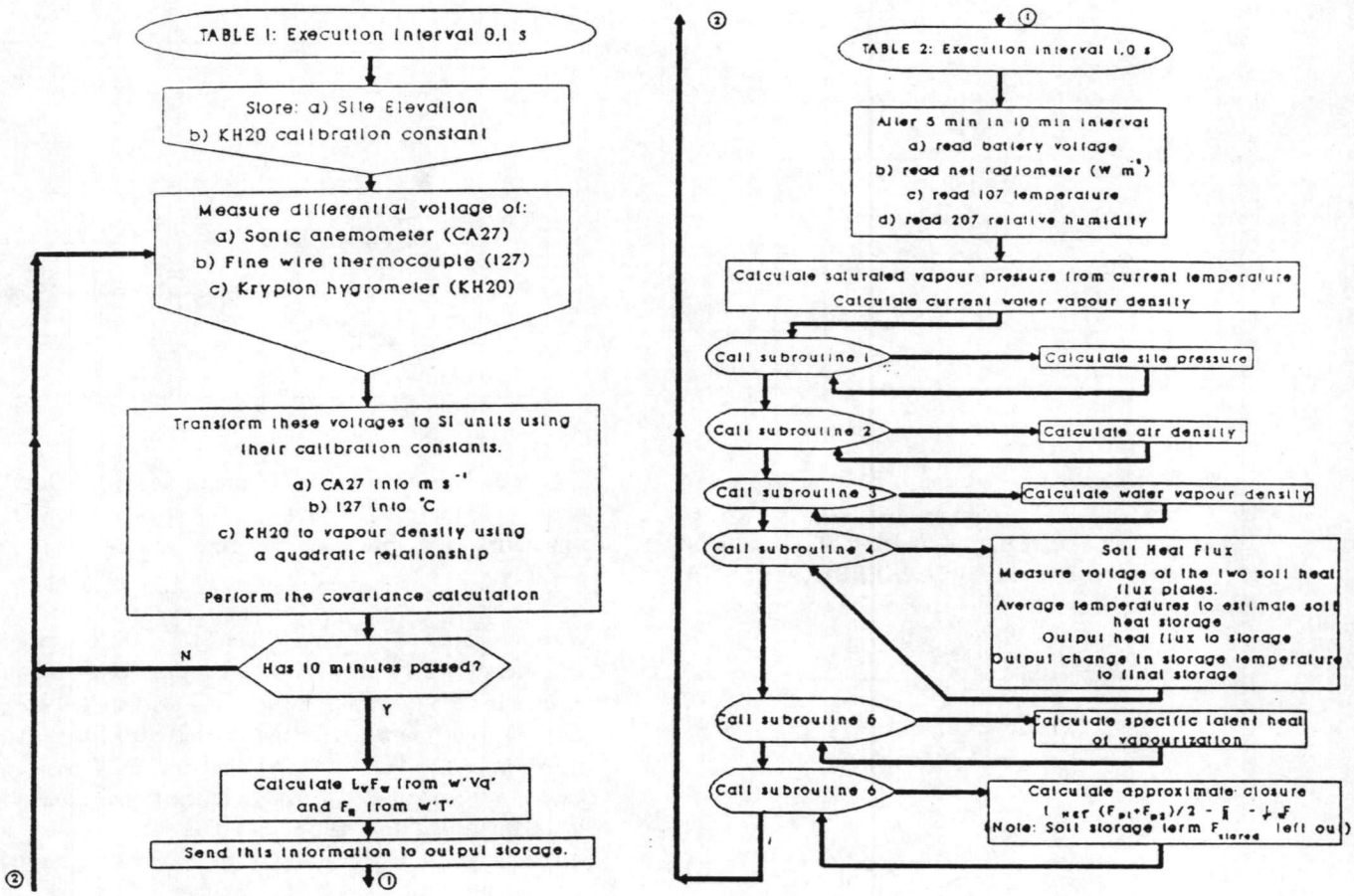


Figure 1 Simplified flowchart of the eddy correlation micrologger program for real-time evaporation measurements.

Institute, Natal. These maize fields were closely monitored by the GCI (Grain Crops Institute) for data validation and verification of daily crop growth simulation models in the RSA. The field used for measurements was planted on the 13 November 1990 at a density of 4.4 plants m^{-2}. This field was rainfed; however some adjacent fields consisted of irrigated pasture.

Results and Discussion

A simple but useful test of eddy correlation data is possible by examination of the energy balance closure ratio (Equation 4). If the closure ratio C is less than 1, then the aerodynamic component $L_vF_w + F_h$ has been underestimated. We have obtained closure values of between 0.581 and 0.893 for our measurements over maize, indicating an underestimation of measured latent or sensible heat flux densities or both for a given measured net irradiance and soil heat flux density. When comparing ECT with EBBR at Cathedral Peak, we found the L_vF_w sensed by the ECT to be consistently below the measurements indicated by the EBBR (Figure 2). This underestimation is also confirmed by comparing equilibrium evaporation with eddy correlation evaporation during periods of low vapour pressure deficit and sufficient soil water (Figure 3). Under conditions of positive Bowen ratio values, that is both latent and sensible heat being removed from the canopy, we have always found eddy correlation sensible heat to be small in magnitude but negative (towards the surface) and latent heat positive. We maintain therefore that the reason(s) for closure value C (Equation 4) being less than unity are due to small sensible heat (Equation 1) and small latent heat (Equation 2) values by comparison with other measurements or calculations of evaporation.

After initially comparing the ECT estimate of evaporation to the EBBR estimate at Cathedral Peak, the ECT estimate has generally been found to be below the EBBR. Since the EBBR has been shown to compare favourably with equilibrium evaporation during the summer season, when soil water is not limiting and vapour pressure deficit is low (Savage, Everson & Metelerkamp in press), we feel more

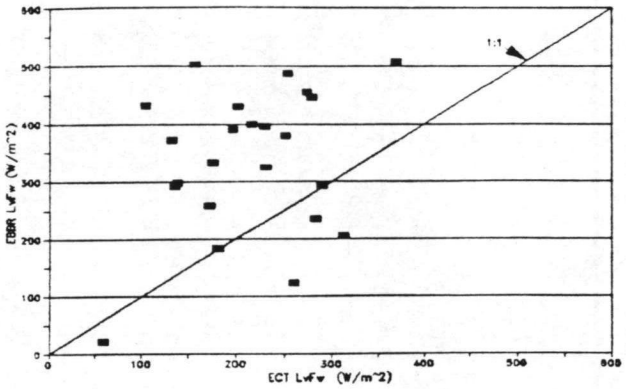


Figure 2 Comparison between L_vF_w measured using the EBBR and ECT over a two day period at Cathedral Peak. Averaging periods of 20 minutes and 10 minutes were used by the EBBR and ECT, respectively. The 1:1 line is shown for convenience.

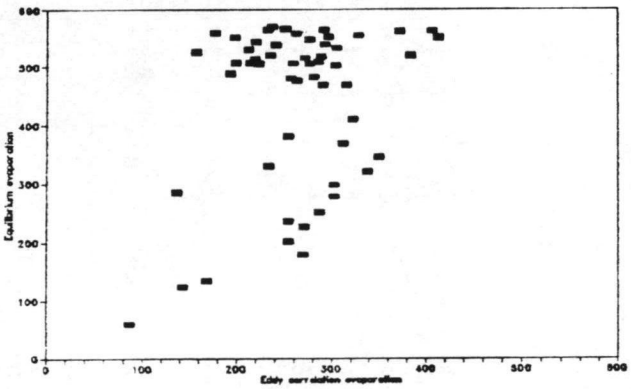


Figure 3 Comparison between equilibrium evaporation and latent heat flux densities, the latter measured using the eddy correlation technique.

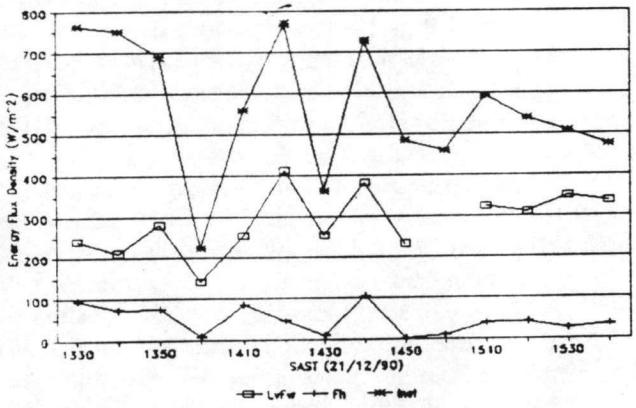


Figure 4 Diurnal variation in some of the energy balance components, the latent and sensible heat flux density being measured using the eddy correlation technique.

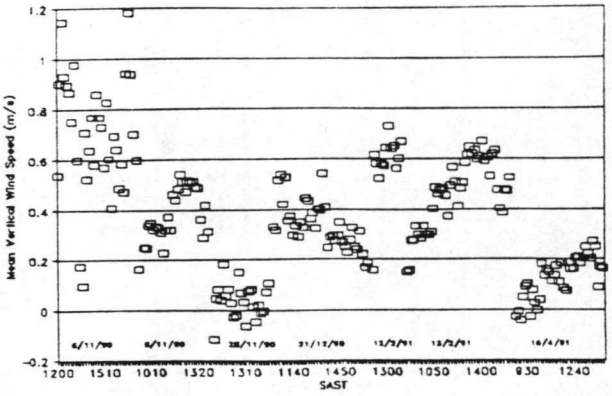


Figure 5 Variation in the 10-minute average vertical wind speed on selected days over a five-month period, illustrating the frequent non-zero nature of this quantity.

attention needs to be given to the ECT L_vF_w estimate.

Generally, L_vF_w was about twice the magnitude of F_h during all our measurements. It is evident that L_vF_w and F_h react immediately and strongly to changes in I_{net} (Figure 4). This indicates that the ECT sensors have a fast response to a change in their environment. It is important to ensure that the sensors have a sufficiently fast response and that the averaging period is of sufficient length to include all scales of fluctuations contributing to the flux density (Miyake & McBean, 1970).

One of the initial assumptions in eddy correlation theory is that for a sufficiently long period of time the quantities of ascending and descending air are equal. However, this is not always the case (Figure 5). The implications of non-zero time-averaged vertical wind speed needs to be examined and quantified.

Conclusions

ECT evaporation estimates have practical potential in South Africa where a reliable, portable and absolute measure of evaporation is required. Both ECT F_h and ECT L_vF_w are underestimated when compared to other measurement techniques such as Bowen ratio and equilibrium evaporation. There are a number of aspects that require further attention. These, in particular, are: 1. the importance of the assumption regarding the quantity of ascending and descending air; 2. the effect of KH20 vapour density measurement on the calculation of L_vF_w; 3. achievement of a closure ratio of unity; 4. the reduction of imponderables caused by insufficient fetch.

The eddy correlation technique has the potential to become a very useful tool for those who need a portable and accurate means of measuring evaporation.

Acknowledgements

We are most grateful to Mr W.A.J. Berry (GCI) for his contribution to the maize experiment at Cedara. Financial support for this research from the Foundation for Research Development, Institute for Soil, Climate and Water, University of Natal, University of Natal Research Fund and the Water Research Commission is gratefully acknowledged. We also acknowledge Forestek (CSIR) for the use of facilities at Cathedral Peak.

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WATER-YIELD FUNCTIONS OF FIVE TEMPERATE FORAGE CROPS

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Abstract

This paper reports on an investigation into the water requirements of *Triticale* (*Triticum* x *Secale*), wheat (*Triticum aestivum*), oats (*Avena sativa*), arrow leaf clover (*Trifolium vesiculosum*) and annual ryegrass (*Lolium multiflorum*). Four water stress treatments (control, slight, moderate and severe stress) were applied to small plots, with sub-surface divisions under a rain shelter. Water yield functions, which are in fact simple crop models containing useful practical information, were obtained. The water yield regression curve for clover had the steepest slope showing that yields are lowered drastically when water application rates are not optimal. Oats on the other hand had the flattest slope and had the hig yield potential. The results suggest that this crop is very well suited for marginal conditions but because of its high yield potential it could also be the most water efficient crop to plant under optimally irrigated conditions. The response of w *Triticale* and ryegrass to water application rates did not differ much, but wheat had a very much lower yield potential under the prevailing conditions.

Introduction

Irrigated forage crops play an invaluable role in intensive livestock production systems. The demands on available water resources by the rapidly expanding industrial sector however, necessitate that water used for irrigation of forage crops be used as effectively as possible. In this respect sound management decisions should be focused on the water use efficiency of alternative pasture crops.

Since the first comprehensive analysis of the relationship between transpiration and yield was offered by De Wit (1958), interest in yield response to water supply has grown. Water-yield functions are empirical crop models describing the proportionality between yield and water use. Streutker (1980, 1983a & 1983b) determined water-use functions for various agricultural crops in South Africa and showed how these relationships can be used for planning purposes. Efficiency of water use and irrigation management can be evaluated when water-yield relationships are known for individual crops.

Planted pastures have in the past been researched under irrigated conditions (Goodenough, Macdonald & Morrison, 1984; Van Heerden, 1986) but water relations were not the primary objective. Apart from lucerne, very little was known about the water requirements of forage crops in South Africa before this study was undertaken in 1989. Green (1985) specified a single set of crop factors "in the absence of specific experimental results" for all planted pastures and all growing areas in South Africa. The aim of this study was to investigate the water requirements of five selected annual temperate species and to characterize their differential responses to water regimes by means of water-yield functions. Priority was given to annual temperate species because of their greater flexibility in double cropping systems and their potential contribution in the critical autumn, winter and spring feeding period.

Procedure

The research was conducted on the F ield Experimental Farm of the University of Pretoria. Small plots (2 000 mm x 2 500 mm) under an auto ed rainshelter were used. Subsurface divisions were installed to a depth of 1 200 mm with minimal disturbance of the soil profile. The soil was a Hutton form (Macvicar, De Villiers, Loxton, Verster, Lamprecht, Merryweather, Le Roux, Van Roo & Harmse, 1977). The trial was planted in 1989 and repeated in 1990.

Triticale (cv. R1), wheat (cv. Inia), oats (cv. Overberg), arrow leaf clover (cv. Yuchi) and annual ryegrass (cv. Midmar) were subjected to four water stress treatments. The 20 treatment combinations were replicated three times in a randomized block gn. Leaf water potential (Ψ_l) was used as the criterion to differentiate between water stress levels. Irrigation quantities were such that soil water contents were restored to the upper level of plant available water with each irrigation. Following on Joubert (1987) and Oosterhuis & Walker (1982) the following treatments were applied after establishment was done on a wet soil profile:

W1 - no stress, irrigate weekly (bi-weekly in late spring and summer)

W2 - irrigate when Ψ_l decreased to 0.7 MPa below of control

W3 - irrigate when Ψ_l decreased to 1.3 MPa below that of control

W4 - irrigate when Ψ_l decreased to 1.8 MPa below that of control

Midday leaf water potentials were determined with a Scholander pressure bomb (Scholander, Hammel, Bradstreet & Hemmingsen, 1965). Soil water depletion was determined by monitoring soil water content with a 503DR neutron hydroprobe. Depth increments of 200 mm were calibrated (Greacen, 1981) separately

monitored to a depth of 1 800 mm. One neutron probe per plot was installed in the middle of the 1 000 mm x 1 000 mm subplot that was harvested. Irrigation quantities were calculated by accumulating soil water deficits for the different soil layers. The deepest 200 mm layer was not taken into account and was allowed to dry out. Thus a reservoir for possible drainage from the top layers was created and maintained.

Water use was calculated every week by taking into account the soil water content difference and irrigation applied. Total water use was determined by adding these weekly calculated water use rates.

All plots received lime, phosphorus and potassium according to the guidelines of Buys (1986). Nutrients were incorporated before planting to ensure that nutrient deficiencies would not occur. All crops but clover were planted with 100 kg ha^{-1} nitrogen (N). The clover seed was innoculated but as this did not appear to be effective, all crops received 50 kg ha^{-1} N after each harvest.

Wheat, Triticale and oats were planted at a rate of 100 kg ha^{-1} seed and ryegrass and clover at rates of 15 and 25 kg ha^{-1} respectively. Planting was done in rows 200 mm apart.

Clover and ryegrass were harvested and dry matter production determined when a height of approximately 150 mm was reached. The other crops were harvested on reaching a height of approximately 250 mm and were not cut again after the reproductive phase had been reached.

The experiment was repeated in 1990 with some changes to the procedure namely:

a) Inia was replaced by Scheepers 69 because the latter is a better wheat cultivar for forage purposes.
b) Water stress treatments were changed to:
   W1 - no stress, irrigated weekly to the upper level of plant available water
   W2 - irrigated weekly at 75% of irrigation used for control
   W3 - irrigated weekly at 50% of irrigation used for control
   W4 - irrigated weekly at 25% of irrigation used for control
c) The grain crops were harvested an additional three times after the winter months, i.e. after commencement of the reproductive phase. This was done to obtain more green fodder from these crops.

Total dry material was determined by accummulating all yields that had been obtained during the year. Although determined, the first yield, which except for clover was on average about 2 000 kg ha^{-1}, and the water use up to the time of the first yield, were not taken into account for statistical purposes. Irrigation treatments started only after the crops were well established and once the first yield had been harvested.

Results and discussion

Linear relationships between dry matter production and water use for the different crops are illustrated in Figure 1. It is clear from these data that a better spr of water use values was achieved in the 1990 season, when another method was used to differentiate between stress treatments.

The results illustrated in Figure 1a demonstrate that the regressions obtained for oats were very similar for the two seasons. These relationships are similar to that reported by Hanks, Gardner & Florian (1969). Maximum yield was 17 500 and 12 500 kg ha^{-1} for the 1989 and 1990 seasons respectively. The reduction in the 1990 yield was caused by the removal of growing points during the post winter harvest, resulting in less grain being produced.

According to the data in Figure 1b clover responds drastically to varying water levels and would appear to be very sensitive to water stress conditions. The maximum yield was 11 800 kg ha^{-1} for the 1989 season but only 6 300 kg ha^{-1} was obtained for the 1990 season. It is not clear why the control yielded so poorly in the second season.

The data for wheat fitted the linear regression very well (Figure 1c). The response of Scheepers 69 v much the same as that obtained for Inia in the 1989 season. The maximum yield was 7 800 kg ha^{-1} for the 1990 season and 7 200 kg ha^{-1} for the 1989 season. The slopes of these water-yield functions are steeper t those reported by Streutker (1983a) in which grain yield was related to water use. However, water-yield functions compiled by Streutker (1980) from estimated total day matter yield also had steeper slopes than those of Streutker (1983a). Hanks *et al.* (1969) similarly reported a steeper slope for the water-yield function of wheat. In both instances, however, the crop had never been cut during the growing season.

The yield of *Triticale* was lower in the second season for the same reason that caused the yield of oats to be depressed. The maximum yield for *Triticale* was 17 300 and 9 400 kg ha^{-1} for the 1989 and 1990 seasons respectively. The reaction to additional water was, however, similar in both years (Figure 1d). Ryegr also reacted similarly in both seasons (Figure 1e). The maximum yields were 13 800 and 11 400 kg ha^{-1} for 1989 and 1990, respectively.

Results for the two seasons were combined to enable comparison of yield responses of the different crops. It can be seen in Figure 2 that the four grass crops reac similarly to increased water regimes. Clover reac markedly differently. The steeper slope of the clover function suggests a crop that is less tolerant to water stress. Yield dropped by 30 units for each unit drop in water availability. The returns on each additional unit of water applied will thus be the greatest for clover but total applied water will not necessarily be utilised the most effectively.

From Figure 2 it is clear that water regime should be taken into account when trying to determine which crop

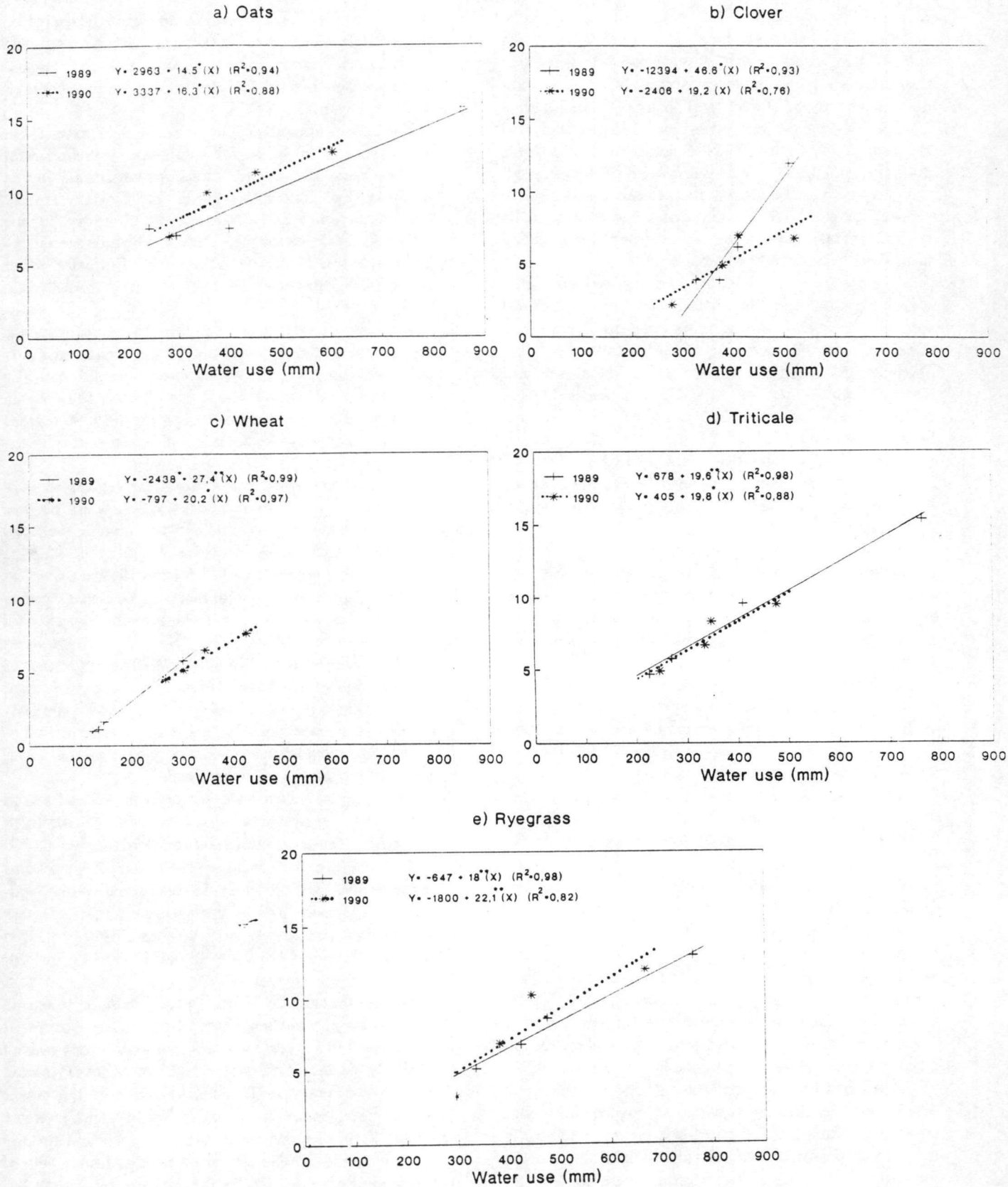


Figure 1 Yield-water use functions for five annual temperature forage crops as obtained for two different seasons

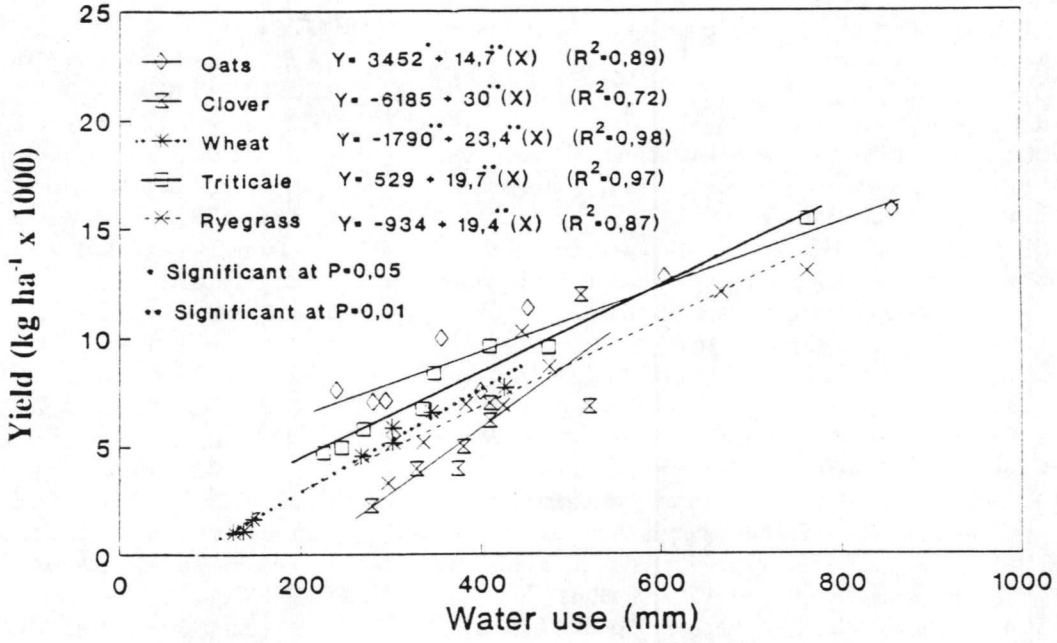


Figure 2 Yield-water use functions for five annual temperate forage crops (data combined for two seasons)

is the most water efficient. Up to a level of 600 mm oats and *Triticale* will yield the highest with the same amount of water suggesting the most water efficient crops. Above the 600 mm level clover will theoretically yield the highest but yields higher than 11 800 kg ha^{-1} (Figure 1b) do not seem attainable under the conditions that prevailed in this experiment. Although clover might not be the most water efficient crop for restricted water supplies, often encountered on farms, it might be planted for other reasons (e.g. high spring production rate, nitrogen fixation, etc.).

If clover were to be planted it appears that a high level of irrigation management would be needed to achieve satisfactory results. The decline in yield with decreased water application is more marked with clover than with the other crops. The risks of losing water and nutrients through deep drainage are higher when water application is maintained at high levels, as is required by clover.

The water-yield function for oats had the flattest slope and the largest y-intercept (Figure 2). It is therefore the most tolerant to varying irrigation levels and has a very good water use efficiency. This will obviously be the crop to plant if the aim is to produce maximally with minimum amounts of water. The other grass crops reacted similarly to oats but on average produced approximately 1 000 to 2 000 kg ha^{-1} less at lower water application rates.

Yields for forage crops are also influenced by cutting height, cutting frequency and production practices other than irrigation scheduling. As such, yield responses to varying water regimes must be seen as situation specific and one would not encourage too wide a generalisation in the usage of these simple models. Yet, when no site specific data are available these models may be used with success by agronomists, engineers and economists for planning purposes. As was shown in this experiment the models are handy tools for evaluating yield responses of different crops to varying irrigation levels.

Conclusions

The relatively low yield potential of wheat and arrow leaf clover suggests that these crops should not be considered when high yielding forages are required under irrigated conditions. Another disadvantage of arrow leaf clover is that a high demand on managerial skills will be made because this crop is very sensitive to suboptimal provision of water. Any one of the remaining three crops should satisfy requirements as their yield potentials did not differ widely under the prevailing experimental conditions. The good linear fit of their water yield regression curves suggests relatively tolerant crops which will, *pro rata*, produce less when less water is applied and more when more water is applied. Oats should be planted when little water per unit land is available or when the risk of water rationing is high as this crop seems to be less affected by decreased water application rates. Production patterns, however, differ between crops and regions and this will be an important deciding factor.

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A COMPARATIVE STUDY OF PAWC AND THE BEHAVIOUR OF WHEAT AND DURUM WHEAT UNDER STRESS CONDITIONS

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Abstract

The profile available water capacity (PAWC) for wheat and durum wheat was determined at different growth stages. The stem elongation rate (SER) proved to be useful for indicating first material stress (FMS) in wheat and durum wheat plants during early growth stages, while pre-dawn leaf water potential (PLWP) could be used to indicate FMS in mature plants. In young plants PLWP was more sensitive to incipient water stress conditions than in older plants. During early growth stages (i.e. until appearance of the first node) FMS was clearly identified when PLWP decreased to about -800 kPa, which is much higher than the PLWP indicating FMS in mature plants. In durum wheat young, immature leaves had lower PLWP values than older leaves and this could mistakenly be interpreted as an indication of FMS if care was not taken to sample leaves of similar age. PLWP of wheat was not as sensitive to leaf age. Other differences between wheat and durum wheat were found: firstly, durum wheat appeared to be more sensitive to water stress during early growth stages than wheat; secondly, the PAWC of durum wheat was constantly lower than the PAWC of wheat at the same growth stage; and thirdly, leaf water potential patterns of durum wheat did not show the rhythmic oscillations found in wheat as FMS was approached.

Introduction

The profile available water capacity (PAWC) for a specific crop grown in a specific soil and under a certain evaporative demand is, by definition, the amount of water which is held in the root zone between field capacity and first material stress (Hensley & De Jager, 1982).

For a detailed review of PAWC by the authors, refer to Vannassche & Laker (1991).

The purpose of this study was to determine the PAWC of wheat and durum wheat in the field, to study the effects of water stress on both crops and to compare the behaviour of both crops under water stress conditions at different growth stages.

Materials and methods

This paper uses experimental data reported by Vanassche & Laker (1989). The research was conducted at the Cradock Research Station of the Department of Agriculture and Water Supply near Cradock in the Eastern Cape Province, Republic of South Africa. Cradock (32 08'S, 25 37'E; 660 m above sea level) is situated about 250 km north of Port Elizabeth at the eastern border of the Great Karoo, a large semi-arid region in the central part of South Africa. The soil is a young soil of alluvial origin and is classified according to the South African binomial soil classification system (MacVicar, De Villiers, Loxton, Verster, Lambrechts, Merryweather, Le Roux, Van Rooyen & Harmse, 1977) as an Oakleaf (Limpopo series). According to Soil Taxonomy (Soil Survey Staff, 1975) the soil is classified as a Mollic Ustifluvent.

Five plots of 5 m by 5 m were layed out at three sites. An aluminium neutron hydroprobe access tube was inserted in each plot to a depth of 1 500 mm. The plants grown on the plots were protected against animals by a fence of strong netting and against rain by movable rainsheds. The type of irrigation was flood irrigation and a centrifugal pump, which was calibrated at regular time intervals, was used to transfer water from an irrigation furrow to the plots. The wheat (*Triticum aestivum*) and durum wheat (*Triticum turgidum*) cultivars were Gamtoos and Mondi. Wheat was planted on 16-06-1986 and durum wheat on 22-06-1987, both at a rate of 100 kg seed per hectare. Fertilizer applications, planting densities and pest and weed control treatments were recommended by the local researcher (Mr J. Pretorius, personal communication, 1986 and 1987) at the Cradock Research Station.

Soil water measurements were done by means of a Campbell Pacific Nuclear neutron hydroprobe (Model CPN 503). The instrument was calibrated against different soil water contents determined gravimetrically at depth intervals of 150 mm.

PLWP measurements were done by means of a pressure chamber similar to the one described by Scholander, Hammel, Hemmingsen & Bradstreet (1964). The method of sampling, measuring and the sequence of measuring were done according to a standardized procedure in order to obtain representative and reproducible values (Vanassche & Laker, 1989).

Stem elongation measurements were done at regular time intervals on ten randomly selected plants in each plot. The different growth stages of wheat and durum wheat at which the different drying cycles were started are listed in Table 1.

Results and discussion

The experiments were conducted during 1986 with wheat and during 1987 with durum wheat. However, evaporative demand during both seasons was comparable, with an average difference of less than

Table 1 Growth stages at which drying cycles for wheat and durum wheat were started.

Days after planting				Phenological stage
Plot	Wheat	Plot	Durum wheat	
a	42	a	45	Tillering
b	52	-	-	Leaf sheaths erect
c	62	c	65	First node of stem
d	72	d	80	Flag leaf visible
	-	f	100	Ears appear

0.4 mm per day. Influences on plant performance due to differences in evaporative demand were, therefore, not significant and the comparison between wheat and durum wheat regarding PAWC, PLWP, vegetative growth and yield can be justified.

PAWC values

PAWC values for wheat and durum wheat at different growth stages are listed in Table 2. The PAWC of durum wheat was constantly lower than that of wheat at all growth stages. Furthermore, when calculating the ratio of the PAWC of durum wheat to that of wheat a more or less constant value of 85% was found. Similar differences were found at other sites (Vanassche & Laker, 1989). Hensley & De Jager (1982) found similar differences in PAWC with maize and sorghum. The ratio of the PAWC of sorghum to that of maize was also about 85%. Durum wheat extracted water at a lower rate than wheat and FMS was reached at the same time after irrigation. This is, interestingly enough, again identical to the sorghum/maize comparisons of Hensley & De Jager (1982).

Table 2 PAWC values for wheat and durum wheat at different growth stages.

Plot	PAWC (mm)		Ratio (%)
	Durum wheat	Wheat	(Durum wheat/wheat)
a	85	102	83
b	-	119	-
c	121	136	89
d	123	145	85
f	125	145	86

Pre-dawn leaf water potential (PLWP)

The PLWP patterns of wheat and durum wheat are illustrated in Figures 1 and 2 respectively. It became clear that during early growth stages (i.e. until stage 7 according to Large, 1954) wheat and durum wheat plants are more sensitive to reductions in PLWP than during later growth stages. During these early growth stages FMS was clearly identified when PLWP decreased to about -800 kPa. During later stages FMS is indicated only by PLWP values of clearly less than -1000 kPa as was also found by Boedt & Laker (1985).

Typical for almost all PLWP patterns of wheat was the fluctuating phase observed at the end of the drying cycles. This phase was characterized by a more or less rhythmic oscillation between low (under -1000 kPa) and relatively high values (-500 kPa) with decreasing low values. This pattern presumably reflects the ability of the plant to recover temporarily. This pattern was not found with durum wheat. Meyer & Green (1981) studied stomatal action in wheat and soybean plants. They found that stomatal behaviour in wheat in a drying situation was apparently modified by osmotic adjustment. Such a reaction would tend to maximize growth while minimizing huge loss of water. They also found differences in stomatal action between wheat and soybeans. From this, there appeared to be little osmotic adjustment in soybeans compared to wheat (Meyer & Green, 1981). In this respect, it is suggested that durum wheat behaves more like soybeans than wheat during drying conditions. Another difference between wheat and durum wheat is the large discrepancies in PLWP values found in young durum wheat plants. Young, immature leaves have lower PLWP values than mature leaves even on well-watered plots and this could be mistakenly interpreted as an indication of FMS. It is therefore very important to standardize the procedure of PLWP measurements even to the point of leaf selection. This was also stated by Boedt & Laker (1985) as a consequence of the results obtained during their research on PAWC of different crops on different soils. During our study the youngest mature leaves were selected for PLWP determinations.

Vegetative growth and yield

The lengths of the wheat plants at the end of the experiments are listed in Table 3 and were statistically analyzed. The design of the experiments is a randomized complete block design with water stress induced at different growth stages (plots a, b, c d and control) as experimental units and sites D6, D12 and D16 as blocks. The variation (ie. differences in soil profile characteristics) among units within a block is less than that among units in different blocks. The analysis of variance for any number of treatments in a randomized complete block design as described by Steel & Torrie (1980) was used. The analysis showed that there were significant differences between the treatment means (Table 4).

Soil water stress induced during growth stages b and c, i.e. shortly before and during the appearance of the flag leaf (stages 7 to 9 according to Large, 1954) resulted in significantly shorter plants relative to those which were stressed before and after this period

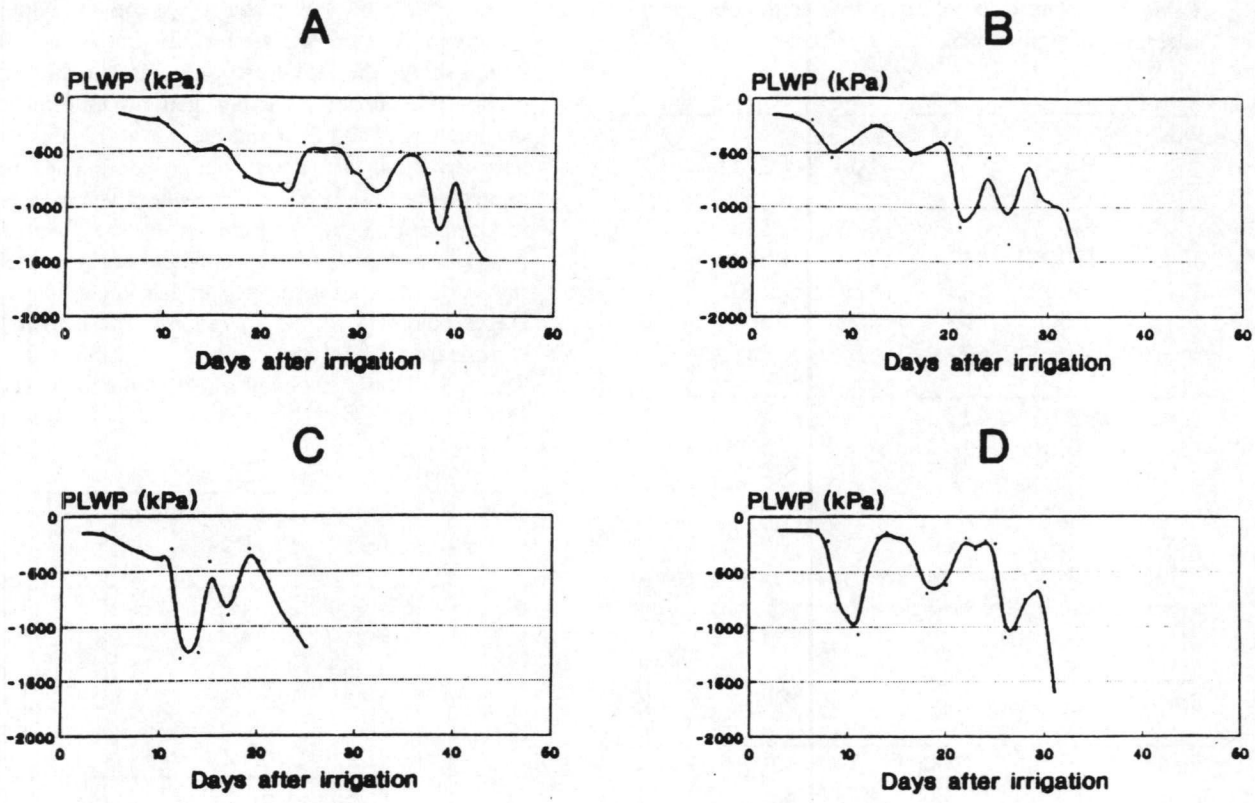


Figure 1 Pre-dawn leaf water potential patterns of wheat.

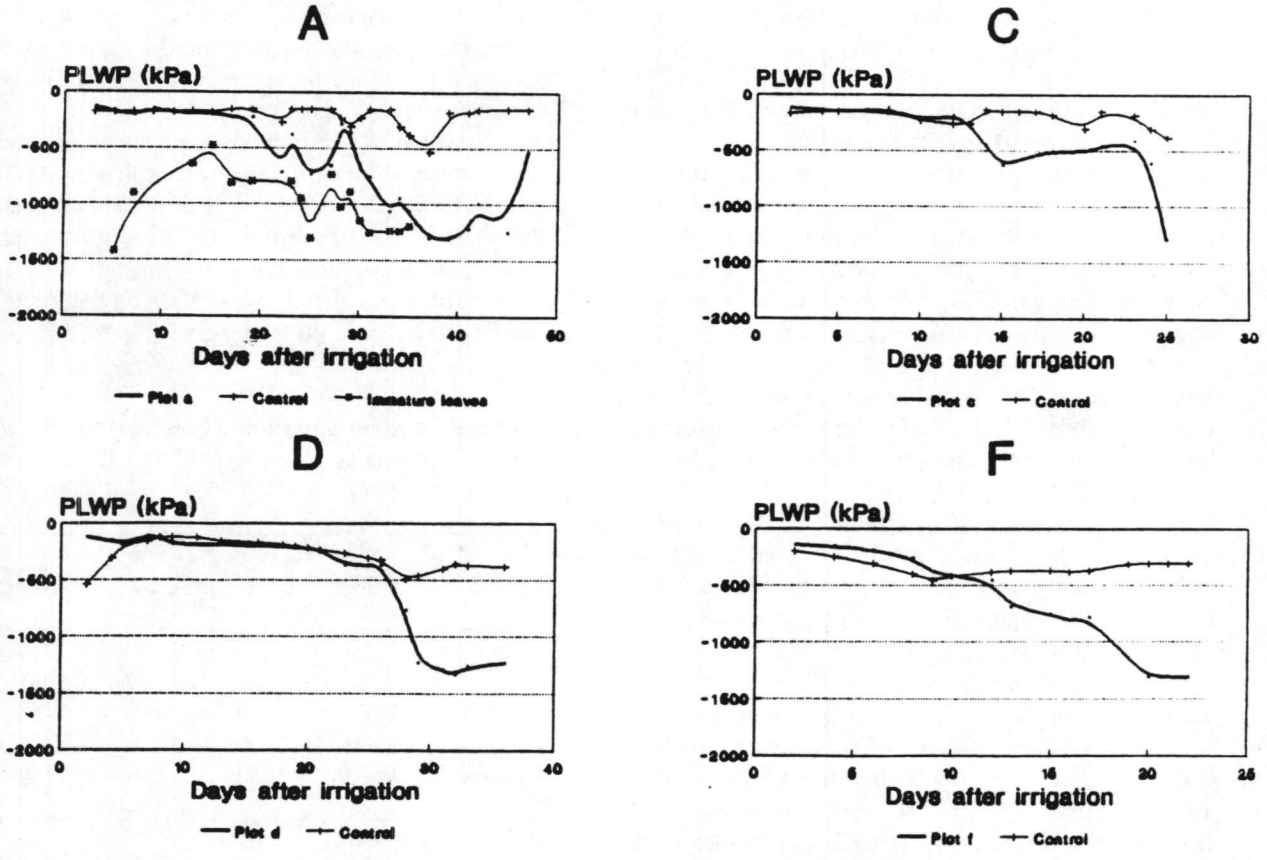


Figure 2 Pre-dawn leaf water potential patterns of durum wheat.

Table 3 Length of wheat plants at the end of the experiments at sites D6, D12 and D16.

Plot	Total length (mm)			
	D6	D12	D16	Average
a	640	630	620	630
b	590	480	470	510
c	540	520	530	530
d	610	590	600	600
control	660	660	620	650
lsd (p=0.05)		52		
(p=0.01)		75		

Table 4 Differences between mean final length of wheat plants stressed at different growth stages.

Growth stages	b	c	d	a
control	140**	120**	50	20
a	120**	100**	30	
d	90**	70**		
c	20			

** = significant at 1% level
* = significant at 5% level

(stages a and d) and to those of the control plot. This illustrates that wheat is sensitive to soil water stress, as far as vegetative growth is concerned, during a period starting with the appearance of the second node (stage 7 according to Large, 1954) and ending with the completion of flag leave development (stage 9 according to Large, 1954). When soil water stress was induced before this period the plants recovered after re-watering and reached a final length more or less equal to that of the non-stressed plants. Soil water stress after stage 9 had no effect on the final length of the plants as the vegetative growth phase had ended by that time.

Although the yields of the stressed treatments were lower than that of the control treatment, statistical analysis of the data listed in Table 5 indicated that there were no significant differences between the different treatments.

However, a least significant difference of 1.00 ton/ha (unprotected by F-test, p=0.5) indicated that the yield of treatment c (stressed at appearance of flag leaf) was significantly lower than that of the control plot. The lower yields at the more remote site D16 relative to sites D6 and D12 were the result of damage by birds.

The effects of soil water stress on the vegetative growth of durum wheat are illustrated in Table 6 which shows the length of the plants on the different plots at the end of the experiments. The effects were the smallest at site D16 and the reason for this was the very effective and deep root system. The smallest plants were found on the plots where water stress was induced during the appearance of the flag leaf (c-plots). The results of the statistical analysis indicated that water stress during any of the vegetative growth stages (stages a, c and d) reduced final plant height significantly

Table 5 Grain yields of wheat at sites D6, D12 and D16

Plot	Grain yields (ton/ha)			
	D6	D12	D16	Average
a	4.00	4.09	3.10	3.73
b	4.21	4.01	2.98	3.73
c	3.26	2.62	3.86	3.25
d	3.58	4.20	3.67	3.82
control	4.13	4.57	4.16	4.29

(Table 7). This is not the same as the results obtained with wheat where only the plants stressed during the late vegetative stages were significantly shorter than those of the control plots. Wheat plants which were stressed during the early vegetative stages recouped the loss and ended up comparable in size to those in the control plots.

The ears of the durum wheat plants on the a and c-plots emerged about a week earlier than on the other plots. Accelerated development is a common response to water stress during the vegetative phase and was also observed in the wheat experiments.

The influence of soil water stress on the grain yield of durum wheat is illustrated in Table 8.

Table 6 Length of durum wheat plants at the end of the experiments at sites D6, D12 and D16.

Plot	Total length (mm)			
	D6	D12	D16	Average
a	1050	1050	1150	1080
c	980	950	1000	980
d	1150	1100	1150	1130
f	1200	1200	1250	1220
control	1250	1250	1250	1250
lsd (p=0.05)		49		
(p=0.01)		66		

Table 7 Differences between mean final length of durum wheat plants stressed at different growth stages.

Growth stages	c	a	d	f
control	270**	170**	120**	30
f	240**	140**	90**	
d	150**	50*		
a	100**			

** = significant at 1% level
* = significant at 5% level

Yields obtained from the plots where water stress was induced during the vegetative growth stages (stages a, c and d) were significantly lower than those of the control plots and the f-plots where stress was induced after flowering stage (Table 9). Again this is dissimilar to the results obtained for wheat where no significant differences between treatments were found. The highest yields were found at site D16 which had the deepest effective root system. For every treatment the yield at site D16 was higher than the respective average of the three sites D6, D12 and D16. The lowest yields were obtained from the plots where water stress was induced during the appearance of the flag leaf (c-plots). This was also found with wheat.

Table 8 Grain yields of durum wheat harvested at sites D6, D12 and D16.

Plot	Grain yield (ton/ha)			
	D6	D12	D16	Average
a	3.70	2.81	4.55	3.69
c	2.33	2.83	3.99	3.05
d	4.05	3.33	4.38	3.92
f	4.71	4.59	5.49	4.93
control	4.55	4.77	5.06	4.79
lsd (p=0.05)	0.78			

Table 9 Differences between mean grain yield of durum wheat stressed at different growth stages.

Growth stages	c	a	d	control
f	1.78*	1.15*	0.91*	0.04
control	1.74*	1.11*	0.87*	
d	0.87*	0.2		
a	0.64			

* = significant at 5% level

Conclusions

During this study the behaviour of durum wheat under water stress conditions was compared to that of wheat. Four differences were found:

Firstly, the PAWC of durum wheat was lower than the PAWC of wheat at every growth stage. The PAWC of durum wheat was about 85% of the PAWC of wheat. Similar differences in PAWC were found by Hensley & De Jager (1982) with maize and sorghum. Durum wheat extracted water more slowly than wheat and FMS was at the same time after irrigation. This is, interestingly enough, again identical to the sorghum/maize comparisons of Hensley & De Jager (1982).

Secondly, oscillations of PLWP found in wheat during the drying cycles were not observed in durum wheat. After FMS was reached, PLWP of durum wheat remained low (-1 000 kPa) when the drying cycle was prolonged. The oscillations in wheat reflect the ability of the plant to recover partially and may possibly be explained by osmotic adjustment in the wheat plants.

Thirdly, PLWP of young, immature durum wheat leaves was constantly lower than that of mature leaves even on well-watered plots. In wheat no differences between mature and immature leaves were measured.

Fourthly, durum wheat plants did not fully recover after water stress had been induced during the vegetative stages. Water stress had a permanent effect on stem elongation and grain yield.

Acknowledgement

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INCREASING GRAIN YIELD BY OPTIMIZING PLANTING DENSITY OF MAIZE: A CROPPING STRATEGY FOR CONDITIONS OF SUB-OPTIMAL WATER SUPPLY

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Abstract

The effect of planting density on the grain yield of maize was determined in a field experiment repeated over three seasons. The study was undertaken with the object of evaluating the cropping strategy of matching planting density in maize to the prevailing level of available soil water. The results demonstrated a positive interaction between level of available water and plant population on grain yield. Optimum planting density exceeded 60 000 plants per ha where the soil water supply was adequate. Where the water supply was inadequate planting density needed to be reduced in accordance with the degree of soil water deficiency. A reduction in planting density resulted in a less rapid depletion of stored soil water, thereby delaying the onset of water stress. The available evidence suggested that maximum benefit from reduced plant populations can be obtained only when the storage capacity of the soil is fully exploited.

Introduction

Most Ciskeian irrigation schemes involved with maize production have adopted sophisticated fertilization programmes and high plant populations in order to maximize grain yields. Because of the high production costs involved, growers agree that yields of 8 tons per ha or more are required in order to make production of irrigated maize economically viable. However, grain yields rarely exceed 6 tons per ha and yields as low as 3 tons per ha are not uncommon. As a result, most schemes have replaced maize with crops which are considered to be more profitable such as carrots, cabbage, tomatoes, potatoes and lucerne.

Available evidence indicates that the disappointing performance of irrigated maize in Ciskei is associated with a deficient water supply to the crop. Local conditions require maize to be planted during the first two to three weeks of October so that the crop reaches the stages of anthesis and early grain filling during late December and early January, thereby causing the grain filling period to coincide with the period of peak radiation as closely as possible. However, December and January also represent a period of maximum water deficit. When irrigation practices fail to meet the water requirements of the crop during this period grain yield is seriously affected. The harmful effect of water stress is further enhanced by high levels of intra-specific competition which occur when maize is planted at the recommended density of 60 000 plants per ha. Some schemes employ populations as high as 70 000 plants per ha. There are several reasons why local irrigators are unable to meet the water demand of the crop.

These include:

1) the inability of irrigation systems to meet peak water demand;
2) the incompatibility of the prevailing labour structure of the irrigation schemes with the demands of irrigated farming;
3) the low infiltration rates of most of the local soils.

The objective of this study was to determine the extent to which a reduction in planting density in combination with a practice of deficit irrigation could increase yield and water use efficiency of irrigated maize on a Oakleaf Ritchie type soil (Soil Classification Working Group, 1991), which is one of the most common irrigation ecotopes in Ciskei.

Methodology

The effect of planting density and level of available soil water on the grain yield of maize was determined in a strictly controlled field experiment repeated over three seasons. The experiment involved a factorial arrangement of three levels of water and seven plant population densities which was replicated three times. The experiments were conducted on Fort Hare Farm, Alice, Ciskei (32°47'51"S; 26°50'55"E). The experimental site is nearly flat, sloping gently in a southwestern direction with a gradient of 0.5%. The soil is classified as being of the Oakleaf form and Ritchie family (Soil Classification Working Group, 1991). The soil texture is loamy throughout the rooting depth of the profile, the clay content gradually increasing with depth from 14% in the surface horizon to 18% at a depth of 2 m. Generally, this type of soil is considered as being highly suitable for irrigated cropping, minor limitations being its susceptibility to compaction and surface crusting. In each experiment both factors were tested over the wi range possible.

Differences in soil water supply were obtained by seasonal variation in rainfall and by supplementing rainfall with irrigation in some of the treatments. The mean water use over all populations for each of the levels of water and for each of the three seasons is presented in Table 1. Summarized treatment designation was as follows:

(FC + P + FI): Full irrigation treatment which involved maize planted in soil raised to field capacity followed by recharging of the profile whenever the crop had extracted a maximum of 70 mm of water from the upper 1 500 mm of the profile.

Table 1 The contribution of stored soil water, rain and irrigation to total consumptive water use of the main plot treatments of three experiments and potential evapotranspiration for each of the seasons obtained by means of the adjusted Penman formula proposed by Doorenbos & Pruitt (1977).

SEASON	WATER LEVEL	STORED SOIL WATER USED	RAIN*	IRRIGATION	TOTAL CONSUMPTIVE WATER USE	ETo*
		(mm)	(mm)	(mm)	(mm)	(mm)
1985/86	FC+P+FI	100	375	165	640	896
	FC+P+DI	146	375	120	641	887
	FC+P	201	375	0	576	855
1986/87	FC+P+FI	80	282	322	674	942
	FC+P	181	245	100	526	926
	P	62	237	50	349	881
1987/88	FC+P+FI	-25	262	459	696	886
	FC+P	86	262	0	348	884
	P	-17	255	0	238	880

* Minor differences in rain and ETo between treatment of the same season are due to differences in the rate of maturation of maize in those treatments

(FC + P + DI): Deficit irrigation treatment similar to full irrigation but less water was supplied than was lost by evapotranspiration; the deficit being made up by extraction from stored soil reserves.
(FC + P): Field capacity treatment consisting of planting in soil at field capacity and leaving the crop to subsist on rainfall thereafter.
(P): Rainfed treatment where maize was planted in soil which received no preplant irrigation and the crop had to subsist on rainfall only.

Planting densities ranged from 4 444 to 111 111 plants.ha^{-1}. Nutrient supply was adequate in all treatments. Soil water was monitored at weekly intervals by means of a neutron probe.

The same experimental procedure was followed each season as far as possible, to permit a comparison of the data obtained in the consecutive experiments. Seasonal variation of environmental factors other than water supply appeared to have only a minor effect on the growth of maize. This is indicated by the consistent yields of grain obtained in the fully irrigated treatment. To facilitate comparison of discrete levels of water the results of all three experiments were combined and treated as if they were obtained in a unitary experiment. This enabled the assessment of the effect of planting density on yield, water use and water use efficiency by maize over a wide range of water levels

Results and discussion

Total consumptive water use during the season

Total consumptive water use by maize over each of the three seasons is presented in Table 2. In Figure 1 some representative curves illustrating the effect of p ting density on the consumptive water use by maize at different levels of water are shown. Under conditi of full irrigation, consumptive water use increased curvilinearly with population up to approximately 30 000 plants per ha. Further increases in planting density resulted in small linear increases in consumptive of the order of 20 mm per 10 000 plant increment in density. When water use was restricted consumptive water use increased curvilinearly with planting sity up to a critical population, whereafter it plateaued. The population at which water use levelled off depended on the degree of soil water availability. The lower the level of available soil water, the lower the population at whichwater use levelled off. Generally, these results e in line with the findings of Yao & Shaw (1964) Timmons, Holt & Moraghan (1966) except with regard to the effect of degree of water availability on the relationship between water use and planting density. In contrast with the findings by Timmons *et al.* (1966), reductions in total water use resulting from reducti in planting density were more apparent as soil water availability increased.

Trends in mean daily consumptive water use and water extraction pattern

Plant population started to influence mean daily consumptive water use from about 30 days after

Table 2 Consumptive water use by maize at seven plant populations and three levels of water over three seasons.

	SEASONS								
	1985/86			1986/87			1987/88		
	LEVELS OF WATER								
	FC+P+FI	FC+P+DI	FC+P	FC+P+FI	FC+P	P	FC+P+FI	FC+P	P
Plant Density per ha	TOTAL COMSUMPTIVE WATER USE (mm)								
4 444	484	600	447	428	430	262	527	256	218
10 000	513	584	531	561	467	319	656	310	220
20 408	665	641	563	672	504	363	616	324	231
30 778*	599	655	614	689	559	357	712	388	268
40 000	708	695	632	754	572	364	669	368	234
62 500	706	665	620	776	544	411	826	401	240
111 111	809	645	624	839	603	365	866	392	256
MEAN	640	641	576	674	526	349	696	348	238
LSD		P(0.05)	P(0.01)		P(0.05)	P(0.01)		P(0.05)	P(0.01)
Level of water means		NSD	NSD		54	82		55	83
Population means		54	74		32	43		37	50
Population means at same level of water		93	129		55	74		65	87
Population means at different levels of water		106	NSD		74	106		81	114

* 27 778 plants.ha^{-1} during 1985/86

planting. During the first month of growth large proportions of the soil surface remained exposed, irrespective of the density at which maize was planted. As a result consumptive water use was determined mainly by evaporation from the soil surface. From the second month of growth onwards, water use tended to increase as plant population and LAI increased, the rate being conditioned by the quantity of available soil water. Where the availability of soil water was adequate throughout the season, consumptive use remained closely related to plant population density until the crop approached physiological maturity, explaining the increase in total seasonal water use with increases in population (see the (FC+P+FI) treatment in Figure 1).

Where soil water availability was limited, high populations used water more rapidly than low populations early in the season, thereby depleting soil water reserves earlier which in turn reduced the rate of water use during later stages of growth. On the other hand, low planting densities used water relatively sparingly at first and were therefore able to maintain a relatively high consumptive use for a longer period of time, a trend previously reported by Muller (1988). In Figure 2 the effect of planting density on the soil water extraction pattern by maize under conditions of limiting soil water availability is illustrated using the data

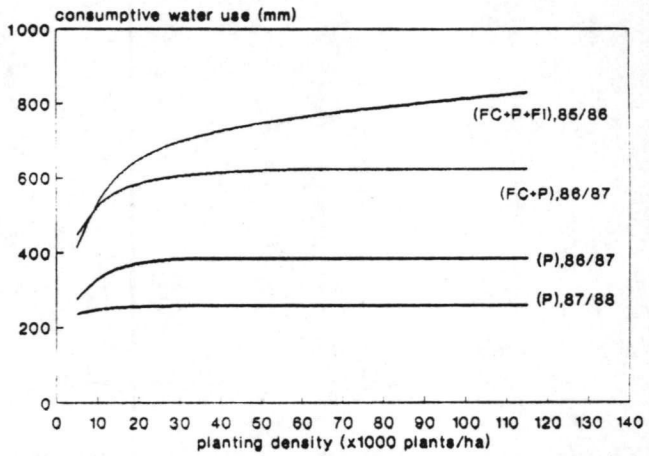


Figure 1 The effect of plant population on the consumptive water use by maize at different levels of available water.

obtained in the (FC+P) treatment during 1986/87. As planting density increased maize depleted the stored soil reserves to progressively lower levels during the vegetative period (0-80 days after planting), causing a corresponding reduction in the quantity of soil water available during the period of economic yield formation. Water stored in the upper half of the profile was most sensitive to the effect of population on the rate of soil

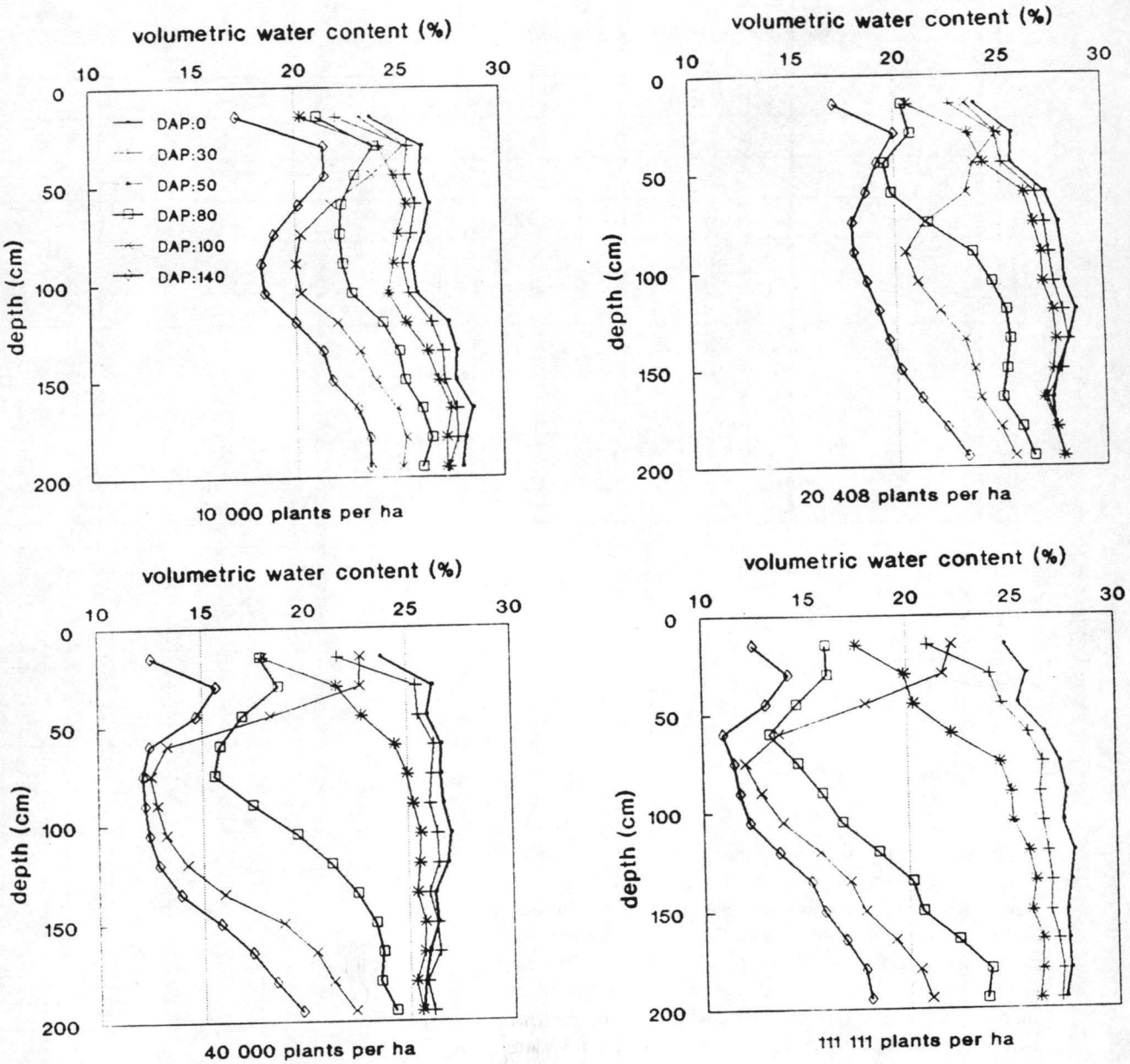


Figure 2 Effect of planting density on the soil water extraction pattern by maize at different numbers of days after planting (DAP) in the (FC+P) treatment of the 1986/87 experiment.

water depletion during this period. As a result, during reproductive growth high populations had to rely increasingly on water stored in the lower part of the profile. A reduction in density from 111 111 to 40 000 plants per ha reduced water consumption during vegetative growth (80 days after planting), but did not reduce total water use as indicated by a similar maximum level of depletion towards the end of the season. This indicated that a reduction in population from 111 111 to 40 000 plants per ha represented a temporary saving of water during vegetative growth, resulting in a more favourable water supply during economic yield formation.

Grain yields

Grain yields obtained over three seasons are presented in Table 3 and some representative yield response curves in Figure 3. When water was severely limiting v the case in the P-treatment during 1987/88, grain yields peaked at a distinct optimum and yield reductions due to supra optimal plant populations were severe. Termunde, Shanks & Dirks (1963) obtained a similar yield respc under conditions of extreme water stress. Increasing soil water availability transformed the yield response curve from a bell-shaped to a flat-topped asymmetrical parabola. At the lower levels of water, namely the (FC+P) treatment during 1987/88 and the (P) treatment

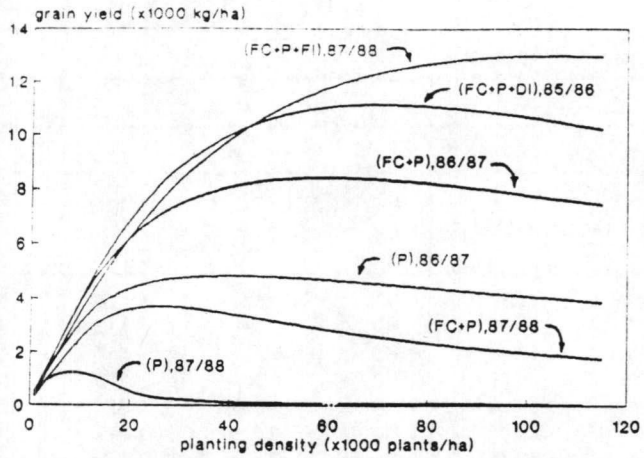


Figure 3 The effect of plant population on the grain yield of maize at different levels of available water.

during 1986/87, the tendency for yields to peak at an optimum density was still clearly evident, but reductions in yield due to supra-optimal populations were much more gradual than when water stress was extreme. Carlson, Alessi & Mickelson (1959) and Olson (1971) reported similar, small reductions in yield when increasing planting density to levels in excess of the optimum for the amount of water available. Further increases in water supply tended to change the response curve from a flat-topped asymmetrical parabola to a pseudo-hyperbola as shown in Figure 3 by the response curves obtained in the (FC+P) treatment during 1986/87 and the (FC+P+DI) treatment during 1985/86. Grain yields were increased by increasing the planting density until a near-critical density was reached at which yields tended to plateau. Supra-critical populations resulted in yield reductions only when the density was increased far in excess of the critical population. In the fully irrigated treatments grain yields increased with plant population over the full range of planting densities. Under these conditions the optimum leaf area index at anthesis was estimated at 6.3 requiring a planting density of approximately 94 000 plants per ha.

Plant populations responded differently to increases in soil water availability. The bunching of all response curves at planting densities of 10 000 plants per ha or less, indicated that an increase in water availability had little effect on grain yield at these low planting densities. At the very high planting densities of 60 000 plants per ha or more, maize responded to each increment in soil water availability. Intermediate populations responded positively to increases in soil water only up to a critical level, whereafter further addition had little or no effect on yield. The critical quantity of water was closely related to planting density and increased as population was raised. In order to describe the relationship between consumptive water use and grain yield at different planting densities, seven regression equations were developed and are presented in Table 4. A prediction equation based on these regression equations was developed using seven data points presented in Figure 4. Five data points comprised the intersects of six of the seven regression equations. A sixth point represented consumptive water use at zero yield at the lowest planting density which could beconsidered to be the minimum water requirement for grain production.

The remaining point was the mean yield over three experiments at the highest level of water at the hig planting density and represented physiological maximum yield within the constraints dictated by physical environment and other variables such as test crop and planting date. Although a straight line fitted the data points very well (r^2 = 0.99), it required a polynomial curve of the third order to describe adequately the exponential and asymptotic nature of the yield resp by maize at the lower and upper end of the water range, respectively.

At an optimum plant population the response of grain yield by maize to increased consumptive water use was given by equation 1.

$$GY = -521 + 1.292\,(CWU) + 4.40 \times 10^{-2}\,(CWU)^2 - 3.14 \times 10^{-5}\,(CWU)^3 \quad (1)$$

Equations 2 and 3 enable the estimation of optimum planting density at a known level of consumptive water use and known level of yield, respectively.

$$Po = 3.282\,(CWU)^{1.562} \quad (2)$$

$$Po = 8.507\,(GY) + 1437 \quad (3)$$

where Po = optimum planting density (plants.ha^{-1})
CWU = consumptive water use (mm)
GY = grain yield (kg.ha^{-1})

Conclusions and applications

The results obtained in these experiments demonstrated that the grain yield of maize can be maximized by adjusting plant populations to the level of available soil water. Under conditions of limiting soil water availability a reduction in plant population resulted in less rapid depletion of stored soil water reserves, thereby delaying the onset of water stress.

Where irrigation practices are expected to fall short of meeting the crop's demand for water, maximum benefit from reduced plant populations is expected to be obtained when the storage capacity of the soil is exploited fully. Under such conditions it is suggested

Table 3 Grain yields of maize at seven plant populations and three levels of water over three seasons (grain yields reported at 12.5% moisture)

	SEASONS								
	1985/86			1986/87			1987/88		
	LEVELS OF WATER								
	FC+P+FI	FC+P+DI	FC+P	FC+P+FI	FC+P	P	FC+P+FI	FC+P	P
Plant Density per ha	GRAIN YIELD (kg.ha^{-1})								
4 444	1 645	1 997	1 587	2 049	1 879	1 741	1 624	1 276	1 069
10 000	3 861	4 183	3 867	3 805	3 851	3 364	3 781	2 832	1 521
20 408	7 443	6 551	6 505	7 639	6 960	4 514	6 307	3 667	253
30 778*	7 993	8 572	7 435	9 422	8 251	4 702	8 368	3 895	244
40 000	9 749	9 896	8 255	10 419	8 026	5 304	9 670	3 550	57
62 500	1 142	11 442	9 273	12 157	8 106	4 447	12 269	2 693	103
111 111	13 213	10 321	8 472	13 162	7 588	3 925	12 958	1 803	42
MEAN	7 997	7 566	6 485	8 379	6 380	4 000	7 845	2 817	469
LSD		P(0.05)	P(0.01)		P(0.05)	P(0.01)		P(0.05)	P(0.01)
Level of water means		728	1 103		1 260	1 909		705	1 069
Population means		606	813		666	893		396	531
Population means at same level of water		1 213	1 626		1 154	1 547		686	919
Population means at different levels of water		1 334	1 848		1 645	2 359		945	1 350

* 27 778 plants.ha^{-1} during 1985/86

Table 4 Regression equations based on results obtained in the 1985/86, 1986/87 and 1987/88 experiments, which relate grain yield of maize (GY) in kg.ha^{-1} to total consumptive water use (CWU) in mm at seven planting densities.

Planting density	Regression equation	r^2	r	F_{test}
(plants.ha^{-1})				
4 444	GY = 2 272- 224 560 (CWU)$^{-1}$	0.54	0.74	*
10 000	GY = 5 353- 781 426 (CWU)$^{-1}$	0.90	0.95	**
20 408	GY = 10 873- 2 389 085 (CWU)$^{-1}$	0.96	0.98	**
30 778	GY = 14 338- 3 674 280 (CWU)$^{-1}$	0.90	0.95	**
40 000	GY = 15 437- 4 072 154 (CWU)$^{-1}$	0.93	0.97	**
62 500	GY = 19 004- 4 209 081 (CWU)$^{-1}$ - 8.48x10^{6} (CWU)$^{-2}$	0.97	–	**
111 111	GY = -5 236 + 22.036 (CWU)	0.95	0.95	**

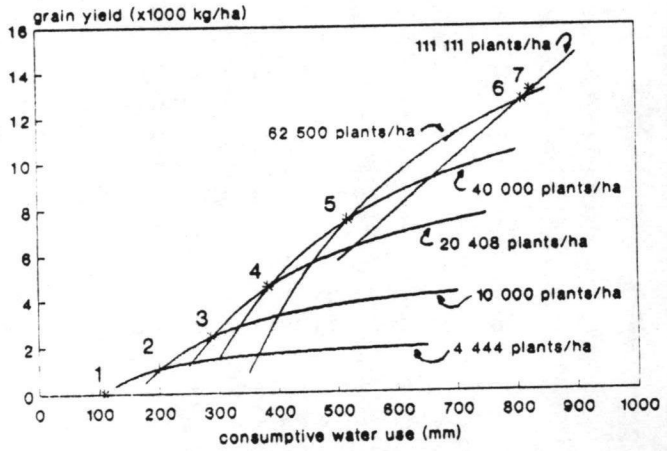


Figure 4 The effect of consumptive water use on the grain yield of maize at six plant populations.

that the soil profile be charged to field capacity before irrigation becomes inadequate to meet crop demand. Preferably, the soil should be charged before planting so as to avoid leaching of nutrients and to exploit fully conditions of maximum infiltration rate brought about by soil preparation. After planting, irrigation practices should be directed at satisfying crop water requirements as long as possible, so as to maintain the stored water reserve in the soil at high levels. Later in the season, when water demand exceeds supply, a form of deficit irrigation may be practised. During this period water

deficits resulting from inadequate irrigation are overcome at least in part by extraction from the soil reserve. However, a reduction in plant population resulting in a less complete cover of the soil surface tends to create conditions which favour weed competition. A reduction in plant population will be beneficial only when weeds are adequately controlled.

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IRRIGATION DESIGN - PROGRESS AND TRENDS IN THE LAST 25 YEARS

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Abstract
Prior to the National Irrigation Symposium in 1967 the mathematical ability of designers exceeded the availability of basic design data. While advances have been made in the hydraulic design techniques the greatest progress has been made in the availability of agronomic design data. In view of this, the focus of this paper is directed on progress in the areas of (a) design data for the determination of crop water requirements, (b) design aids for the hydraulic design of flood, sprinkler, micro-jet, drip and centre pivot systems and (c) some economic considerations. Focus is directed on what agronomic information is available, what design aids have been developed and what analyses irrigation designers should possibly conduct for their clients in the future.

Introduction

The process of irrigation design has been separated into several different steps by numerous authors in the past and most designers should be familiar with the ASAE S262T standard with respect to farm information, design and specification and economic analysis (ASAE, 1981). In this paper the design process will be addressed in three main areas. The three areas will be (a) the agronomic considerations of crop water use or irrigation requirements, (b) the hydraulic design considerations of irrigation systems such as flood, sprinkler, drip, micro-jet, and centre pivot, and (c) the economic considerations. The comment made by Wessels (1967) at the National Irrigation Symposium (Dept ATS, 1967) that the mathematical ability of designers had outstripped the availability of basic design data is no longer valid. Great strides have been made in establishing crop water requirements in South Africa for irrigation design purposes. However, the significant increase in the recommended crop water requirements for irrigation design has caused some uncertainty amongst irrigation designers about their validity.

Crop water requirements

For design purposes irrigation designers have to modify the theoretical crop water requirements into what is referred to as the design application amount. This design application amount takes cognisance of *inter alia* the crop water requirement, effective rainfall, evaporation, the soil irrigated and irrigation system. Until the early 1970's when the first "Green Book" was published by the Department of Agriculture (1975), the Department of Water Affairs and also the Department of Agricultural Technical Services laid down the norms for the design application amount for irrigation schemes in the different regions in South Africa. This first "Green Book" was accepted by industry but had deficiencies which were addressed in the second version (Green, 1985).

A great deal of research has been done since the publication of the second "Green Book". The tables in the "Green Book" for the irrigation requirements of crops are based on a relatively simplistic moisture balance model and a target crop yield which is the maximum possible crop yield that is associated with good management, cultivar choice etc and which cannot be increased by the addition of water through irrigation. The irrigation requirements recommended in the "Green Book" are significantly larger than previously used and uncertainty exists about the validity of present design figures. In a more recent publication on crop water requirements for irrigation planning by Dent, Schulze & Angus (1987) the irrigation requirements seem to be less than those recommended in the second Green Book. The irrigation requirements that will be exceeded for specified percentiles are contained in both publications. A number of other simulation models to predict irrigation requirements have been developed and calibrated. However, most of this work has been directed at irrigation scheduling or the crop water requirements for a pre-specified target yield (Bennie, Coetzee, van Antwerpen, van Rensburg & Burger, 1988). In the process, new insights have been gai into the importance of the level of expected crop yield (Target Yield) and management in relation to the fraction of potential crop water requirements that should be met through irrigation.

The practice of applying less than the crop water requirement is known as deficit irrigation and can be practised in more than one way. First, by applying a fraction of the design irrigation amount (which would fill the soil profile to field capacity), the effectiveness of any natural rainfall during the cycle is increased. With this method, however, the "target yield" is that maximum yield, associated with *inter alia* good management, cultivar choice and fertilizer level, that cannot be increased by the addition of water by irrigation (Green, 1985). Second, a design irrigation amount associated with a "target yield", which is than the maximum yield (as defined by Green, 1985), is applied. In this case the total irrigation amount is

distributed throughout the growing season according to the plant's development.

The above methods of deficit irrigation need to be examined carefully. The choice of the method of deficit irrigation that may be applied and the resulting system design would depend on the objectives of the operator. In Natal, the recommendations of the Directorate of Agricultural Engineering and Water Supply (1985) at Cedara, are widely used for design purposes.

System design

Flood irrigation systems

The most popular flood irrigation method in South Africa is Border Strip Irrigation which is used most commonly in the eastern Cape and the northern Cape. We do not know what design methods were used for the older systems, but the design procedures presented to students in agricultural engineering 25 years ago for the design of flood irrigated border strips, were trial and error methods. These methods were based on a recommended range of border strip dimensions, stream sizes and land gradients for different soils. The values were established from field trials, most of which were conducted in the USA. For design purposes, it was recommended that at least two different border strips should be constructed at different gradients, based on the range of recommended dimensions. By irrigating these trial border strips the advance and recession curves were determined and the design parameters for local conditions could be established.

Chen (1965) reported that researchers in flood irrigation realized as early as 1938 that the progress phase should be considered separately from the drying off phase. He also reviewed the various attempts that had been made to develop mathematical relationships to predict the advance of the progress phase or advance front. The drying off phase, or recession front, received less attention from researchers until Shockley, Woodward & Phelan (1964) developed a mathematical equation to predict the time delay, or recession time, of the drying phase. They also developed a quasi-rational method for design. However, the mathematical model that was developed was so complicated that it was never readily used by designers.

For closed end border strips (border strips with no runoff or tail water), the volume-balance principle has been accepted for many years. That is, the net volume of water that is diverted on to the field is equal to the volume of water that filters into the soil. In 1972 Badenhorst used this principle to develop a formula to calculate stream size. He assumed that the cutoff time was equal to 80 percent of the infiltration time. Using the Shockley *et al.* (1964) definition, that recession time was equal to the recession volume divided by the stream size, Badenhorst (1973) developed a relationship for the cut-off coefficient to replace his previous assumption. Van Heerden (1989) contended that the so-called "Badenhorst formula" was fairly widely used by flood irrigation designers and developed a computer programme for the design of flood irrigated border strips using this relationship. Kruger (1989) used an hydrodynamic computer simulation model to simulate border strip irrigation and demonstrated the practical application of computer simulation data to generate design criteria.

Furrow irrigation has been neglected in South Africa in the last 25 years. It was only in 1989 that Kruger published design curves for the design of furrow irrigation systems after he found that overseas design manuals were not applicable to the local conditions. He expressed the hope that the design manual containing local design data might encourage a closer look at furrow irrigation systems in the future as they have considerably lower development costs.

Sprinkler irrigation portable systems

Classical permanent to portable sprinkler irrigation systems have been the norm in sprinkler irrigation over most of the past 25 years. The trends have been towards the less labour intensive semi-portable systems such as the "drag line " systems with much unresolved debate concerning the spacing of the laterals and sprinklers. With the energy crisis in the eighties lower pressure sprinklers were used in South Africa and greater attention was focused on the uniformity of distribution (CU) in low pressure systems. The CDS nozzle was introduced in an attempt to improve the CU as lower operating pressures were utilized.

The advancement which has occurred in the hydraulic design of overhead irrigation systems has been in the aids that are available for this purpose. Initially the mathematical slide rule and custom slide rules were the basic tools of the trade for irrigation designers. Nomographs for the graphical design of systems were developed to decreas the time and remove the drudgery of the design calculations. Computers are now being used in the hydraulic design of irrigation systems and comprehensive packages such as IDES (Murray, Biesenbach & Badenhorst, 1989), IRRICAD (AEI, 1990) and WCADI (Weizman, 1989) are available. The use of these packages can decrease the time required for the hydraulic design of pipe networks and plan preparation and allow the consideration of alternatives which otherwise would not be possible.

Drip and microjet irrigation systems

The invention and development of the concept of drip irrigation is claimed by Blass (1969). The concept was developed in Israel and was initially known as "drop irrigation". By 1969 the concept, although controversial, had gained acceptance by many leaders in irrigation in Israel and USA (Goldberg & Shmueli,

1969). Micro-jet irrigation, however, is a South African development. Originally small, on line plastic moulded emitters were used to control dust on mine dumps and from 1969 micro-jet irrigation developed rapidly in the Western Cape (Weiss, 1972). It is now used world wide for the irrigation of field crops and in green houses. Further reference to trickle or daily flow irrigation in this paper will include drip irrigation, micro-jet irrigation, micro-tube irrigation and any other irrigation system in which water is delivered to the crop in a daily cycle through small low pressure emitters. With the advent of drip irrigation (and micro-jet irrigation) systems in the seventies new horizons were opened up in the irrigation industry and designers were faced with new challenges. As a result greater attention was focused on the hydraulic design of irrigation systems.

The initial procedures used to design trickle irrigation systems in the early seventies were based upon the graphical Poly-Plot procedure (ICI, 1970). The expensive Poly-Plot publication was condensed by Jobling (1972, 1974) when he showed that irrigation laterals with the same Specific Discharge Rate (SDR) have similar friction curves if there are 10 or more uniformly spaced outlets. Through the use of an index chart the friction curve, for a particular SDR/pipe combination, can be selected from a family of curves and used to design the lateral, taking cognisance of the ground profile. The design procedure was computerised by Perold (1979).

There was a flurry of work on friction losses in trickle irrigation laterals during the seventies. This resulted in the publication of other design aids such as the Trickle Irrigation Design Calculator (Wu, 1975). In South Africa, with the local production of trickle irrigation fittings, polyethylene pipes and other pipes, local manufacturers produced design aids such as AG-PLOT (Anon, -) for Dripin emitters and flow charts for pipes such as the Flow Charts for Duroflo uPVC Pressure pipes (Anon, -). These aids are widely used by designers of small to medium trickle irrigation systems in South Africa. Green (1981) showed that for micro-jets and other on line emitters, friction losses could be up to 30 percent greater than those for smooth bore pipes and designs should be suitably modified. Larger irrigation systems, designed by engineering consultants, are usually done with the use of computer design packages such as IDES (Murray, Biesenbach & Badenhorst, 1989), IRRICAD (AEI, 1990) and WCADI (Weizman, 1989).

Centre pivot irrigation systems

Since the inception of centre pivots in South Africa during the early seventies, dramatic changes have taken place in the design approach for this method of irrigation. The philosophy of design has changed and the level of sophistication in the design procedure has increased. The following three phases in the metamorphosis of centre pivot design have been identified.

1. Start up phase

During the early days in the history of centre pivots (1972-1980) no norms for local designs existed. Most systems were imported from the USA and the designs were based on American norms. Graphical design procedures were used (based on USA curves and graphs) and most systems were equipped with high pressure sprinklers operating at pressures of 400-500 kPa. The majority of these early systems incorporated hydraulic drives. These water driven systems utilized either piston or rotary sprayers as the primary drive. Water from the sprinkler lateral pipe, at a pressure of 400-500 kPa, was used to power these drive mechanisms. The lateral pipe on which the sprinklers were mounted was either suspended by cables or supported by trusses between the drive units. The power of these mechanisms, as well as the effective speed regulation on rolling ground, limited the use of these units to relatively flat ground.

2. Span optimization phase

The period 1981 to 1986 was the "boom" time for centre pivots. Variations of pivots like linear move and corner systems were introduced to the local market. The trend was towards bigger machines (60 - 80 ha) and lower sprinkler pressures. These changes, together with the energy crisis in the eighties, necessitated the use of electric drive machines. These centre pivot towers were driven by a small electric motor on each tower. Electric power was supplied through underground cables to the pivot from a commercial network. This electrical supply obviated the need for high water pressure in the lateral pipe to power the hydraulic drive mechanism. As a result much lower sprinkler pressures could be used without any effect on the drive unit performance.

The application of low pressure sprayers (140 kPa) on bigger machines caused major runoff problems and soil erosion as application rates increased. Thus the use of "drop pipes" and booms were introduced in a effort to match the application rate of the machine to the infiltration capacity of the soil. One major problem for the designers, however, remained unsolved. No accurate method existed to determine the infiltration capacity of the soil. The only guideline was the rule of thumb in which the application rate of the pivot should not exceed 3-5 times the infiltration capacity of the soil determined with a double ring infiltrometer.

During this period major efforts were made by private companies to set design norms for local conditions and in-house training programmes for designers were provided. The major focus of design was to optimise the selection of pipe diameters for the big machines. Pipe sizes ranged from 250 mm to 127 mm and the selection of the optimum combination could have a profound impact on the economics of the system. At this stage the uniformity of distribution was

emphasised and the importance of the Coefficient of Uniformity (CU) was overrated. The modified Heerman & Hein (1968) formula for the calculation of the uniformity of distribution on pivots was accepted by the industry and is still used widely today.

3. Pressure optimization phase

Since 1987 the trends have been towards smaller machines (10-30 ha) and ultra low pressures (40-120 kPa). The major breakthrough came with the invention of the infiltration meter and the publication of the graphical design procedure by the Division of Agricultural Engineering (1984). This is a major tool with which designers can choose the optimum sprinkler package for a specific machine/soil combination. The combination of drops and booms equipped with ultra low pressure regulators and 360 degree spray nozzles leads to good energy efficient designs. This spray arrangement also reduces evaporation losses resulting in designs with lower peak requirements.

The more general use of personal computers has resulted in most designers developing their own complete design packages. The main aim of most of these packages is to optimise the span selection and/or pressure requirements.

Economic assessment of irrigation

In the last decade there has been a lot of discussion about the evaluation of irrigation systems. The Council of the South African Irrigation Institute (SABI) together with the Directorate of Agricultural Engineering and Water Supply compiled an assessment form. However this did not enjoy wide use. Regional design norms have now been established by SABI and will be published soon. Further development in the design of all irrigation systems seems to be in project optimisation. Designers will have to establish the feasibility of a project and determine whether the farmer can afford it. Feasibility studies will have to include an optimised irrigation system design and cash flow projections for various crops and watering combinations. The IDES computer design package (Murray Biesenbach & Badenhorst, 1989) was developed specifically as a tool to evaluate micro-emitter and non-mechanised irrigation systems. The package, developed in South Africa, enables a designer to evaluate and optimise a design in terms of layout and cost.

With the economic pressures in the agricultural industry, greater competition has developed amongst irrigation designers. To be competitive in the long run designers will have to focus greater attention on the reconciliation of capital costs and running costs in the design of their systems (Green, 1990).

The cost spiral of agricultural production inputs will further force less energy efficient centre pivots off the market. Older, high pressure machines will be redesigned for low pressure sprinkler packages and there will be major improvements in the design of nozzles with respect to their efficiency at low pressures. The application of chemicals will increase significantly as more products will become available and be modified for sprinkler application. Lastly, smaller, cheaper centre pivots machines, flood irrigation systems and other overhead sprinkler irrigation systems will have to be developed for small scale farming enterprises.

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SURFACE IRRIGATION IN SOUTH AFRICA - THE CHALLENGE

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Introduction

As in almost all sectors of the economy, the changing socio-economic environment in South Africa has also had a significant influence on agricultural practices. Irrigation farming, one of the important branches of agriculture, experiences this quite intensively. Although the economic climate may be the most important factor for new trends in irrigation, other factors also play a role. These factors have the effect that surface irrigation is becoming more important again, and opening up new challenges for irrigation scientists. To diagnose these challenges, the current status of surface irrigation will first be reviewed, and possible actions then discussed.

Current status of flood irrigation in South Africa

Area irrigated by surface methods

Of the approximate 1.2 million ha irrigated in South Africa, (Bruwer, 1987) about 50% is irrigated by surface irrigation. It is estimated that at least 350 000 ha of the 0.6 million ha is provided with water through state or irrigation board schemes, by means of gravity-fed canals. The water supply to these areas can be regarded as reliable, and the soils vary from very sandy, between 8% and 11% silt + clay, to heavy clays. Where it has been evaluated the efficiency varies from high to low, but is unknown for most of the schemes.

The rest of the area under surface irrigation (250 000 ha) is made up of individual schemes along rivers and below farm dams, where irrigation is done on a scale varying from on a permanent basis to occasional irrigations whenever water is available.

Trends in irrigation methods

In the recent past, two trends occurred. Firstly, existing flood irrigation systems were replaced by overhead systems. Secondly, overhead sprinkler systems were installed on almost all new developments. Some of the reasons for this were:

* Low efficiency occurs with surface irrigation where systems are mismanaged or badly designed, with consequential disadvantages.
* Design problems. Very few people are capable of designing surface systems with sufficient confidence to ensure satisfactory results.
* Labour requirements for flood systems.
* Inefficient germination of sensitive seeds.
* Availability of electricity and overhead sprinkler equipment, while there is a scarcity of commercially available flood irrigation equipment.
* Characteristics of sites that are not suitable for surface irrigation.

Despite these reasons, this trend has now ceased due to economic reasons. Surface irrigation is no longer being replaced by overhead systems. Where mechanised sprinkler systems are still being installed on current new developments, site characteristics normally eliminate flood irrigation. This observation is confirmed by representatives of irrigation firms and their sales statistics. Where conditions are favourable, surface irrigation is seriously considered. Highly sophisticated and expensive permanent micro-irrigation systems are only installed in favourable climatic conditions for high income crops, where the topography is in any case unsuitable for flood irrigation.

Potential for new developments

In most parts of the country the climate allows only for the production of agronomic crops with a moderate income potential. Moreover most of these crops are overproduced on dryland during high rainfall years. This suppresses producer prices. However, a good market still exists for these crops in dry seasons. Keeping the high population growth and resultant longterm demand in mind, irrigation of crops with a moderate income potential is still a proposition if development and operational costs can be limited. This favours low-cost flood systems.

Countrywide there is still a limited amount of water available for irrigation development (Department of Water Affairs, 1986). The exploitation of available water in areas where storage exists and where suitable soil is available, has however almost reached exhaustion. Further developments would require very expensive schemes. It can thus be concluded that a very limited amount of water is available for new developments. Future new irrigation developments will consist of schemes utilising water of unreliable availability, for which low-cost storage will have to be provided privately on farm dam scale, as against earlier, large state schemes. For such developments, flood systems would be the most appropriate.

The unfavourable economic climate for irrigation

Production costs are rising excessively in relation to producer prices (Figure 1). This influences the viability of existing irrigation, and leaves very little room for capital investment to improve efficiency.

This scenario puts much pressure on irrigation farming for the future. Two contradictory goals have to be met.

Firstly, capital expenditure for development as well as production costs must be kept as low as possible. This means that the replacement of existing systems will very rarely be economically viable. Areas with existing surface systems will have to stay the way they are. Reversion back to flood irrigation from sprinkler irrigation is even being considered where the running costs of sprinkler irrigation is getting too high.

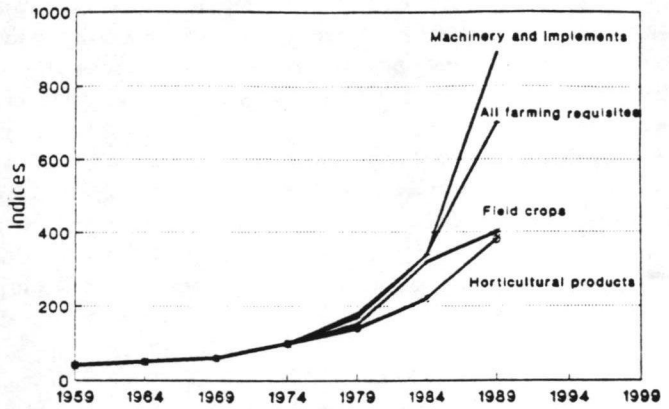


Figure 1 Price indices for production costs and product prices (Source: Abstract of Agricultural Statistics, 1990).

Secondly owing to limited water availability and economic reasons, efficiency will have to be increased. This normally implies capital investment.

The challenge will be to effectively increase the efficiency of the existing surface irrigation without excessive expense, and to design economically viable systems for the few new future developments

Comparison with international trends

Some of these trends are also being experienced internationally. A World Bank workshop (Petit, 1988) was held during 1988, in order to investigate whether available technologies in irrigation had been adequately and effectively exploited throughout the world and certain tendencies were identified.

At the workshop the importance of irrigation on a global basis was established with the unqualified premise that "to meet the future growth in demand for food and fibre, there will be a need for substantial new investment in irrigation." In South Africa this has become a clichè. Although some people experience famine, food and fibre are overproduced, and farmers have problems in marketing their agricultural products. Investments in irrigation are limited because of low or negative returns. Our motivation for further investment in irrigation expansion will have to be much clearer and more convincing.

The workshop concluded that flood irrigation methods need more research in both hydraulics (i.e. design) and management, where it has lagged behind the more spectacular irrigation methods. Large areas in the world, especially older developments, are still being flood irrigated, although not very efficiently. The potential for efficient flood irrigation exists, however, and the upgrading of these areas would be a more economic proposition than replacement by other methods. In some cases, even a higher efficiency is attainable with flood irrigation than with other methods, a situation also found in South Africa. The only difference is that we regard research on adapting existing knowledge to local conditions, a higher priority than research on the basic hydraulics of flood irrigation. The results of a survey of irrigation efficiencies in California in 1987 (Burt, 1988) also show that flood irrigation systems can be very efficient (see Figure 2).

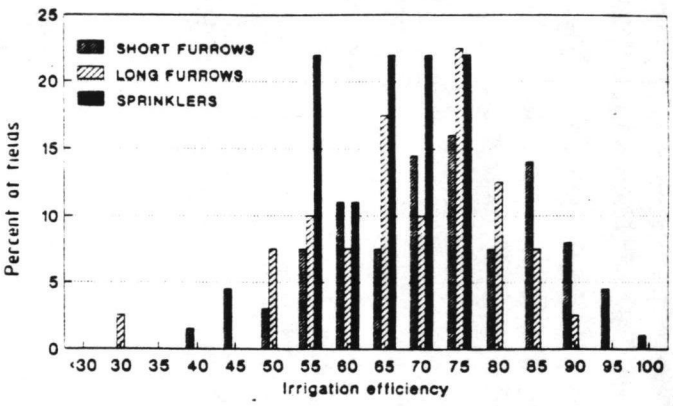


Figure 2 Regular irrigation efficiency - all crops: results of evaluations on 190 fields in Central California, 1987.

Another aspect in the international irrigation scene that coincides with the current approach in South Africa is manifested in the financial policy of the World Bank. The bank has shifted from developing new land for irrigation to rehabilitating and modernising existing projects. Financing of projects is done where management and policy issues are the focus.

The value of increasing flood irrigation efficiency

Increased efficiency can have a pronounced effect on available water. Results of a research project at Vaalharts showed that in 95% of the irrigations measured, the efficiency exceeded 80% where more than 40 mm was to be applied (Du Rand, Kruger, Streutker & Van Rensburg, 1986). Based on these evaluations, an average on-farm irrigation efficiency of 75% for the Vaalharts scheme does not seem an inflated figure. It is possible to reach a fairly high efficiency on a large irrigation scheme.

For the rest of the flood irrigation schemes, based on *ad hoc* evaluations, an average on-farm efficiency of 50% does not seem a bad guess. It is within the managerial ability of farmers and the technological

skill of designers to increase this to 70% as was shown possible on Vaalharts with soils that were not even ideal for flood irrigation. If this can be achieved, it would release 600 x 10^6 m^3 of water per annum for farms where the necessary infrastructure for irrigation already exists. At this stage this is the best possible investment in irrigation development. It would be the equivalent of another Vaalharts Irrigation Scheme.

Methods to increase flood irrigation efficiency

Increasing the efficiency of flood irrigation requires both the upgrading of the layout and the management of many systems applied in irrigation districts and on government irrigation schemes. To achieve this, the final responsibility lies with the farmer. Without the participation of the farmer nothing will be accomplished. The first challenge of scientists and public institutions will be to mobilise the farmers to realise these goals with whatever methods are available. Possible tools of persuasion are financing, technology transfer, and policy manipulation. Secondly, the correct technology must be provided. Dedicated officials with integrity, who have gained the confidence of the farmers, will be needed. Thirdly, the opportunity to supply affordable and effective equipment must be realised and exploited by the private sector.

The mobilisation of farmers and the application of correct technology will now be discussed. Many efforts towards this goal have failed in the past. The mistakes made must be identified and prevented in future.

Scheduling of irrigation

One of the best ways of convincing farmers of the need to upgrade their systems is to introduce a scheduling program. To schedule irrigation, it is necessary to quantify the water consumption of crops very specifically. Only when farmers know how much water has been used, and find they cannot apply what is needed, do they realise the inefficiency of their systems.

The difficulty is to motivate farmers to schedule irrigation. This problem is, however, to some extent being appropriately solved by the current economic environment. Higher water prices, high production costs and limited water quantities are the order of the day. It just needs an able extension officer to use the many negative factors as incentives to promote scheduling. Fortunately the changed environment does not only present negative factors for irrigation. Research has developed effective scheduling models that can already be practically implemented.

The following experience at the Rietriver Irrigation Scheme indicates that the philosophy behind the above approach to persuade farmers to upgrade flood irrigation systems, holds some promise. The Free State Region of the Department of Agricultural Development, together with the South Western Transvaal Cooperative and a farmers' association is at this stage developing a scheduling service, where the water consumption of crops is supplied to the community on a weekly basis. The PUTU model, developed by De Jager of the University of the Orange Free State, was selected to calculate the water consumption for this project. As a result of this scheduling service, farmers now know how much water is required per irrigation and are beginning to ask for the replanning of flood systems so as to be able to apply the correct amount of water. In the past other campaigns to promote the upgrading of surface irrigation systems on this particular irrigation scheme have failed, while this effort is now beginning to show positive results.

Evaluation of existing systems

In the past many mistakes were made in designing the upgrading process. A most important but very unobtrusive error could be a careless evaluation of the existing system. By using incorrect criteria, a superficial evaluation can very easily lead to the erroneous conclusion that a system is inefficient. People by nature tend to consider surface irrigation to be less efficient because, compared to the positive control exercised with overhead irrigation, there is less control on applications. They, therefore, are easily satisfied if even somewhat careless investigations confirm this. An example of where a system was superficially regarded as being inefficient is the Vaalharts irrigation scheme. Quite a number of farmers changed to centre pivots because of, among others, efficiency reasons while in fact, when carefully evaluated, the efficiency of surface irrigation was reasonably good.

At this scheme soils are very sandy (8% - 11%, silt + clay) and the infiltration rate is high, conforming approximately to a 4-inch (100 mm) intake family. Calculated according to convential methods, the allowable water abstraction from the root zone is approximately 40 mm. These characteristics indicated unsatisfactory conditions for flood irrigation. Applications of up to 60 mm and higher were made. Against these norms and considering high water tables, efficiency was assumed to be very low, at best less than 50%.

After carefully considering the criteria, it was discovered that PAWC (Profile Available Water Capacity) for wheat and maize was in the region of 70 mm and not 40 mm. It is clear that just this one norm completely changed the calculated efficiency. The relatively high actual efficiency was confirmed by Hamman (1986) who, in assessing crop yields achieved with given quantities of irrigation water on Vaalharts farms, found these to be very similar to FAO norms (Table 1).

Table 1 Yield per cubic metre water at Vaalharts compared to FAO norms (FAO Irrigation and Drainage Paper No 33).

Crop	Yield per unit water (kg m^{-3})	
	Vaalharts	FAO Norm
Lucern	2.3 - 2.7	1.5 - 2.0
Cotton	0.65 - 0.73	0.4 - 0.6
Groundnuts	0.3 - 0.9	0.6 - 0.8
Maize	1.1 - 1.4	0.8 - 1.6
Wheat	0.9 - 1.1	0.8 - 1.0

Sound system design

The design of flood systems has always been a problem. Firstly there has, in the past, been a shortage of capable design personnel. They were limited almost exclusively to the Department of Agriculture. Secondly the technology was not well developed. Conditions in this respect have, however, changed for the better. Models are now available to simulate the hydraulics of flood irrigation. Design procedures are now being developed from these models. The SCS design procedure, based on Strelkoff's hydrodynamic model, is being adapted for local conditions. This will enable designers to plan with much more confidence.

There is also a great advantage in upgrading a system rather than designing from scratch. The opportunity to evaluate the old system, makes it possible to determine and calibrate parameters which would otherwise be difficult to determine. Despite the new models, it must, however, be realised that flood irrigation design and management is still complex. Parameters such as infiltration rate, roughness coefficient, and PAWC change during the season. Determination of these parameters is difficult, time consuming, and requires experience. Only one parameter, the stream size, can be positively adapted during the season to compensate for other variations. This is, however, impractical on most irrigation plots, and this alternative must be regarded as of limited value. Farmers must therefore realise from the start that even with the best design it is only possible to achieve applications varying between limits that are much wider than with sprinkler irrigation. The variation is, however, to a certain extent predictable, and can be compensated for by management.

Appreciation of reasons why farmers change to overhead irrigation

A very important condition for acceptance of upgrading of surface irrigation systems by farmers will be revealed by taking cognisance of the reasons for wishing to switch to overhead irrigation. The reasons listed in a previous paragraph are very real, and many farmers change to sprinkler systems only for convenience even though they may be less economical. Sometimes they misjudge the situation, and due to small irritations they make financially unjustifiable decisions with disastrous results. To convince them to rather upgrade their flood systems would require solutions to flood irrigation problems, or providing proof that the alternative is financially totally non-viable. The economic quantification of flood irrigation problems, including the risk attached to unreliable labour, is however, not so easy.

Many of the problems experienced with surface irrigation can be related to the poor preparation of irrigation beds. The introduction of equipment like laser levelling must also be practically demonstrated, and its advantages proved. It will have a significant effect on labour requirements and germination conditions.

Another measure to alleviate germination problems is to use small and relatively cheap mobile sprinkler systems for the initial irrigation, a practice already adopted by some farmers.

Economically justified modifications

The mistake of over emphasising efficiency was made in the past, when farmers were advised on upgrading. Scientists tend to go for optimum efficiency and to conserve resources at all costs. Irrigation is, however, now an economically struggling enterprise and every bit of capital investment must be economically justified.

Unsophisticated systems where "wild flooding" is done with unreliable or opportunity water must not be financially "overdeveloped". Under certain conditions an inefficient system is the most appropriate system, and money must not be wasted in upgrading.

Example of a typical system considered for upgrading

To demonstrate some of the principles discussed, the planning of the upgrading of an irrigation plot under the Riet River Irrigation Scheme will be described. The farmer asked for assistance with improving his irrigation system. The present system has existed for many years. The plot was surveyed and a contour map prepared, as shown in Figure 3.

Infiltration was measured by means of a double ring infiltrometer. A border planted to wheat was irrigated, measured and evaluated to determine the dynamic properties of infiltration, energy balance and resistance to flow. The data were subsequently used to calibrate the parameters with the help of a hydrodynamic simulation design model (Kruger, 1989).

The performance of the present system was first evaluated. The defects and reasons for poor performance were then identified and different options proposed to solve them. The new options have been evaluated to test the efficiency, and the cost

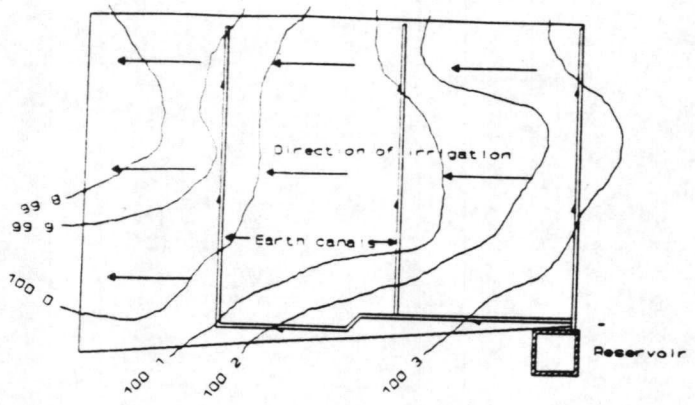


Figure 3 Contour map of the irrigation plot with the present layout.

implications of proposed changes calculated to decide whether the alterations would be justified.

Present system

The plot is at this stage divided into three blocks. Border lengths are 115 m or 145 m, depending on the specific block. The infiltration rate is in the 1.5 inch "intake family".

Water is supplied for 24 hours a day. Canal flow supplied during the night is stored in an unlined reservoir, and is used together with "day flow" during day time. All the canals are unlined earth canals. The slope varies from border to border. Borders were grouped into similar slope categories. The optimum irrigation for each slope group was then calculated. Only one stream size was used to evaluate irrigation for the different conditions, because variation of stream size is not possible on this farm. The stream size that suited the different conditions best was used.

The amount of water applied on the border receiving the smallest application was used as the norm to calculate the efficiency of application over the total farm. Applications larger than this amount were regarded as a loss, because the irrigation cycle has to be based on the most limiting profile. With the existing distribution system, it would not be possible to supply water to the required border, were it attempted to schedule according to the varying applications applied on the different borders. Considerable managerial skill would also be required to cope with such a complicated record system. Table 2 shows the possible theoretical applications and application efficiencies that could be attained for the groups of borders on different blocks.

The application varied from 42 to 60 mm. A stream size of 16 m^3 h^{-1} m^{-1} was found to be the most suitable. The overall application efficiency was 79%. To improve the efficiency, three levels of sophistication in upgrading were investigated. The cost was determined and benefits quantified.

Table 2 Applications (Apl) and efficiency (Ea) attainable with the present layout.

Block 1 Length: 115 m		Block 2 Length: 145 m		Block 3 Length: 145 m	
Appl (mm)	Ea (%)	Apl (mm)	Ea (%)	Apl (mm)	Ea (%)
58	95	44	92	60	93
42	90	50	93	50	94
55	96	60	95	46	92
55	96	60	95	46	92
58	95	50	93	50	92

Option 1

The least sophisticated improvement was to change only the slope on 25% of the irrigation beds where a net application of less than 50 mm could be achieved. The slope was decreased to such an extent that at least 50 mm could be applied. The required earth- moving and finishing costs for this purpose, at current construction costs, amounted to R200 per ha.

This adjustment could increase the overall application irrigation efficiency (Ea) from 79% to 85%.

Option 2

Grade the whole plot to a uniform slope of 0.001 m/m in the direction of irrigation. Adapt the distribution system to form two blocks with even border lengths of 202 m on each block. The cost of these adjustments would amount to R800 per ha. With these changes the efficiency could be improved to 93%.

Option 3

Do the same upgrading as in Option 2, but, in addition, line the storage dam and distribution system to limit seepage losses. The total cost of this alternative would be R3 600 per ha. The water savings due to the lining were calculated with the hydrodynamic model by determining the water infiltrated in both the storage dam and unlined canals.

Results

In all the options a 4% lower efficiency than optimum was assumed to allow for insufficient operator skill. Table 3 shows the cost of water and the efficiencies of the different options.

The water costs and efficiencies in Table 3 are portrayed in Figure 4 and 5. Two further factors for defining the performance of upgrading are also shown on the curves. They are the indirect benefit and the potential benefit.

The **indirect** benefit in Figure 5 is based on higher yields because of the better planning, and was

quantified in conjunction with the farmer, and based on logical reasoning. The potential benefit in Figure 5 is determined by the production that can be realised from utilisation of the saved water. The value of this production was calculated by using the gross margins in the Combud Enterprise Budgets compiled by the Directorate Agricultural Economics (1990).

The curves in Figure 5 show that in Option 1 an

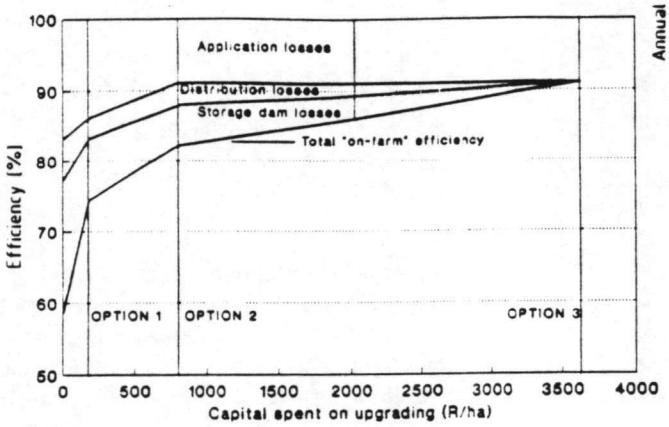


Figure 4 Financial benefit for irrigatiom of wheat.

investment of ±R200/ha would result in an immediate annual saving of ±R80/ha on water costs.

Option 2 requires an investment of ±R800/ha. The direct saving in water costs would be ±R91/ha per annum for wheat. If no indirect or potential benefit can be accomplished by these adjustments, this option

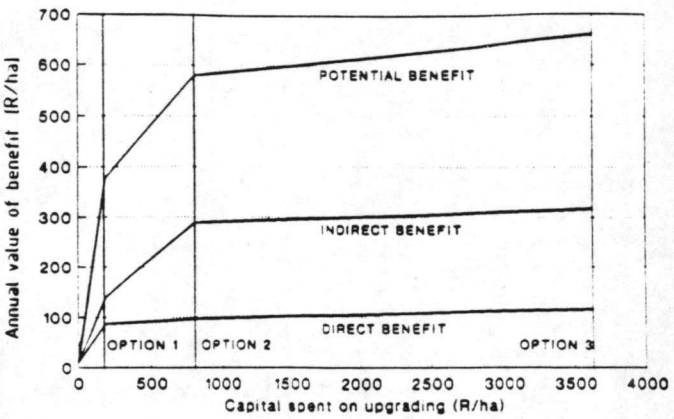


Figure 5 Capital/efficiency curves.

will not be viable under the present economic conditions.

Option 3 would only be advisable under conditions of severe water limitations, and after careful long-term financial analysis has shown its viability.

Conclusion

Economic and other factors in the new South African environment inhibit further expansion of overhead and sophisticated irrigation systems. These factors also promote the need for an improvement in irrigation efficiency. A reappraisal of flood irrigation is indicated.

The expected future trend will be: (a) that some sprinkler systems will change to flood irrigation, (b)

Table 3 Water consumption and value per ha of different up-grading options.

ITEM	PRESENT SYSTEM		OPTION 1		OPTION 2		OPTION 3	
	Water consumed	Water value	Water consumed	Water value	Water consumed	Water value	Water consumed	Water value
Available water	6000 m^3	R180	6000 m^3	R180	6000 m^3	R180	6000 m^3	R180
Application losses	(Ea=75%) 20000 m^3	R 60	(Ea=85%) 1 060 m^3	R 32	(Ea=92%) 521 m^3	R 16	(Ea=92%) 521 m^3	R 16
Distribution channel losses	(4%) 333 m^3	R 10	(4%) 294 m^3	R 9	(4%) 271 m^3	R 8	-	-
Storage dam losses	(5.6%) 494 m^3	R 17	(5.6%) 436 m^3	R 13	(5.6%) 433 m^3	R 13	-	-
Dam level management losses*	(13.1%) 1330 m^3	R 47	-	-	-	-	-	-
Total losses	4157 m^3	R134	1790 m^3	R 54	1225 m^3	R 37	521 m^3	R 16

* with the present system the reservoir is being used to store water over long periods, while with the proposed new options 1 + 2, it must only be used for the temporary storing of "night" water.

where conditions are suitable, flood irrigation will be seriously considered for the few new developments, and (c) upgrading of large areas currently under flood irrigation will take place.

The challenge lies in mobilising farmers to upgrade their systems and to compromise between the cost of upgrading and the benefits of improved efficiency. The new technology available to upgrade flood systems must be applied. The errors that were made in the past, in introducing such technology to farming communities, as identified in this paper, must be avoided.

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SOFTWARE AND AUTOMATION FOR EVALUATING AND IMPROVING SURFACE IRRIGATION EFFICIENCY AND UNIFORMITY

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Abstract
Surface irrigation practices represent by far the most common set of methods for applying water to agricultural lands. Recent developments in surface irrigation technology have contributed substantially to improving the efficiency of such practices. Laser land levelling, where applicable, enables the very important field grading operation to be performed rapidly, accurately and economically. Since the advent of the microcomputer, software has been developed which enables simulation of all forms of surface irrigation and frees design from dependency on rules of thumb and engineering judgement. Designs can be optimised for various farm configurations, including consideration of aspects such as cultural practices, soil erodibility, crop cultivaion and harvesting requirements, etc. Attempts to automate surface irrigation have frequently not been successful because the required flexibility has been lacking. The "surge flow" approach to automating the management of surface irrigation overcomes many of the difficulties and has been tested on nearly every type of surface irrigation system and over a full range of soils.

Introduction

Surface ("Flood") irrigation describes methods of field irrigation in which water is conveyed and distributed by gravity utilizing the field surface itself as the conveyance medium. These methods are generally classified in three categories: (1) basin systems; (2) border systems; and (3) furrow systems. Basins consist of level, typically square fields with dikes around the entire perimeter. Borders are usually long, narrow diked strips, level normal to the direction of flow but sloping in the direction of flow. Borders may also be diked at the downstream end of the field. Furrow systems are characterised by individually fed micro-channels in a field with variable slopes in both directions and are usually not diked at the lower end of the field.

The practice of surface irrigation represents by far the most common set of methods for applying water to agricultural lands. A number of important advantages are related to these methods, including minimum capital investment, low maintenance costs and low energy requirements. The major disadvantage of surface irrigation, however, is that it is typically less efficient than sprinkle and trickle irrigation. Recent developments in surace irrigation technology have partially overcome the recognised irrigation efficiency advantage of pressurised systems. Nevertheless, the fact that the soil must be used to convey and infiltrate the water over the field represents an important limiting factor. The major problems of the temporal and spatial variability in a field's infiltration characteristics constrains the ability to simulate surface irrigation behaviour with a high degree of reliability and, thereby, consistently achieve the levels of irrigation efficiency that are obtainable with pressurised systems.

The three essential requirements for achieving substantial improvements in surface irrigation have been developed in the last decade: (1) precision land levelling; (1) microcomputer software for analysis, design, and simulation; and (3) automation. When taken and implemented together, these three technologies provide the basis for substantially higher surface irrigation efficiencies, in many cases well in excess of 80%, thereby making the surface irrigation methods comparable to sprinkle and trickle alternatives at a fraction of the cost and energy requirements.

Advances in land levelling

Levelling, smoothing and shaping the field surface is as important to the surface system as the design of laterals, manifolds, risers and outlets is for sprinkler or trickle irrigation systems. It is a process for ensuring that the depths and discharge variations over the field are relatively uniform. Levelling or smoothing operations may be required nearly every cropping season where substantial cultivation disrupts the field surface. The preparation of the field surface for conveyance and distribution of irrigation water is as important to efficient surface irrigation as any other single management practice.

Given the role of the field surface itself in conveyance and distribution, the most important factor in achieving the goals of better design and management of surfce systems is the precision with which the field surface is levelled. Laser guided equipment can reduce topographical variations by more than an order of magnitude over traditional procedures involving topographical surveys and manually-controlled grading. In the time typically spent staking, surveying and computing adjusted field grades, a laser controlled system can complete the entire levelling operation.

In the U.S. and elsewhere, the costs of lower land levelling are about the same and perhaps somew lower than traditional land levelling, even though the added cost of the laser equipment is about one-third the cost of tractor and scraper. In central Utah, the yield increases derived from laser land levelling alone

on a 300 hectare farm repay the cost of an entire laser levelling system every two to three years.

The emission and detector devices are the heart of the laser system. The emitter involves a battery operated laser beam generator which rotates at relatively high speed on an axis normal to the field plane. This rotating beam creates a plane of laser light above the field which is used as the levelling reference rather than the elevation survey at discrete grid points in conventional land levelling techniques. This reference plane of laser light is an extremely advantageous factor in the levelling operation because it is not affected by the topography of the surface, or the movemement of the grading equipment. Further, the laser system does not require a field survey to establish the high and low spots, and does not require the operator to judge the magnitude of cuts and fills. The laser emitter is generally located on a tripod or other tower-like structure on or near the field and at an elevation such that the laser beam rotates above any obstructions on the field as well as the levelling equipment itself. The beam is targeted and received by a light sensor or detector mounted on a mast attached to the land grading implement. The detector is actually a series of sensors situated vertically so that as the grading implement moves up or down, the light is detected above or below the center detector. This information is transmitted to the control system which actuates the hydraulic system to raise or lower the implement until the light again strikes the centre detector. It is in this manner that the sensor on the mast is continually aligned with the plane on the laser beam. It is important to note that the sensitivity of the laser sensor system is at least 10 to 50 times more precise than the visual judgement and manual hydraulic control of an operator on the tractor. Consequently, the land levelling operation is correspondingly more accurate. The skill of the operator is substantially less critical to the levelling which allows farmers and other personnel access to the land grading equipment.

As a final note on levelling in general and laser levelling is particular, it is probable that the importance of accurate field grading has been underestimated. The precision improves irrigation uniformity and efficiency and as a result the productivity of water and land. On large fields, the improved productivity has been shown to pay economic dividends that easily exceed the cost of the levelling. However, the equipment is expensive and quite beyond all but the largest of farmers. There remains the solution as to how such equipment can be made useful for the small farmer.

Microcomputer software for analysis, design and simulation

Mathematical modelling provides an important tool for achieving significant and sustainable improvements in surface irrigation performance (Walker & Humpherys, 1983). Since the advent of the personal or microcomputer in the early 1980's and the subsequent software development programs, the applications to surface irrigation have yielded programs to evaluate infiltration in real-time, design systems more effectively and simulate a wide array of conditions. Infiltration is the single most important variable in surface irrigation and the ability to develop reasonably accurate estimates of the infiltration processes during the early stages of an irrigation provides the basis for adjusting field discharge and watering times to achieve high uniformities and efficiencies during each irrigation.

With the microcomputer and better methods of quantifying infiltration came new numerical procedures for solving the hydrodynamic equations of motion. The resulting software now simulates all forms of surface irrigation with nearly any configuration of inlet and downstream boundary conditions. Perhaps no other advance has closed the gap between the researcher and the irrigator quite so much as the surface irrigation simulation model.

The design of surface irrigation systems can now be made without the dependency on rules of thumb and engineering judgement (guesses). The verification of the infiltration analyses and simulation models has resulted in design procedures which are quantitative and accurate. Designs can be based on optimised uniformity and efficiency and alternative surface methods can be compared and evaluated. Field and farm configurations are possible which include consideration of a much larger array of input data such as cultural practices, soil erodibility, water supply characteristics and crop cultivation and harvesting requirements, etc.

Surface irrigation automation

In 1980 the general conclusion regarding surface irrigation automation would most likely be that it had been a universal failure to date. The reasons are varied and numerous but are typically the result of inadequate reliability and flexibility. The almost infinite array of field configurations and farming systems means that it is difficult if not impossible to standardise equipment and controls which would allow improvement through adaptation and repetition. Since the field roughness and infiltration change measurably and unpredictably from irrigation to irrigation, the automated system must be capable of adjustment and regulation in real-time, a capability not available to date.

In 1979, Stringham & Keller (1979) reported a new approach for automating surface irrigation systems in which problems with slow advance and excessive surface runoff occur. The approach was called "surge flow" to describe the hydraulic regime of the flow over the field. In 1986, a US patent was granted to

Professors Keller and Stringham of Utah State University for the concept. A trademark registration was issued for the term "Surge Flow" although by the time of this writing, the term has become widespread as a surface irrigation water management concept.

Under the surge flow regime, an irrigation is accomplished through a series of individual pulses of water onto the field. This differs from traditional or continuous flow surface irrigation in which the objective is to add water to the field until it has covered the surface and as much as the root zone will store has been applied. Under a surged regime, each surge applies part of the root zone requirement. For instance, a continuous flow application of six hours under traditional practices would be replaced by six surges of one hour each. Each surge is characterised by a cycle time and a cycle ratio. The cycle time is comprised of an on-time and an off-time related by the cycle ratio which is the ratio of on-time to the cycle time. The cycle time can range from as little as one minute to as much as several hours. Cycle ratios typically range from 0.25 to 0.75. By regulating these two parameters, a wide range of surge flow regimes can be produced which can significantly improve irrigation efficiency and uniformity.

It is perhaps worth noting that surge flow, while appearing quite simple, is nevertheless an advanced irrigation technology. The design and evaluation require an advanced level of hydraulics and the equipment needed to implement surge flow fully is often feasible only in large farming operations. This is not to imply that surge flow cannot or should not be considered in developing countries, only that special adaptations will be necessary.

Surge flow has been tested on nearly every type of surface irrigation system and over a full range of soils. Results vary, depending on the selection of cycle time, cycle ratio and discharge. Generally, the intermittent application significantly reduces infiltration rates and/or substantially reduces the time necessary for the infiltration rates to approach the final or "basic" rate. To affect infiltration rates, the flow must completely drain from the field between surges. If the period between surges is too short, the individual surges overlap or coalesce and the infiltration effects are generally not created.

Research shows that the surging effect on infiltration is primarily due to the consolidation of the thin layer of fine material deposited in the bottom of the furrow or on the border or basin surface by the destruction of soil aggregates and erosion caused by the water flow. As the water drains from the field between surges, the negative pressure that develops in the soil consolidates the surface layer, collapsing the larger pores, attracting small particles, and orienting clay and silt into a layered structure. As a result the permeability of the field surface is reduced and thereafter infiltration rates are lowered. The reductions in surface permeability seem to be more pronounced in sandy loam soils than in clay loam soils. The rate of aggregate wetting and erosion affect the thickness and extent of the surface layer.

The effect of having reduced the infiltration rates over at least a portion of the field is that advance rates are increased. Generally, less water is required to complete the advance phase by surge flow than with continuous flow. Surging is often the only way to complete the advance phase in high intake conditions like those following planting or cultivation. As a result, intake opportunity times over the field are more uniform. However, since results will vary among soils, type of surface irrigation, and the surge flow configuration, tests should be conducted in areas where experience is lacking in order to establish the feasibility and format for using surge flow.

The hydraulic regime of a surge flow system is composed of two parts: (1) the distinct surge phase; and (2) the coalesced surge phase. The distinct surge phase is noted above. Each pulse of water advances and recedes over a portion or all of the field. This phase is used during the advance phase for the entire field, i.e. during the time needed to wet the entire surface of the field. Surges during the distinct phase must be of sufficent duration and discharge to fill cracks and depression storage along the pathway so there is enough volume and energy to continue advancing at an adequate rate over the succeeding field section, but short enough to limit cumulative intake and maximi or minimize the infiltration reduction.

In the coalesced phase, the individual surges run together, overlap and result in a nearly steady flow in the downstream sections of the field. In this situation, the flow rate below the point of convergence is about one-half of the instantaneous rate at the field inlet. If the cycle ratios are reduced, the flow in the continuous flow reaches will be correspondingly reduced. It is therefore possible to adjust the cycle ratios until practically no surface runoff occurs. The reader thus immediately sees the coalesced phase as being exactly equivalent to the cutback phase in traditional surface irrigation. Indeed, the original research of Stringham & Keller (1979) was directed toward the development of an alternative cutback method. The advantages of surge flow during the advance phase came as a welcome surprise.

Thus, by combining the distinct and coalesced phases of surge flow into one system, the solution of the long-standing surface irrigation dilemma is available, a high flow for the advance phase and a low flow for the wetting phase.

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DEVELOPMENT AND USE OF COMPUTER-AIDED ANALYSIS, EVALUATION AND DESIGN METHODS FOR IRRIGATION SYSTEMS

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Introduction

The use of computers in the different facets of irrigation system analysis, evaluation and design is fairly common. Although the International Commission on Irrigation and Drainage (ICID) predicted in 1985 that an integrated computer process would be the norm for the future, in 1991 this is still not the case. However, the computer exposure gained over the past few years, together with the rapid development of hardware, has provided a solid foundation for the further development of programs and the interrogation of processes. The irrigation design process can be divided into the basic graphic and physiographic data input, the determination of the system parameters, the design of the block and mainline and the presentation of the final output in terms of drawings and a bill of quantities. The computerized analysis and evaluation of a predesigned irrigation system can be regarded as part of the design process. In this paper a review is given of the current state of the art regarding available computer software, as well as its use in the design and evaluation process. The authors base their findings on the available literature and would certainly not regard this overview as fully representative.

History

The first developments from 1975 to 1980 involved in-house computerisation of elements of the design process, for example the design of the laterals and branch lines for sprinkler irrigation.

As early as 1977, algorithms for more advanced design procedures such as the polyplot procedure were developed and thereafter a great deal of developmental work was done in respect of the computerisation of trickle/drip irrigation designs. The design of sprinkler configurations on centre pivot irrigation machines as well as the design of furrow and basin irrigation were computerized.

A survey regarding the status of computer-aided analysis, design and drafting applications in irrigation by the Systems Analysis Working Group of the International Commission on Irrigation and Drainage (ICID) in 1985 reports as follows:

* "Almost all respondents have acquired an in-house capability for C-A (computer-aided) analysis with the exception of the members of the African grouping."
* "Most ICID members have obtained C-A analysis software through in-house development and purchase."
* "Although most respondents are using their C-A drafting feature in drafting and design, the American grouping, and to a lesser degree the European grouping, have found its application advantageous in other areas such as analysis, marketing, project management, and administration."
* "Approximately 30-50 per cent of the respondents, with an automated capability (excluding Africa), also possess design software. These programs have been primarily developed in-house, but they have also been obtained via purchase from service bureaus or other sources."

Research and program development

Development of computer assisted irrigation design is being undertaken in several countries.

Many papers are being published on software development in this field, and in the following paragraphs a number of these are discussed briefly. Most of the projects are research orientated, and are therefore carried out by the universities.

a) Perold, R.P.: 1977 & 1979 (University of Stellenbosch - South Africa) - *Design of Irrigation pipe laterals with multiple outlets.*

   An iterative solution procedure based on four dimensionless parameters, that can be applied using a programmable pocket calculator, was proposed. The coefficient of uniformity was used as a criterion for acceptability. The procedure was restricted to a single diameter pipe on uniform sloping ground. The computerized solution has been developed based on the polyplot algorithm. The hydraulic calculation is executed on a step by step basis, incorporating the calculation of the varying discharges along the length of a pipe.

b) Balogh, Biro, Gauser: 1983 - (Hungary) *Dimensioning trickle lateral groups by computers.*

   A program developed to determine the length of up and down slope laterals and to determine head losses in the lateral as well as the inlet pressure for a lateral.

c) Zazueta, Smajstrla, Harrison: 1985 (University of Florida) - *Micro-computer aided design and management of trickle irrigation systems.*

   A Personal Computer (PC) based program, which can be used for the design and management of trickle irrigation systems, was developed. The system consists of a number of separate programs. From the limited information available it appears to be useful and is said to be used extensively by extension personnel, the irrigation industry, and growers in Florida.

d) Sands, Moore & Warner: 1984 (University of

Kentucky) - *A computer model for irrigation planning and management.*

This computer model was developed to simulate the economic consequences of planning and management scenarios for irrigation projects. Apart from the extensive evaluation modules (yield prediction and economic evaluation) it appears to include also design routines.

e) Pitts, Ferguson & Wright: 1985 (University of Arkansas) - *A computer model to evaluate drip irrigation lateral design.*

This model was developed to perform analyses of lateral lines. It predicts the uniformity of emitter discharge and evaluates alternative designs. In the process it attempt to provide a rational basis for the selection of the emitter.

f) Meshkat, Warner: 1985 (University of Kentucky) - *Interactive computer trickle irrigation design systems.*

A program was developed for the design of trickle irrigation systems, and comprises three separate modules, namely (1) preliminary design consideration, (2) sub-unit hydraulic design, and (3) main water distribution network design.

g) Bralts, V.F. *et al.*: 1985 (Michigan State University) - *Microcomputer aided design of drip/trickle irrigation submain units*
and Kelly, S.F.: 1989 (Michigan State University) - *Finite element analysis of drip irrigation hydraulics using quadratic elements and a virtual emitter system.*

The use of the finite element method in the analysis and design of drip/trickle irrigation lateral (submain) lines was investigated and developed and proved to produce a fast, efficient and accurate method for analyzing large drip irrigation networks. A differential equation describing flow in a drip irrigation system was developed. Several different methods were found to incorporate emitters in a virtual emitter system where several emitters are combined into one element or node, as a point source.

The virtual node concept can analyse large irrigation systems of 10 000 or more emitters more accurately. It is not known if the finite element analysis method of design has been incorporated in a commercially available irrigation design program.

h) Murray Biesenbach & Badenhorst Inc.: 1987 (South Africa) - *The development of procedures for design and evaluation of irrigation systems*

In a research project, supported by the Water Research Commission (South Africa), the irrigation design principles and procedures were studied in depth and evaluated critically. Design algorithms for the laterals, manifolds (submain) and branched distribution networks were developed. The iterative techniques based on the polyplot principles were used as a basis for the design algorithms. These algorithms were altered to enhance the design process with the PC computer. The development of a technical and financial evaluation model formed part of the project as the search for an optimal design to fulfil different design objectives was viewed as part of the design process. The research eventually resulted in the development of the IDES irrigation design and evaluation program. Close collaboration between South Africa and Israel took place during this research.

i) Curley, Knutson & Hanson: 1989 (University of California) - *PC computer model for matching and evaluating and irrigation application system, pump and powerplant.*

This PC computer based program predicts how a pump will perform when coupled with an irrigation system, and how changes in the system will affect pressures and flows throughout the system.

j) Pleban, S.: 1989 (Orange Software) - *Jack, the irrigation system design program.*

This paper deals with a fully integrated commercial software package for the design of blocks and mainpipe networks.

There are probably many more ongoing research projects in different parts of the world and it appears that most of these have resulted in a computer program of some sort which can be used or as in use in the planning or design process of irrigation systems.

If all of these programs could be brought together, one would probably find that almost the whole process is covered by the various programs. This is however not a way to approach the computerisation of the design process, since it will make the integration of the process very difficult, if not impossible.

Integrated programs

Commercially developed irrigation design programs are more widely used than the academically derived programs. It is probably also true that the developers of most of the commercial packages envisage a fully integrated design package, and therefore feel that their present development is a step in this direction.

There are numerous programs forming one or other aspect of the design procedure. There are however only a limited number of integrated programs commercially available on PC. Between these software packages the design procedure is programmed from the fieldbook right through to the bill of quantities and drawings.

A brief technical overview will be given of some of the commercially available programs. It is not possible and it is also not the intention of the authors to make a qualitative comparison of the programs.

BOERESAKE

Developer: Boeresake - (South Africa).

Users: Irrigation designers.

Description: Design of lateral and manifold (submain) lines. Material quantities beyond the control valve are abstracted and priced automatically. Graphical capabilities limited to block layout and design curves.

IDES

Developer: Murray Biesenbach & Badenhorst and Water Research Commission.

Users: Agricultural and turf irrigation designers.

Description: Integrated program consisting of modules for: block design; mainline design (optimisation); techno-financial evaluation. The branch mainline network is optimized linearly giving pipe sizes and classes. The design modules are linked to a fully developed digital terrain modelling program (Model-maker - DTM) which allows topo-graphical inputs in electronic format and a complete general CAD program (MAPCAD).

IRRICAD

Developer: Agricultural Engineering Institute, Canterbury, New Zealand.

Users: Mainly agricultural and turf irrigation designers.

Description: Integrated program with modules consisting of planning (preliminary design), block design, mainline design, network analysis and bill of quantities.The graphical capabilities are well developed and can also be coupled to packages such as AUTOCAD. The topographical information can be captured directly from an electronic field book or by digitizing. A turf irrigation design program is under development (July 1991).

JACK

Developer: Orange Software, Fresno, USA.

Users: Mainly agricultural irrigation designers.

Description: Modules consist of: block design, mainline design, network analysis and bill of quantities. The bill of quantities module keeps record of stock (purchases and sales). From available information it seems that the graphical capabilities are limited.

WCADI

Developer: Weizman Industries Ltd, Israel.

Users: Mainly irrigation designers, but also larger agricultural estates.

Description: Fully integrated and developed program with the following modules: planning (preliminary design); block design, mainline design; network analysis; scheduling; bills of quantities. Topographical data input by digitizer and transferred automatically to the design program. Graphical output with a CAD program. Turf irrigation design package linked to other modules to perform all design functions.

LANDCAD.D

Developer: Landcadd, USA.

Users: Turf irrigation designers and landscape architects.

Description: Graphical program for the planning, description and design of turf irrigation systems. Pipe sizes are determined in the design and the quantities calculated. Program is linked to AUTOCAD.

WADISO

Developer: Geusteyn, Loubsher & Streicher, South Africa.

Users: Mainly consulting and munic engineers as well as irrigation designers.

Description: Network analysis program consisting of modules for: network analysis; network analysis with time simulation; optimisation of pipelines, reservoirs, pumps and energy requirements.

Future developments

It is safe to accept that there will be considerable development in future due to the rapid scientific and technological development. The development will take place with regard to improvement of design procedures and algorithms and also the integration of the design packages with other computer management, information and design software.

Improved procedures and algorithms

* The evaluation of the finite element design procedures and testing thereof in contrast to the already proven iterative (polyplot) procedures will take place.
* The rewriting and upgrading of present software packages can be a useful exercise if it can be financially justified. A very broad and glc outlook should be adopted when a decision on this subject is taken. The irrigation industry is a lim and specialised market for computer software in comparison to the more general uses for computer software such as spread sheets or word processing. Future development will have to be financially

supported by governments or the larger irrigation industry due to the high cost of such developments.

Integration

Further integration of the irrigation design process with other programs can take the form of:

* Linking of the design programs with expert systems to assist the farmer and designer in the techno-economical aspects of decision making.
* Linking of the design programs to physiographic data bases. In South Africa a design package such as IDES can be linked to the ACRU system.
* Linking to management systems such as geographic information systems (GIS).
* The input data and output features of the design packages can be enhanced by linking them to advanced digital terrain modelling (DTM), CAD, material data base and bills of quantities programs.

Conclusion

The irrigation specialists have interesting and challenging tasks ahead in order to evaluate and integrate technology and to develop new technology. The developments in the computerisation of irrigation design procedures to date have been remarkable and have taken place on the different continents of the globe. Can cooperation be established? The authors express the hope that enthusiasm, resources and every effort will be directed towards perfecting computerised design systems and programs, in order to enhance the utilization of water as a scarce resource in the optimal production of food for the nations.

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PROGRAMME FOR EVALUATING IRRIGATION EQUIPMENT

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Introduction

Irrigation practices and techniques can be revised and improved only by research and evaluation of irrigation equipment. To ensure functional efficiency and the ultimate success of irrigation projects, the equipment must comply to certain performance standards.

A programme for evaluating irrigation equipment was therefore established within the Subdirectorate: Irrigation Technology of the Directorate of Irrigation Engineering, to determine whether such equipment is suited to South African conditions. The Subdirectorate is an independent evaluation authority on the performance of irrigation equipment and systems. Both laboratory and field evaluations are carried out according to locally developed and internationally recognised standards and procedures.

Laboratory evaluation programme

In 1971, evaluation of irrigation equipment commenced on a very small scale. Two decades later, evaluation is being done at a very high level of engineering sophistication, which compares with the best in the world. The main purpose of evaluating irrigation equipment is:

- To obtain performance results.
- To establish performance credibility.
- To verify in-house evaluation results.
- To obtain independent evaluations.
- To verify system designs.
- To develop new products.
- To aid in sales.

Quite a large area is being irrigated world wide and a lot of equipment is being used. To assist in evaluation programmes, there are nine major evaluation centres throughout the world, namely:

- Australia - Australian Irrigation Technology Centre, Adelaide.
- Canada - Prairie Agricultural Machinery Institute, Thumboldt, Saskatchewan.
- England - Silsoe College, Silsoe, Bedford.
- France - Cemagref Testing Station Irrigation Equipment, Le Tholonet, D'Aix en Provence.
- Israel - Centre for Water Works, Tel Aviv.
- New Zealand - Agricultural Engineering Institute, Lincoln College, Canterbury.
- South Africa - Directorate Irrigation Engineering, Silverton, Pretoria.
- U S A - Centre for Irrigation Technology, Fresno, California.
- West Germany - Puifstelle Feur Landmaschinery, Cross Umstadt.

All these institutes evaluate equipment according to internationally recognised standards and procedures.

At the Directorate of Irrigation Engineering a wide range of irrigation equipment is being eval ed. Evaluations are carried out on:

Continuous basis:	Ad-hoc basis:
- Sprinklers	- Travelling guns
- Drippers	- Centrifugal pumps
- Filters	- Submersible pumps
- Microsprayers	- Accesories
	- Hydraulic valves

Sprinkler evaluation:

In the sprinkler evaluation programme the efficiency and suitablility of sprinklers are determined in the laboratory where conditions are controlled, so that all equipment will be subject to identical test conditions. After a running-in period of 8 hours on a set of 3 sprinklers, a distribution pattern is determined. The sprinkler with characteristics best coinciding with the average is selected for further testing. The characteristics on which the judgement is based are:

- The radius of the wetted circle.
- The rotational speed of the sprinkler.
- The rate of flow through the sprinkler.
- The uniformity coefficients of the sprinkler.

The tests that will then be conducted on the selected sprinkler are the following:

- The delivery of the sprinkler at different pressures.
- The distribution pattern of the water at 0.5 m intervals along the wetted radius of the sprinkler at the minimum, average and maximum recommended working pressure of the sprinkler.
- These values are entered into a computer which simulates up to 34 different spacings of the same sprinkler in different spacing patterns and from that the coefficient of uniformity (CU-Value) is calculated for the sprinkler.

Using the aforementioned information, an evaluation report (see Appendix A) is then compiled to give the technical data and performance characteristics of the sprinkler. For demonstration purposes, or as part of a special report, three dimensional printouts are presented to visualise the effect of the distribution efficiency.

Filter evaluation:

In the filter evaluation programme the filtering capacity of the filter is tested by evaluating the friction loss with clean water and dirty water, respectively. A whole range

of filters have been tested to date.

First, the friction loss test is done with clean water and a graph of friction loss against flow rate is drawn to ascertain the most suitable flow rate for the filter.

The filter is then tested with dirty water at six different levels of dirtiness, and a dirty water capacity curve is drawn for the filter. It is then possible to deduce how often it will be necessary to clean the specific filter in different circumstances. At the same time the filter efficiency is evaluated by comparing the degree of dirtiness of the water after filtering with the degree of dirtiness before filtering. This is done with the help of a locally developed dirtiness index meter.

This information is then presented in performance reports which include valuable design information, showing, for example, the impact of a blocked filter on the whole system.

Dripper evaluation:

In the dripper evaluation programme various tests are carried out.

The first test is a friction loss test at different flow rates on each of five different lengths of the same type of lateral. A mathematical equation for the friction loss of the laterals with the installed drippers is deduced from this test.

Secondly, the delivery against pressure test is done on a set of 100 drippers simultaneously to ascertain the average delivery of the drippers at different pressures. The average delivery at 100 kPa is accepted as the nominal capacity of the drippers.

Thirdly, the average coefficient of variation (based on the delivery of any 25 drippers) of the 100 drippers is measured at pressures corresponding to the minimum, average and maximum recommended working pressures.

Lastly, a length of pipe with ten drippers is used to determine their sensitivity for blocking, which is then compared with a "standard" control dripper line.

All this is done on a sophisticated testbench with accurate electronic equipment and with computers. Testing of equipment is carried out up to 24 hours a day, each day of the week. The relevant evaluation reports are then compiled with this information.

Micro Sprayer evaluation:

In the microsprayer evaluation programme the following tests are performed.

Firstly, a delivery against pressure test is done on 100 sprayers simultaneously to ascertain the average delivery of the sprayers at different pressures.

Secondly, the average coefficient of variation (based on the output of any 25 sprayers) of the 100 sprayers is measured at the minimum, average and maximum recommended working pressures for the specific nozzles.

Lastly, three sprayers with deliveries closest to the average of all the sprayers are selected. These three sprayers are then tested to obtain their distribution pattern at three heights and at four pressures.

All the information is then analysed and evaluation reports are then compiled to give the technical data performance characteristics of the microsprayers.

Field evaluation programme

In the field programme, a mobile irrigation laboratory is used to evaluate irrigation systems. Evaluations are carried out from the suction pipe to the last emitter. Suction loss, pump performance, power requirements, system pressure, delivery losses, application variations, uniformity tests and wear measurements of installed systems can all be evaluated with this unit. The mobile irrigation laboratory is a custom-built trailer, fitted with all the measuring equipment. Soil augers, pressure gauges, infiltrometers, flow meters, calibration phase meters, wind velocity meters and general l d equipment are all part of this unit. The following questions are often asked:

- How efficient is my irrigation system?
- Does it apply water evenly at a uniform rate?
- Can changes be made in its design, operation, or maintenance that will make it more efficient?

Questions such as this are successfully addressed and answered with the mobile irrigation laboratory.

It has commonly been observed that there is a drop in crop yield with a decrease in CU and therefore it is important that an irrigation system must operate correctly in order to maximise the CU.

Evaluation of the total system furnishes valuable information to the operator and it indicates where repairs, changes to the system itself, or adjustments to the operation or management is needed. The movement of water through an irrigation system, from its source to the crop, can be regarded as three separate operations, namely conveyance, distribution and field application. To determine the efficiency, measurements are carried out and used in appropriate formulae to provide answers on the system's performance.

In the pivot evaluation programme, different measurements are carried out. Catch can measurements, especially, reveal the system's real performance. From the catch can measurements, a graphic printout is produced and the CU calculated. The design and management of the system can also be checked and the irrigator advised accordingly.

Sprinkler systems are evaluated by taking flow rate readings against pressure, catch can tests and verification of nozzle sizes. The right working pressure is very important, because pressure and spacing determine the coefficient of uniformity of the system.

With drip irrigation, flow rate, inlet pressure and

volumetric measurements of at least 25 drippers throughout the field will reveal the uniformity of the system. Field evaluation data show problem areas and it is clear that management and operation of the system also play a vital role in the end result of a system. Flood irrigation evaluation entails flow rate readings, advance and recession fronts and depths of application.

By analysing all the data, a recommendation can be made to assist the irrigators and to rectify the problems.

Conclusion

The Directorate Irrigation Engineering's programme for the evaluation of irrigation equipment operates successfully, while it enjoys the full co-operation of the manufacturing and distributing industries.

For the designer, the programme provides information on which to base designs, specifications and project monitoring. For the irrigator, the programme provides a suitable basis for the comparison of commercial products; and for the manufacturer, the programme provides an incentive for marketing quality products and insurance against misapplications.

THE SOUTH AFRICAN INSTITUTE OF AGRICULTURAL ENGINEERS' VIEWPOINTS ON APPROPRIATE IRRIGATION TECHNOLOGY IN DEVELOPING AREAS

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Abstract

In general the contribution of irrigation to development in subsistance farming areas has fallen short of expectations. The conclusion reached is that each development is unique and that planners must identify with the community and develop proposals which are affordable and with which the community will feel comfortable. Regimented high technological developments requiring that farmers be trained to conform to "modern methods" seldom achieve objectives. Farmers need to grow into technology; initially the objective may be modest yields associated with affordable inputs and familiar cultivation practives. Crop water requirements should be assessed in the light of target yields and irrigation methods kept as simple as possible without impairing functional efficiency. Financial policy needs to be in line with the objectives of development and maximum use made of private sources. Design and construction should keep the requirements of development in mind and while durability and effectiveness should be adequate every effort must be made to avoid luxury specifications or unrealistic safety margins. Regular monitoring at grass roots level is essential if projects are to be kept on track.

Introduction

A symposium on irrigation farming and mechanisation in developing areas in Southern Africa was first proposed during an International Agricultural Engineering Symposium held in 1986, in Pretoria, under the auspices of the Commission International Du Genie Rural (CIGR). Subsequently five annual symposiums on Mechanisation and Irrigation in Developing Areas (MIDA) have been organised by the SA Institute of Agricultural Engineers with the emphasis on communicating the aspirations and needs of the men and women on the ground to the professions engaged in planning, design and construction.

The first MIDA symposium (MIDA, 1986) had the following very specific objectives :

a) to provide an opportunity for farmers and operators to communicate and share experiences,
b) to expose institutions, advisers and consultants to requirments at practical farm level, and
c) to transmit knowledge and experience from the bottom up, instead of talking down to delegates.

The symposium was centered around panel discussions by farmers and others directly involved, such as extension officers, project leaders and project managers. It was attended by 230 delegates and confirmed the need for a forum where agricultural development issues could be discussed.

The symposium brought to light that there were successful farmers and operators whose experience could be shared, and that lessons could be learned not only from successful projects, but also from failed ventures provided these were brought into the open. Much insight was gained and certain priorities for the attention of planners, managers and politicians, as well as the agricultural engineer, were identified.

The second MIDA symposium (MIDA 1987) aimed at emphasising the positive and worthwhile role of agricultural projects in developing areas. As far as the main theme of the symposium was concerned, namely achievements, the symposium came to the conclusion that it required an entrepreneurial spirit, hard work and the assimilation and utilisation of all available relevant information, for a farmer to ensure success.

The third MIDA (MIDA1988) was in the form of a specialist workshop attended by 40 Institute members and other specialists (including overseas visitors) directly involved in development situations.

Participants discussed and prioritised the contribution the Institute and its members could make in developing areas. After the workshop, focus was directed on overseas experiences in developing countries and the conclusions formulated at the specialist workshop.

The fourth MIDA (MIDA 1989) concentrated on pooling views and experience, in order to hammer out a clear course of action and to extend and optimise the contribution of the engineering profession in the agricultural sector of the developing areas.

The fifth MIDA was held in October 1990 and took the form of "a hands on" workshop which, in the case of irrigation, concentrated on developing an approach to monitoring and evaluating irrigation projects.

Policy Statement (1989)

A sub-committee nominated at the 1988 MIDA symposium developed a policy statement which was accepted at the 1989 symposium. The statement included the following on irrigation :

"Irrigation is a support function towards agricultural production in developing areas"

In development, an irrigation system is considered appropriate first, when it enables the user to utilise the natural resources to the optimum, and second, when these systems enable a farmer to farm economically. It means that irrigation systems must help the

community to utilise the natural resources and, it must be affordable to them.

To make sure that these irrigation projects will stimulate development, it is very important that the proposed irrigation system will not be contradictory to the development objective, which should be defined prior to any planning being undertaken.

Some of the reasons for failures are:

a) Irrigation systems were planned for estate farming, and not to settle individual farmers.
b) Equipment used was too costly.
c) The demand of the end user was not adequately taken into consideration.
d) Inappropriate tendering/contracting procedures were used.

Phasing into irrigation

Maitlin made valid points at the 1989 symposium, (Proceedings of the 1988 and 1989 MIDA symposiums). The size of the area to be farmed by each operator is important. The area must be large enough for the farmer to make a good enough return and yet be within his managerial capabilities, say 5 ha modules to start with. The system should allow the farmer to acquire extra modules as he profits from experience and is capable of managing a larger area. The social implications associated with the development of rural irrigated farming can lead to the failure of a development scheme, or be the cause of some of the problems that arise as the scheme develops, rather than inadequately applied technology.

Operators usually do not appreciate the full implications of participation in a development scheme. The monoculture normally imposed, the (high) risk, the (high) cost, the level of mechanisation and irrigation associated with the scheme all result in a debt that the farmer does not appreciate and is not able to carry.

The expectation of the rural emerging farmer normally encompasses an enterprise consisting of mixed farming with a flexibility which will accommodate multi-culture. His targeted yields would be relatively low requiring low inputs and minimal costs so that profits may be realised. Rural farmers need to grow into the technology which will help them become successful larger operators.

The results of the Fish River Project are interesting. Profits of R230/ha were realised by farmers who were dependent on the scheme during their operation whereas profits of R1 450/ha were realised by farmers who used their own labour, relied on their own management and who were subject to minimal offical involvement in the development scheme.

Badenhorst & Haasbroek (1990) disclosed that farmers on a well known project, using their initiative, greatly reduced costs and despite lower than budget production achieved satisfactory net profits.

Legoupil (1985) confirms this approach, stating that many of the problems are due to the difficulty experienced in integrating national development objectives and the personal objectives and aspirations of farmers. There is a gap between a traditional farming system and an intensive irrigated system.

He maintains that one can only propose a progressive intensification process based on

a) the analysis of the traditional rainfed farming system and the environmental conditions,
b) the development of complementary irrigation to secure food production during the rainy season,
c) a balance between irrigated areas and traditional rainfed areas,
d) an efficient extension and training service, and
e) the development of a pilot project where all the technical innovations and social organisation will be tested before extrapolation to a larger scale."

How much irrigation water is required?

The emerging farmer, if he has freedom of action, will not aspire to high yields; indeed, management and resource limitation will preclude the yield levels achieved by the advanced farmer with access to sophisticated equipment and inputs.

The schemes proposed for the developing areas have in the past been expected to conform to the same standards as those applicable to intensive irrigation areas despite the intuitive realisation that in the light of achievable yields this represented a possible excess. In the era of "development at all costs" this was accepted without question but in the present economic and political climate funding on this scale is not available, and needed projects are being put on ice.

In practice there are many management factors which determine achievable yield, including fertiliser status, disease and weed control, planting dates, and tillage and irrigation scheduling, and water reuirments should be related to the realities of the situation.

Lower water demand has a direct influence on the size of dams and distribution systems and, coupled to the use of relatively unsophisticated irrigation methods, can result in reduced capital expenditure and operating costs in the important initial years but long term upgrading should always be considered in the planning phase.

Construction standards

Badenhorst (1989) examined the standard of construction specifications. As engineers, we have developed, over the years, very good construction specifications in order to make sure that there are no snags during construction and subsequent operation. The overall effect has been the escalation of tender prices which, in the long run, place a financial burden on the farmer, who may not have the same view as the engineer and may have been thinking in terms of a "hose and basin" system of irrigation with low cost water distribution.

When construction is undertaken by a contractor after the submission of a successful tender the client and financing body are entitled to the protection afforded by accepted engineering specifications and codes of practice.

Every attempt must be made however to select, identify, or develop, appropriate standards for the task on hand which may not require the stringent control demanded of major civil engineering works.

Financing

Infrastructure is important and must be geared to the developing needs of the people and financing policy must be in step with production decision making. The participation of commercial banks and suppliers of requisites should be encouraged.

Financing was illustrated by Badenhorst & Haasbroek (1990) in a case study. There is farmer pre-occupation with sympathetic financing and one feels for the officials who are subject to rules and regulations and have to play the role of bankers without the years of experience available to commercial finance houses. Normally bank loans are negotiated on a personal "one on one" basis but development authorities deal with groups, and discipline by regulation. This is possible, if not desireable, because they operate in a non-competitive environment. There is a strong case for "freeing" both farmer financing and requisite purchasing in order to mobilise the full resources and experience of the private sector.

Monitoring/evaluation of irrigation projects

Badenhorst & Haasbroek (1990) reported on a study undertaken in June 1990. Projects financed by development organisations should be monitored on an ongoing basis, to assess effectiveness, efficiency and impact, in respect of the perceived development objectives. It is believed that information gained and lessons learned from monitoring, would be useful as reference for future planning or re-directing existing activities.

Monitoring also provides an opportunity to assess whether all aspects as agreed to in loan agreements are adhered to. This not only concerns implementation of infrastructure but also includes social aspects, supporting infrastructure and other requirements. Monitoring is not conducted as a policing action, but should serve as a method by which all development organisations involved can learn from each other, i.e. cross pollination of experience to improve understanding of the difficult subject of irrigation farming development. Monitoring is all too often overlooked in the scramble to meet target dates of new projects, but this can have grave consequences.

Conclusions

It is important that the ground rules for future development be based on the shared experiences of the five symposiums, which have revealed many of the pitfalls associated with the development of irrigations "schemes". Conclusions reached appear to be in line with international experience. In general the contribution of irrigation to development has fallen short of expectations and has seldom proved to be economically viable.

This is not to say that there are not very effective irrigation farmers in the developing areas; there are. It has also become evident that in planning irrigation projects, generalisations are unacceptable and each situation is unique. The first duty of the professional planners is to determine, beyond any shadow of doubt, the real requirements of the community and to establish the applicable physical, sociological and economic restraints. The planners must identify with the community, and this can only be achieved by talking with all strata of the society out in the field.

A regimented high technological development requiring that farmers be trained to conform to "modern methods" to attain high yields will seldom achieve objectives. The expectations of the rural emerging farmer normally encompasses an enterprise consisting of mixed farming with a flexibility which will accommodate multi-culture. His targeted yields would be relatively low requiring low inputs and minimal costs so that profits may be realised. Rural farmers need to grow into technology which will help them become successful larger operators.

Infrastructure is important and must be geared to the developing needs of the people and financing policy must be in step with production decision making. The participation of commercial banks and suppliers of requisites should be encouraged.

The emerging farmer, if given the choice, will not aspire to high yields; indeed, management and resource limitations will preclude the yield levels achieved by the advanced farmer with access to sophisticated equipment and inputs. The irrigation designer should accept lower management levels and reduce the estimates of crop water demand to a level compatible with the cropping and scheduling approach opted for by the farmers.

Lower water demand has a direct influence on the size of dams and distribution systems and, coupled to the use of relatively unsophisticated irrigation methods, can result in reduced capital expenditure and operating costs in the important initial years.

Attention must also be given to construction specifications. It has become practice to accept the normal well tried and proven civil engineering specification standards adopted for major works. It is not easy to deviate from these standards when public funds are involved and the work is being undertaken by contractors, but with escalating costs new schemes are costing too much to be tenable. The development of more appropriate specifications incorporating

innovative construction approaches has now become urgent.

Regular monitoring of projects is essential but is all too often neglected because of budget constraints and a shortage of people trained to undertake the task.

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OPTIMISATION OF DISTRIBUTION LOSSES IN IRRIGATION CANALS

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Abstract
An optimisation system consisting of a water office data base, monitoring stations, communication system and simulation model is described. The main objective of the optimisation system is to minimise management related distribution losses in irrigation canals. The optimisation system can be implemented in part, or as a whole, depending on the requirements of the user. This feature makes it flexible and facilitates systematic implementation on an irrigation scheme.

Introduction

Management related distribution losses on irrigation schemes are, among others, caused by inaccurate dam releases, faulty sluice gate control, inaccurate lag time calculations, errors in water requisition calculations and insufficient monitoring of canal end points. The main objective of the optimisation system is to minimise these management related distribution losses in irrigation canals (Benadé & Annandale, 1987, Benadé, Engelbrecht & Annandale, 1990).

The optimisation system consists of a water office data base, a simulation model, monitoring stations and a communication system. The optimisation system can be implemented in part, or as a whole, depending on the requirements of the user. This property makes it flexible and facilitates systematic implementation on an irrigation scheme.

Water office data base

Work in a water office on an irrigation scheme consists of keeping the water register up to date, handling requests from farmers and managing the distribution of water in the canal system. A water register and water requisition forms are currently being used to log water requisitions for the processing of water distribution reports, calculation of outflow hydrographs and for the compilation of water accounts.

The water office data base is a PC based program that computerizes the system currently used by the Department of Water Affairs on the majority of irrigation schemes in South Africa.

This program simplifies the handling of water requisitions and the calculation of water accounts and water reports. Orders for water placed by farmers can be processed quickly, monthly and yearly reports can be compiled rapidly, inflow hydrographs can be calculated and recalculated immediately and water requisition data is readily available for use in the simulation model.

Experience has shown that the program significantly increases productivity in the water office and that calculation errors are greatly diminished. The calculation of a typical water distribution report that previously took days can now be done in only a few minutes.

The computer program was developed and tested with the assistance of Water Affairs personnel that are involved with water registers. The standard terminology used for Departmental irrigation schemes in the current water register system is used in the program, making it easy for the personnel to understand and accept the computerized system.

Allotment information

The water office data base is set up by feeding all the information on the allotments into the computer. This information typically consists of the allotment number, size, owner, lessee, address, telephone number etc. As soon as the data for an allotment is fed into the computer, a water balance sheet is created. The water balance sheet keeps a record of all the water transactions of an allotment for that specific water year. Passwords are used for protecting data and suspending transactions on a specific allotment.

Water requisitions

The data base provides for original water requisitions, additional orders, cancellation of requisitions and for water transfer between allotments. Water is currently requisitioned by farmers on a weekly basis on various water requisition forms. The combined form, as simulated on the computer, is shown in Figure 1.

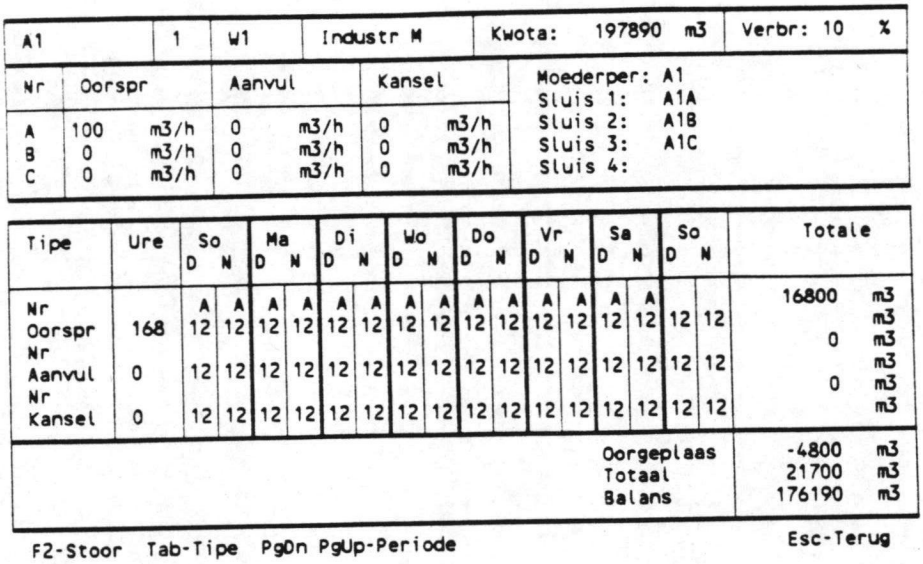
Orders for water are fed directly from the original requisition forms into the computer. This method is an improvement in comparison with the current system, where a number of persons are involved in the compilation of water requests and calculation errors occur frequently.

Reports

The water office data base can generate reports on any request regarding allotment information, water balance sheets or water summaries. An example of a water balance sheet and a water summary report is shown in Figures 2 and 3 respectively.

Monitoring stations

The monitoring stations are used in canals to measure and log water depths as a function of time. These stations can be used for measuring lag times,



A1	1	W1	Industr M	Kwota: 197890 m3	Verbr: 10 %

Nr	Oorspr	Aanvul	Kansel
A	100 m3/h	0 m3/h	0 m3/h
B	0 m3/h	0 m3/h	0 m3/h
C	0 m3/h	0 m3/h	0 m3/h

Moederper: A1
Sluis 1: A1A
Sluis 2: A1B
Sluis 3: A1C
Sluis 4:

Tipe	Ure	So D	So N	Ma D	Ma N	Di D	Di N	Wo D	Wo N	Do D	Do N	Vr D	Vr N	Sa D	Sa N	So D	So N	Totale
Nr		A	A	A	A	A	A	A	A	A	A	A	A	A	A			16800 m3
Oorspr	168	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	m3
Nr																		0 m3
Aanvul	0	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	m3
Nr																		0 m3
Kansel	0	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	12	m3

Oorgeplaas -4800 m3
Totaal 21700 m3
Balans 176190 m3

F2-Stoor Tab-Tipe PgDn PgUp-Periode Esc-Terug

Figure 1 Combined water request form

calibrating the simulation model and monitoring dam releases at the dam wall, canal end points or at any point in the system.The standard Ott-recorder that is commonly used for monitoring water depths on irrigation schemes throughout South-Africa does not have the accuracy and accessibility to suit the task.

The monitoring stations that are used for the computerized system consist mainly of loggers and transducers which record water depth as a function of time. These stations are connected via a radio modem to a computer in the water office. This connection makes it possible to monitor canal operation from the water office and can be used as an aid in water loss control.

The monitoring stations also play an important role in the calibration of the simulation model.

Data from the monitoring stations are stored in a data base that can be queried for any post-processing if necessary. The telemetering system also features:

- CRC-16 error checking
- Auto baud rate selection (1200,600,300 baud)
- Automatic re-route facility
- 128 Kbyte event buffer
- Date/time stamp of events
- Up to 16 I/O cards per station
- Data and speech on the same radio channel
- Mains or solar power with stand by battery

A schematic layout of the telemetering system is shown in Figure 4.

Simulation model

The simulation model is a computer program that

S23	SAND1	Moederper	Kwota: 160560 m3	Balans: 20160 m3

Per	Oorspr	Aanvul	Kansel	Kumula	Balans	%-Verbr	Kwota
1	0	0	0	0	160560	0	7200
2	0	0	0	0	160560	0	0
3	0	0	0	0	160560	0	0
4	0	0	0	0	160560	0	0
5	0	0	0	0	160560	0	0
6	0	0	0	0	160560	0	0
7	0	0	0	0	160560	0	0
8	0	0	0	0	160560	0	0
9	0	0	0	0	160560	0	0
10	0	0	0	0	160560	0	0
11	0	0	0	0	160560	0	0
12	0	0	0	0	160560	0	0
13	0	0	0	0	160560	0	0
14	10800	0	0	10800	149760	7	0
15	10800	0	0	21600	138960	13	0
16	10800	0	0	32400	128160	20	0
17	0	0	0	32400	128160	20	0
18	0	0	0	32400	128160	20	0

Figure 2 Water balance sheet

Waterverslag van: Skema		Datum: 16-04-1991		Tyd: 05:34		Totaal: 18907512
Per	Ma Dag	Ma Nag	Di Dag	Di Nag	Wo Dag	Wo Nag	Do Dag
1	112444	47940	28620	26400	22200	18300	15300
2	26700	32100	46740	43140	45540	38040	29340
3	0	0	62400	61440	52740	40800	35520
4	27600	26100	30600	34500	29400	19800	12900
5	0	0	0	0	0	0	0
6	6600	6600	5400	3600	3600	3600	3600
7	23400	19800	15300	12900	19200	14400	0
8	29700	25200	24300	24000	22500	17100	0
9	21000	19200	16800	16800	21600	21600	30000
10	48000	39000	44400	42900	39000	34800	31200
11	51300	45000	36600	35400	36600	34200	35100
12	66420	54120	46200	49500	51120	43920	37800
13	56700	48000	45300	42600	37500	37500	33000
14	32700	28800	26520	26220	27720	25200	3600
15	42600	39000	37920	37920	43200	45600	39120
16	56100	51900	55800	47100	48300	45300	42600
17	52320	50220	42900	33300	37020	31920	34920
18	79620	77700	70200	54600	58500	60000	51900

Figure 3 Water summary report

simulates subcritical, unsteady flow in irrigation canals.

The program simulates flow in any type of canal, regardless of the number of control structures. The program automatically prompts default properties on all common canal sections. Control structures in the form of sluice gates, sharp and broad-crested weirs and culverts can be inserted in the canal. Canal transitions such as rises and drops in the canal floor, as well as expansions and contractions can be handled. Turn-outs can be made in the form of a constant turn-out discharge as well as through side weirs and side gates. Sluice gate openings that will help maintain constant water levels in a canal system can also be calculated during a simulation.

The simulation model simplifies the calculation of lag times and makes it possible to compare management alternatives. The program can also be used in the operation of irrigation schemes and for the training of canal operators. Validation of the model has shown that a good representation of unsteady flow in irrigation canals is given. It stands to reason that the accuracy of the results depends on the accuracy of the input data.

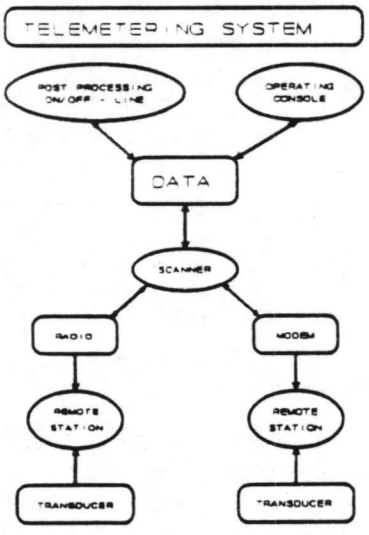


Figure 4 Schematic diagram of telemetering system

Example of a calculation on Loskop irrigation scheme
The ability of the program to simulate unsteady flow in canals was validated with real data from the left bank canal at Loskop irrigation scheme. Flow conditions as from 28 September to 7 October 1989 (230 hours) in the first 42 km of the canal were simulated.

The geometry of the canal was taken from plans of the canal drawn up by the Department of Water Affairs. The release out of Loskopdam at the beginning of the canal was measured with a telemetric measuring station and is shown in Figure 5.

The withdrawals from the canal were taken from water distribution reports that were compiled by the personnel of the Department of Water Affairs at Groblersdal. Seepage losses were estimated as 0.5 ℓ/s per 100 m^2. Evaporation loss was neglected because it was minimal compared to seepage losses.

The outflow discharge at the end of the canal was simulated and compared with the real discharge that was measured with a telemetric measuring station. The results are shown in Figure 6.

It can be seen that the difference between the simulated and measured values is very small except for the period between 50 and 80 hours. The difference is due to sluice gate settings that were made during this period. The gate settings could not be quantified and it was therefore not possible to incorporate them into the simulation.

DEVELOPMENT OF A SPRINKLER IRRIGATION SIMULATOR

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Abstract
A field model sprinkler irrigation simulator, capable of simulating typical situations under various irrigation systems, has been developed for the purpose of studying crust formation of various soils under specific sprinkler irrigation conditions. This paper deals with the design parameters as well as the construction and operation of the simulator. Primary factors influencing the design of such a simulator are: drop size distribution, droplet impact velocity and impact angle, intensity of application, and continuous or intermittent wetting of the test area.

Introduction

The Department of Soil Science of the Potchefstroom University for Christian Higher Education, together with the Department of Agricultural Engineering of the University of Pretoria, is currently undertaking a research project entitled "Development of criteria for sprinkler irrigation systems to minimise sealing of the soil surface". This project is fully sponsored by the Water Research Commission.

The aim of this project is to study the effects of droplet impact on the crust formation and infiltration ability of various so-called "problem soils" under sprinkler irrigation.

The research team of the Potchefstroom University did a preliminary investigation during which various soil samples from localities all over the country, were subjected to different droplet treatments with the aid of a laboratory simulation apparatus. Data thus collected were used to predict the amount of crust formation to be expected on a certain soil subjected to a specific sprinkler irrigation treatment.

In order to verify such predictions a relatively small field model sprinkler irrigation simulator was needed. The Department of Agricultural Engineering of the University of Pretoria was specifically contracted for the purpose of developing such an apparatus. The simulation apparatus developed is capable of simulating typical droplet characteristics as found under various types of sprinkler irrigation systems.

This paper deals with the development of such a field model sprinkler irrigation simulator, together with its characteristics and abilities.

Features required

Typical features required of an irrigation simulator suitable for research on the crust formation of soils under sprinkler irrigation, are:

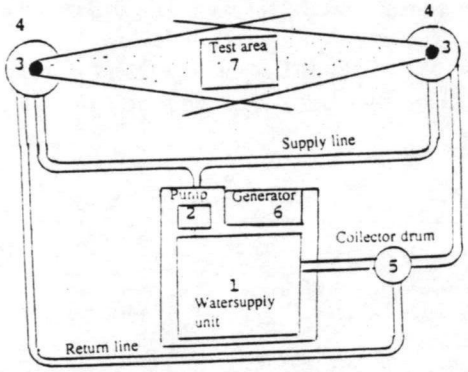
* Reproducibility of given situations with regard to:
  - Water application intensities;
  - Drop size distribution;
  - Impact velocities of drops.
* Continuity of abovementioned for duration of test.
* Application over a sufficiently large representative area.
* Sufficiently uniform distribution over test area.
* Portability between sites.
* Ease of operation and maintenance.

Construction of apparatus

General

The construction of the apparatus is based on the principle of Tovey (1963) and Reinders & Louw (1984), but extended to include two sprayers surrounded by customised circular shields.

Figure 1 shows the general layout of the sprinkler irrigation simulator. The trailer (1) is equipped with a 1000 litre watertank and pump (2) that supplies water to two stationary sprayers (3) which wet the test area from two opposing directions. Each sprayer is surrounded by a rotating shield (4) with a variable opening in the outer circumference through which the jet of water is ejected to the test area. Excess water captured within the shield is delivered to a collector drum (5) and recirculated with another pump to the main water tank. A portable generator (6) supplies the necessary power for the electrical components.



1-Trailer with water tank, 2-pump, 3-stationary sprayers, 4-rotating shield, 5-collector drum, 6-generator, 7-test area

Figure 1 Schematic layout of simulator.

A frame covered with dense shade netting is used to protect the sprayer units and test area from excessive wind effects. It enhances the uniform distribution of droplets and reproducibility of a set of characteristics.

Sprayer units

Each sprayer unit consists of a galvanised pipe framework, electric motor driven rotating shield, and sprayers fitted to quick coupling mountings.

Originally, ordinary Rainbird sprinkler nozzles were used but the dimensions of the wetted area resulted in an impractically large covering frame. In order to keep the physical dimensions of the "test area" as well as the amount of water needed for each test within practical limits, flat-spray Veejet type nozzles were chosen.

In addition, impact velocities can be varied by altering the ejection angle of the nozzles from horizontal to a maximum of 30° downwards, thus providing the necessary variation in energy for different tests. The frame also acts as a water conduit and houses the pressure regulating tap and pressure meter.

A fine mesh screen adjacent to the inside of the shield dissipates the energy of the jet from the sprinkler nozzles and allows the water to run down the sides of the shield into a collector drum underneath. It also prevents the water from forming a spray obstruction in the outlet openings. By changing the V-belt position on the pulleys located on top of the shield, the rotating speeds of the shields can be varied to obtain different intermittent applications.

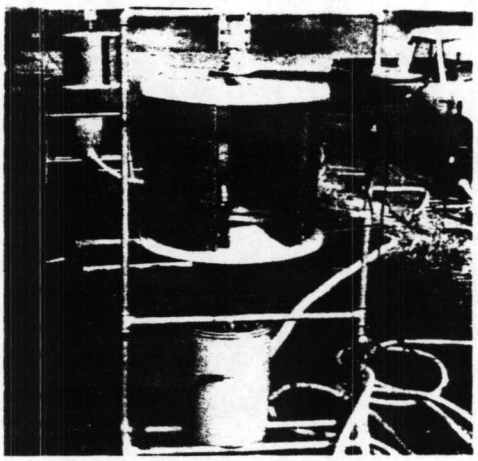


Figure 2 Apparatus in action during a test.

Calibration of apparatus

Drop size distribution

The drop size distributions for horizontally mounted nozzles and nozzles aimed 30° downwards were obtained at 0.5 m intervals for distances of 1.5 to 5 m from the sprinkler units. For each nozzle size, pressure was varied from 60 kPa to 200 kPa in steps of 20 kPa.

Drop size distribution was obtained using the stain method as described by Hall (1970) and also Eigel & Moore (1983).

Impact velocities of drops

A photographic technique was used to determine drop velocity and impact angle. The jet of water from the sprayer was directed through an opening that caused the drops to pass in a vertical plane in front of a 35 mm single lens reflex camera. Two electronic flash units with thyristor circuitry to produce flash durations of less than 1/2000 of a second, were sufficient to stop the images. The pictures were taken in darkness, with the shutter opened manually until the double flash occurred. Slide projections of the images were used to determine the velocities and angle of impact of the drops.

Application intensity

The intensity of water application was measured at each drop size distribution location. The amount of water applied to the test area is a function of the opening size in the circular shield. By changing the size of the opening in the circular shield application intensities can be varied from 0 to 100 mm h^{-1}.

Results

Tables 1 and 2 are typical extracts from the final results showing droplet sizes and velocities for specific nozzles, nozzle angles and operating pressures. The weighted mean droplet diameter and velocities were used to calculate the energies applied to the test areas.

Table 1 Extract of typical characteristics for specific operating conditions (nozzle mounted horizontally).

Pressure	P = 80 kPa	Distance	D = 3 m
Nozzle	N = 80/100	Angle	H = 0° (Horizontal)
Intensity	I = 7.3 mmh^{-1}	for 50 mm opening	

Weighted mean diameter	= 1.44 mm
Weighted mean velocity	= 3.52 ms^{-1}
Energy applied	= 6.20 $Jm^{-2}mm^{-1}$

Drop size (mm diam)	AV velocity (ms^{-1})	Angle of impact (Degrees)	Percentage (%)
1.25	3.39	35	63.4
1.75	3.73	31	34.9
2.25	4.07	30	1.7
2.75	4.41	29	0
3.25	4.75		0

Discussion and conclusion

The simulation apparatus fulfils the desired features mentioned earlier to a great extent. Water application intensities and impact velocity of the drops can be varied as necessary. Drop size distribution is controlled by the nozzle design. To keep the physical dimensions of the apparatus within practical limits, ordinary sprinkler nozzles producing a weighted average drop diameter of 3 to 5 mm cannot be used with the covering frame eliminating wind effects, and such tests are restricted to windless days.

The apparatus is portable, covers a large enough

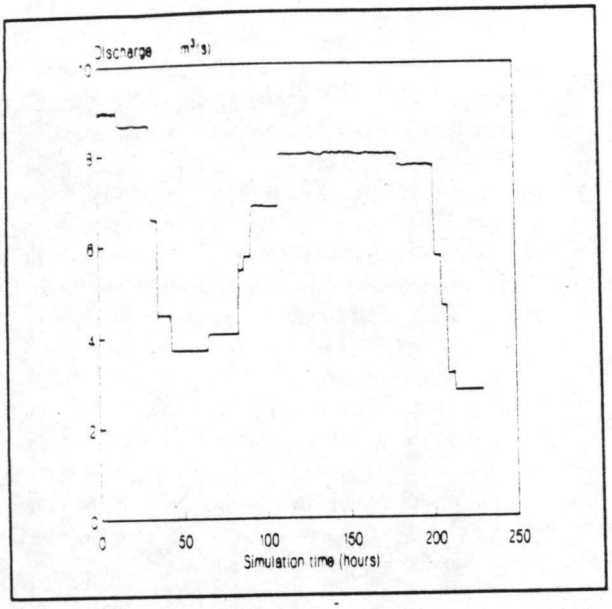


Figure 5 Release out of Loskopdam

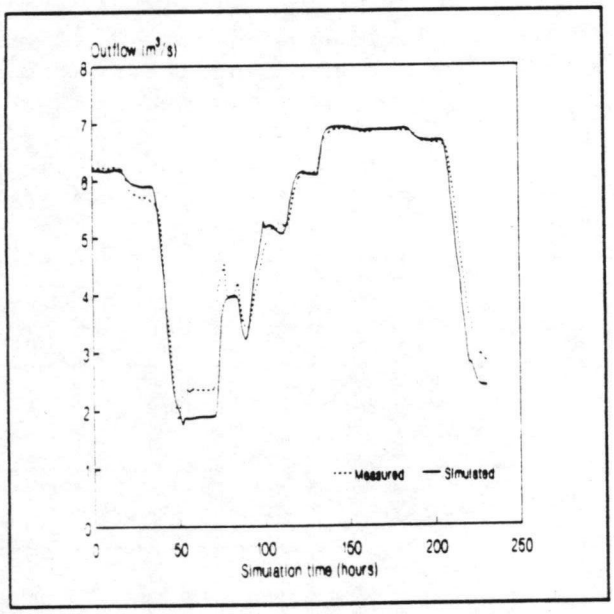


Figure 6 Comparison between measured and simulated values

Application of the optimisation system

The optimisation system can be applied in several ways, depending on the specific needs of an irrigation scheme. A typical application will, however, always use the Water Office Data Base which is updated on a weekly basis by means of information from water requisitions.

Once the data base is updated, water accounts can be generated by the computer and the outlet hydrograph at the dam is readily available from a water summary report. To do calculations of this type by hand on a regular basis without the data base is impractical, if not impossible.

Once the outlet hydrograph is available it may be used in the simulation model to calculate lag times and alternative operational procedures very rapidly.

Operational errors contribute a great deal to losses on most irrigation schemes and current monitoring methods make it difficult to detect such errors. The remotely controlled monitoring stations can be used to determine the water levels at various points along the canal. This data is displayed on the computer in the Water Office, enabling the personnel to detect any deviations and implement corrective action without having to physically monitor the conditions along the canal.

The optimisation system has been partially implemented, with great success, on various irrigation schemes in South Africa. Several calculation and/or operational errors were detected and corrected on each of the participating irrigation schemes.

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BENADÉ, N., ANNANDALE, G.W., 1987. Die ontwikkeling van 'n rekenaarprogram om watervloei in besproeiingskanale te simuleer. *Water SA*, 13, 103-108.

Table 2 Extract of typical characteristics for specific operating conditions (nozzle aimed 30° downwards).

Pressure	P = 150 kPa	Distance	D = 1.8 m
Nozzle	N = 80/50	Angle	H = 30° (Downwards)
Intensity	I = 7.5 mmh^{-1}	for 50 mm opening	

Weighted mean diameter	= 1.50 mm
Weighted mean velocity	= 5.27 ms^{-1}
Energy applied	= 13.89 $Jm^{-2}mm^{-1}$

Drop size (mm diam)	AV velocity (ms^{-1})	Angle of impact (Degrees)	Percentage (%)
1.25	4.88	42	57.6
1.75	5.66	41	35.3
2.25	6.44	36	6.3
2.75	7.22	34	0.7
3.25	8.00	34	0.16

representative area and can reproduce given situations on different test areas with sufficient accuracy. As with most projects, the end product does not reflect the problems experienced as well as the amount of time spent in the development process.

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DROP SIZE DISTRIBUTION OF WATER APPLIED BY CENTRE PIVOT IRRIGATION SYSTEMS

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Abstract
The energy of water droplets applied by irrigation may cause the breakdown of soil aggregates resulting in the formation of a crust. Such a surface seal may dramatically reduce the infiltration rate of a soil leading to excessive water loss by runoff. While drop energy exerted on the soil is calculated from drop size and impact velocity, this study addressed the measurement of drop size distributions. Measurements of drop size were made on three typical centre pivot systems, a technique of irrigation prone to runoff problems. The method involved intercepting the drops with a pan of flour, oven drying the samples and separating the pellets formed through a nest of sieves into different size fractions. A calibration curve, obtained from drops of a known size, was used to estimate the average drop size for each fraction. Drop size distributions were determined at various positions along the lateral of each pivot. Drop si were found to be somewhat larger in one pivot than in the other two, with median drop sizes averaging 2.3 mm, 1.4 mm and 1.0 mm. An increase in nozzle size resulted in an increase in the median drop diameters from a minimum near the centre to a maximum near the outer perimeter of the pivot, but increases were only 6%, 23% and 22%, respectively. Measurements taken perpendicular to the lateral showed an increase in diameter with distance away from the sprinkler line.

Introduction

Water emitted from an irrigation sprinkler separates into stable, discreet drops before reaching the soil surface. Among the factors influencing the resultant drop sizes are the pressure at the nozzle and the nozzle aperture, two parameters that can easily be manipulated in existing sprinkler systems. The drop size distribution is important in that it influences the degree of wind drift as well as evaporative losses before the droplets reach the soil. Most importantly, however, the infiltration rate of bare soil may be seriously reduced due to the formation of a surface crust, particularly where the drop size, and hence the impact energy, is fairly large (Mohammed & Kohl, 1987; Agassi, Morin & Shainberg, 1985).

The impact energy of the falling drops (kinetic energy, KE) can be calculated according to the equation

$$KE = 0.5\ mv^2 \qquad (1)$$

where m = the mass of the drop, and
v = the velocity of the drop on impact.

Both components of KE in Equation 1 are related to the diameter of the impacting drops. The mass is a function of the volume, and hence the diameter of the spherically shaped drop, and velocity is influenced by the surface area, and therefore the diameter, of the drop. The larger drops exert a relatively greater kinetic energy on the surface on impact, primarily through a higher impact velocity. This may promote the disintegration and compaction of the surface aggregates enhancing the formation of a crust. Such a surface seal generally has a very low permeability (McIntyre, 1958) which may dramatically restrict the overall infiltration rate, resulting in excessive water loss by run off (Mohammed and Kohl, 1987).

The centre pivot system of irrigation is often regarded as being particularly hazardous in regard to run off problems, since application rates tend to increase towards the outer extremity of the lateral, with an associated increase in the mean drop size. For an accurate evaluation of the distribution of kinetic energy it is necessary to measure the drop si distribution as well as the application rate (Kinnell, 1987). In an attempt to evaluate the former, two well established techniques of measuring drop size, viz. the stain method and the flour pellet method, were investigated. The stain method, introduced by Lenard (1904), assumes that a drop falling onto a highly absorbent, dye-dusted surface produces a stain with a diameter proportional to the diameter of the drop. Drop size distributions can then be obtained by comparing the stains produced with those produced by drops of a known size. A wide variety of absor surfaces, including filter paper, blotting paper, paper towelling and photographic paper, as well as a range of dyes have been used in the past. A detai description of the method and its problems is presented by Hall (1970). Preliminary investigations showed the stain method to be unsuitable for this application, for the following reasons:

(a) drops larger than 1.0 mm in diameter tend to splatter.
(b) The size of the stain was found to be a function of the fall velocity, i.e. height of fall, for drops of diameter greater than 1.0 mm (Hall, 1970).

In this study drop sizes were measured on centre pivot systems using the flour pellet method similar to that used by Carter, Greer, Braud & Floyd (1974). This method assumes that drops falling into highly

absorbent powder, such as baking flour, form pellets proportional in size to the diameter of the drop. The objective was to characterize drop size distributions on three typical centre pivot systems.

Materials and Methods

Flour Calibration

Drops of a known size and mass were allowed to fall into a pan of freshly sieved (210 micrometre) flour, 20 mm deep. The pellets were allowed to air-dry, sieved out from the flour and then oven dried for 24 hours at 105°C. The average mass of the pellet was plotted against the corresponding average drop diameter (Figure 1).

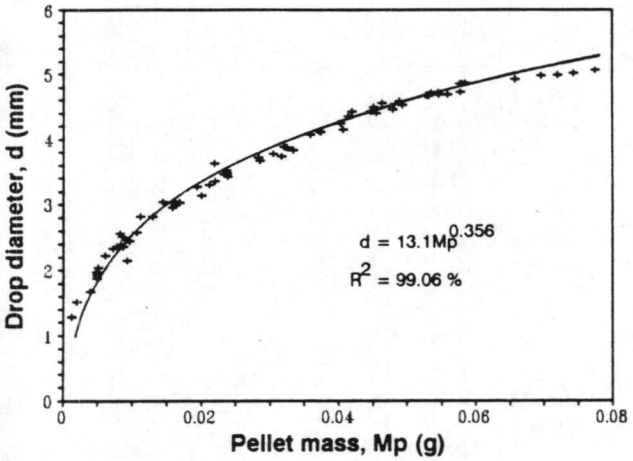


Figure 1 Calibration curve for the flour pellet method

Drop Size Measurement

Drop size distributions were measured on three different centre pivot systems, the characteristics of which are shown in Table 1. Actual field measurements were made using aluminium pans, 380 mm x 160 mm and 20 mm deep, filled with freshly sieved flour and then exposed to the falling drops. The pellets that formed were dried in the same way as for the calibration. The contents of each pan were passed through a nest of sieves with apertures of 300, 500, 710, 1000, 1200, 1680, 2000, 3350, 4000 and 4500 micrometres. The average mass of the oven dried pellets for each size fraction was then calculated and the corresponding drop diameter obtained from the calibration curve (Figure 1).

Measurements were taken at three positions along the lateral of the centre pivot as well as at three points perpendicular to the lateral (Figure 2). The results are presented as cumulative percentage volume curves as a function of drop diameter for each position along the lateral (Figure 3). The median drop diameter, i.e. diameter at 50% volume, at each position along the lateral was read off the curves (Table 2).

The application rate at each point along the lateral was measured using a siphon rain gauge, which recorded one full revolution in 4 hours. The average application rate was calculated over the entire wetting period, while the peak application rates (Table 1) represent the application rate of the central 25% of the wetting period.

Table 1 Some characteristics of the centre pivots systems studied

Pivot	No. of towers	Sprinkler type	Pressure (kPa)	Application rate (mm/h) mean (peak)		Depth (mm)
				Pos. 1	Pos.3	
1	6	impact	200	15 (18)	44 (65)	15
2	9	impact	300	12 (17)	55 (74)	15
3	6	spray nozzle	120	19 (25)	63 (84)	27

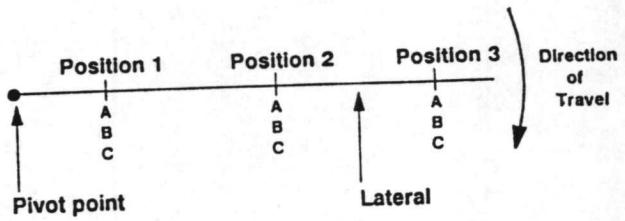


Figure 2 Diagram showing the sampling positions

Results and Discussion

Calibration of the flour produced a very strong relationship ($R^2 > 99\%$) between drop diameter and pellet mass using a power function (Figure 1). Other researchers (Hudson, 1963; Carter *et al.*, 1974) have found it necessary to plot pellet mass against the ratio of drop mass to pellet mass in the calibration curve, but this approach did not appear to be the best option.

For the three centre pivot systems studied, the drops ranged in diameter from less than 0.3 to just over 4 mm (Figure 3). For pivots 2 & 3 very few drops were found to exceed 2.5 mm in diameter, while for pivot 1, an impact sprinkler with a lower operating pressure than pivot 2, the proportion of drops with a diameter greater than 2.5 mm was much higher. The median drop diameters measured for each position (Table 2) showed that there was an increase in median

Table 2 Median drop diameters (mm) at the three sampling positions for the centre pivot systems studied

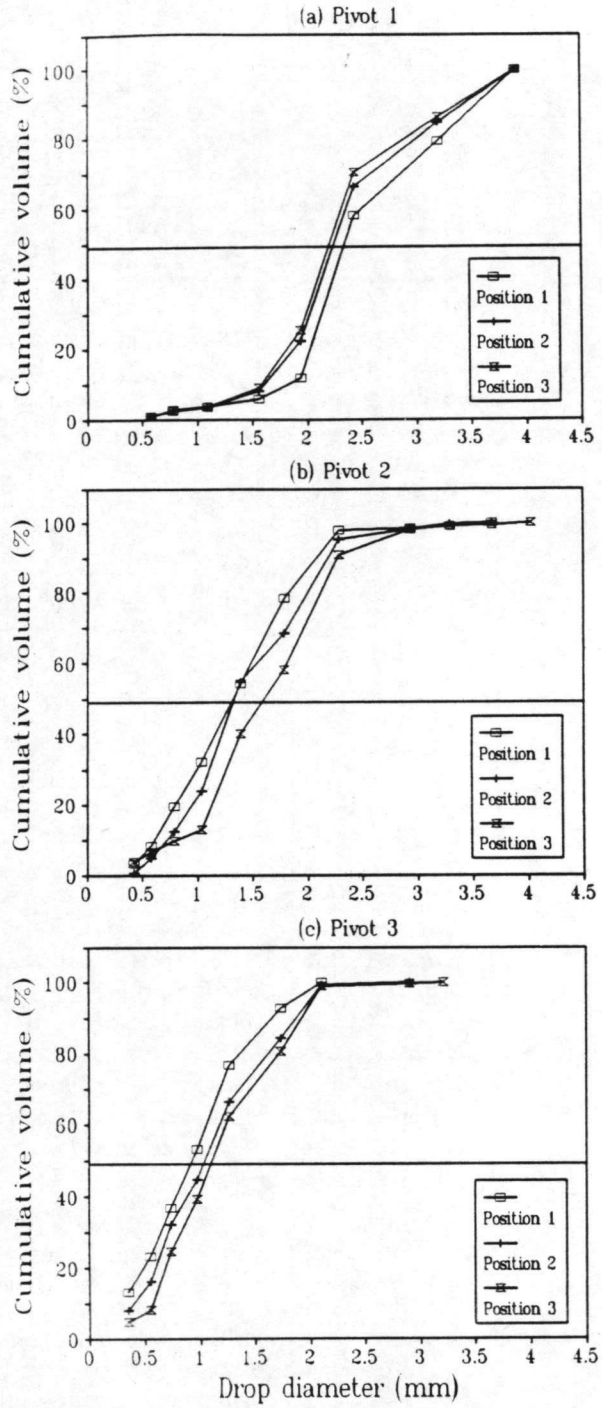


Figure 3 Cumulative volume as a function of drop diameter for the different positions along the laterals of the three centre pivot systems.

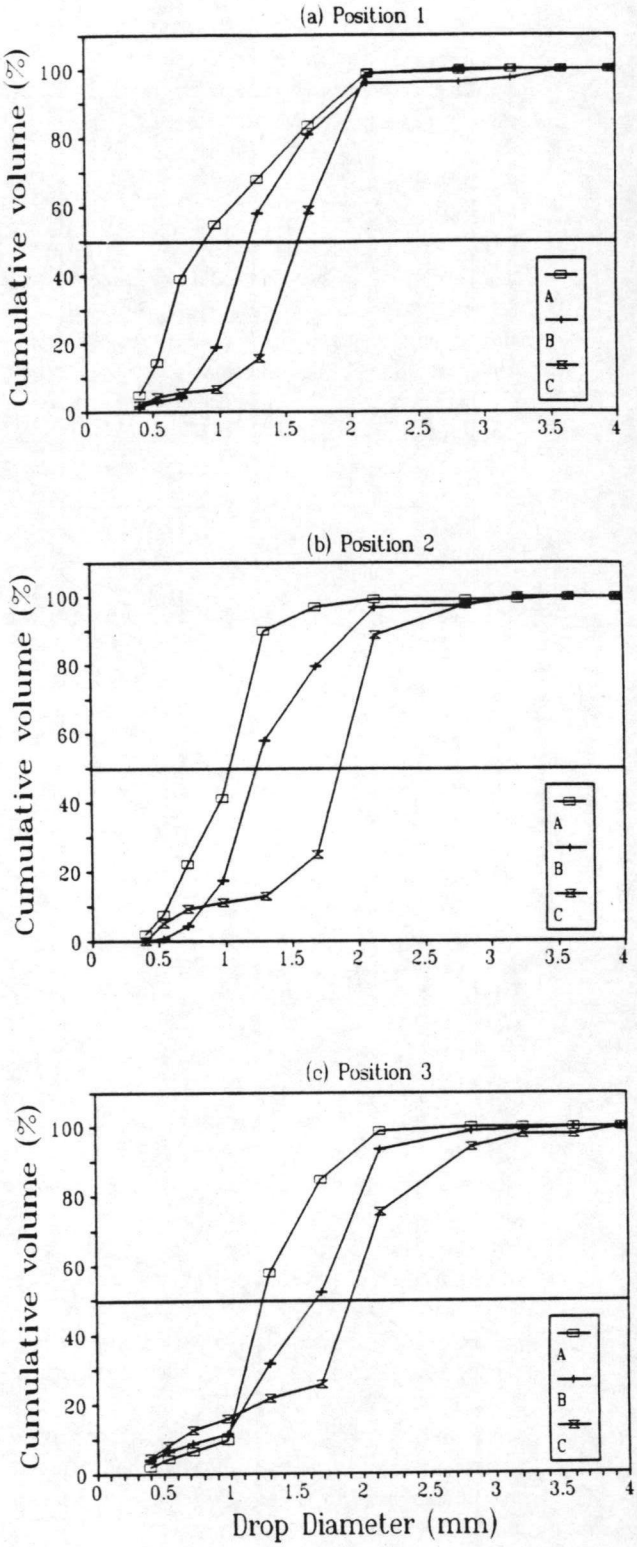


Figure 4 Cumulative volume as a function of drop diameter for three points perpendicular to the lateral of Pivot 2.

drop diameter with distance away from the centre of each pivot. This increase is primarily ascribed to an increase in nozzle size (Kohl, 1974; Hills & Gu, 1989). Although these increases appear to be quite small, Stillmunkes & James (1982) reported that the kinetic energy impacting per unit area is very sensitive to small changes in drop size for drops less than 2.5 mm in diameter. The increased impact velocity is the major contributing factor (Equation 1). Together with the increase in application rate along the lateral (Table 1), this moderate increase in drop size could have a meaningful effect on crust formation due to the

increased energy flux density.

Figures 4a to 4c show the drop size distributions for pivot 2 measured at three points (A, B & C) perpendicular to the lateral at the three sampling positions (Figure 2). It is clear that a greater proportion of smaller drops fell close to the sprinkler line, while a high percentage of the larger drops fell towards the outer edge of the wetting band, at point C. Despite small inconsistencies, similar trends were found for the other two pivot systems studied. It is noteworthy that the drops with the highest impact energy are the first to strike the dry soil surface ahead of the pivot. The physical disintegration of the dry surface aggregates by these drops could conceivably accelerate crust formation, but this requires further study.

Conclusion

Drops emitted from the nozzles of the three centre pivot systems studied increased in size quite markedly along the lateral, with median diameters ranging from a minimum of 0.9 mm near the centre to 2.4 mm near the outer perimeter. This was primarily due to the increase in the nozzle size, which was necessary in order to maintain a uniform depth of application under the pivot. The maximum drop sizes were generally not as great as was anticipated, and diameters seldom exceeded 2.2 mm in pivots 2 and 3, and 4.0 mm in pivot 1. Nevertheless coupled with the increased application rate, this increase in drop size near the outer perimeter will result in a much greater impact energy per unit area, which could reduce the infiltration rate to a greater extent than near the pivot point. The median drop diameter at any one point along the lateral was also found to increase perpendicularly away from the lateral.

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INTRODUCING *CPIP*: A CENTRE PIVOT IRRIGATION PLANNING MODEL

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Abstract

Scarce water resources, escalating energy costs and competition from urban and industrial interests for water utilised to date in the agricultural sector have prompted irrigators to consider the irrigation application efficiencies of their irrigation systems. Computer models are capable of simulating the efficiency of irrigation systems and of predicting their performance under a variety of operating and environmental conditions. This enables the irrigator to test various operating scenarios and to select the irrigation system best suited to a particular set of conditions in the field. A centre pivot planning model, first developed at the University of Idaho in the USA and referred to as the Idaho model, has been modified to incorporate, *inter alia*, an option for variable sprinkler spacing and has been verified under southern African conditions. Further modifications and developments include metrication of input and output information, user friendly menu driven input of information and the introduction of state-of-the-art spray loss and depressional storage routines, to produce the ***CPIP*** model. Field experiments were conducted at "Chailey", a farm belonging to the Pioneer Seed Company near Greytown in the Natal midlands. Application uniformity, infiltration and runoff were monitored under different climatic and irrigation conditions in order to verify the performance of ***CPIP***. A user manual for ***CPIP*** and a floppy disk containing a personal computer version of the model have been produced and are available from the authors.

Introduction

Irrigation to date remains the biggest single user of stored water in southern Africa (Dept. of Water Affairs, 1986). With increasingly scarce water resources and escalating energy costs a need has therefore arisen for greater application efficiency in irrigation. Simulation models provide a method of making objective decisions where these are needed for planning, management and design of, for example, irrigation systems. Site specific parameters related to irrigation and various combinations of system components can be simulated using computer models in order to estimate irrigation performance characteristics under a variety of environmental and operating conditions, and from such simulations operating improvements may be suggested.

A centre pivot irrigation model, referred to as the *Idaho* model in this paper, was developed at the University of Idaho, U.S.A. (Sauer, King & Busch, 1987) for use as a planning tool in the design and installation of centre pivot irrigation systems. The Idaho model operates assuming a constant sprinkler spacing. It was decided to introduce a variable sprinkler spacing option as opposed to the constant sprinkler spacing (Schruer, 1991). This formed the basis of a refined version of the Idaho model and after further modifications ***CPIP*** (***C***entre ***P***ivot ***I***rrigation ***P***lanning), a menu-driven and user friendly model, was developed for which a user manual has now been produced (Schruer & Schulze, 1991).

Spray loss and depressional storage routines, developed by Spurgeon, Thompson & Gilley (1983) and Onstad (1984) respectively, were incorporated in the ***CPIP*** model. Further modifications included the ... driven input program, metricated input and output information into and from the model and a breakdown of runoff losses at each evaluation point to determine the distribution of runoff losses along the centre pivot lateral. Verification studies of the ***CPIP*** model were conducted on "Chailey" farm (29° 05' 40" South, 30° 34' 40" East) belonging to the Pioneer Seed Company near Greytown in the Natal midlands.

Centre pivot performance modelling

CPIP, which is programmed in Fortran 77 and developed for use on IBM compatible PCs, is a ... friendly menu-driven model. Input information is ... from an input file to be completed by the user and performance results are displayed in an output file which may be read on the screen or printed as required.

Once the model has been run using the specified input information the user is able to assess the system's performance. Any of the input variables may then be altered and the model rerun to observe changes in the simulated performance of the centre pivot. This approach enables the user to determine the centre pivot system and mode of operation best suited to a particular location.

CPIP uses a water budget approach to estimate the application efficiency, whereby the sum of water l... occurring through evaporation, wind drift, surface runoff and deep percolation are deducted from the depth of water applied.

In the fixed sprinkler spacing option the type of

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sprinkler and nozzle chosen by the user determines the sprinkler spacing and the number of sprinklers required. Alternatively, the sprinkler spacing and number of sprinklers may be defined by the user's choosing the variable sprinkler spacing option.

Design flow rate and lateral pressure are calculated for each sprinkler assuming a level lateral. Design flow rates are determined by the sprinkler's distance from the pivot point. Sprinklers with pressure regulators are assumed to operate at the minimum required sprinkler pressure for the particular sprinkler type, with each sprinkler delivering its computed design flow rate. Pressures required for non-regulated sprinklers are determined from lateral pressures.

The pressure required at the pivot point is determined using an iterative process implementing the Hazen-Williams head loss formula, starting from the endgun, or last sprinkler if there is no endgun, and proceeding along the lateral to the pivot point. The elevation difference between the pivot point and the lateral, when the lateral is in the constant uphill slope position, is added to the computed minimum pivot pressure.

Once the individual sprinkler pressures and flow rates have been computed assuming a level lateral, sprinkler lateral pressure and flow rates for non-regulated sprinklers are determined taking the gradient of the lateral into consideration. This is achieved using an iterative procedure, similar to that suggested by James (1982).

The runoff losses under the centre pivot system are evaluated at four points in the field using a technique developed by Gilley (1984), and the average runoff is taken of the results at the four points. It should be noted that Gilley's (1984) technique does not take surface sealing into account. These points are situated at 0.30, 0.62, 0.82 and 0.94 of the lateral length from the pivot point and represent the midpoints of four concentric circles, each containing approximately one quarter of the total area covered by the centre pivot lateral.

Depressional storage volumes, which are deducted from the potential runoff volumes at each evaluation point, are estimated from an equation developed by Dillon, Hiler & Vittetoe (1972). Artificial surface storage, such as pits formed by various cultivation practices, and soil conservation practices, such as minimum tillage, are assumed to reduce the runoff by 85 per cent (Sauer *et al.*, 1987). If both random roughness and field slope information are available, the depressional storage is calculated using a formula developed by Onstad (1984), viz.,

$$DS = 0.112 * RR + 0.031 * RR^2 - 0.012 * RR * SS$$

where

DS = depressional storage (mm),
RR = random roughness (mm), and
SS = slope steepness (%).

The gross application depth is adjusted to account for spray losses (wind drift and evaporation combined) which, if no details of wind velocity and vapour pressure deficit are available, are a function of wind regime and sprinkler elevation. For average wind velocities less than 2.2 $m.s^{-1}$ these losses are estimated to be 0.5 per cent of the gross application depth per 0.3 m of sprinkler elevation above ground level and 1.0 per cent per 0.3 m of elevation for wind velocities greater than 2.2 $m.s^{-1}$ (Kincaird & Busch, 1986 cited by Sauer *et al.*, 1987).

Alternatively, spray losses may be calculated using a formula developed by Spurgeon *et al.* (1983) provided that both wind velocity and vapour pressure deficit information is available. This formula was developed specifically for centre pivot systems with impact sprinklers and is expressed as follows:

$$E = 3.89 * \exp(0.19 * u) * V_d^{0.689}$$

where

E = evaporation loss (%),
exp = base of the natural logarithm,
u = wind velocity at 2 m elevation ($m.s^{-1}$), and
V_d = vapour pressure deficit (kPa).

If spray nozzles are specified by the user, the model defaults to the spray loss formula used in the *Idaho* model. Once again, as in the case of sprinkler spacing and random roughness, two levels of sophistication are offered in ***CPIP*** depending on the input information available.

The adjusted application depth calculated for each sprinkler point is used to calculate the Christiansen uniformity coefficient (Christiansen, 1941). The computed value of the Christiansen uniformity coefficient (C_u) is converted to the low quarter distribution uniformity (DU) measure. C_u is assumed to be 90 per cent for impact sprinklers and 85 per cent for spray nozzles (Sauer *et al.*, 1987). Thus, DU of impact sprinklers and spray nozzles are approximately equal to C_u-7 and C_u-9 respectively (Sauer *et al.*, 1987). Deep percolation losses are calculated by assuming that the only deep percolation losses are those due to non-uniformity of application and not soil physical properties.

Output information from the model is as follows:

i) required pivot pressure (kPa),
ii) runoff losses at each evaluation point (mm),
iii) total irrigated depth (mm),
iv) losses due to spray, runoff and deep percolation (mm and % of application depth),
v) average net irrigation depth (mm),
vi) application efficiency (%), and
vii) coefficient of uniformity.

This section has described briefly the operation of the ***CPIP*** model. The following section discusses the verification of the variable sprinkler spacing option.

Model verification

The introduction of a variable sprinkler spacing option into ***CPIP*** was expected to affect predictions of sprinkler flow rates, runoff, application efficiency and

application uniformity. For this reason the fieldwork conducted was concentrated on the verification of these components. The "Chailey" centre pivot had a lateral length of 854 m spanning 14 towers. As illustrated in Figure 1, the centre pivot irrigated a 226° arc covering a total crop area of 130 ha. Sites 501 to 504 contained runoff plots and rows 1, 2, A and B were rows of raingauges used to record the application uniformity.

The centre pivot performance on "Chailey" was simulated using the *Idaho* and ***CPIP*** models to compare the predicted flow rates with observed flow rates. Results of this simulation are illustrated in Figure 2.

These visual results confirmed that the ***CPIP*** model simulated the flow rates of an observed centre pivot system more accurately than the *Idaho* model. It was envisaged that this modification would also improve the prediction of runoff, application uniformity and application efficiency; this hypothesis will now be investigated.

Runoff losses collected from the runoff plots mentioned previously were compared graphically (Figure 3) to predicted runoff losses.

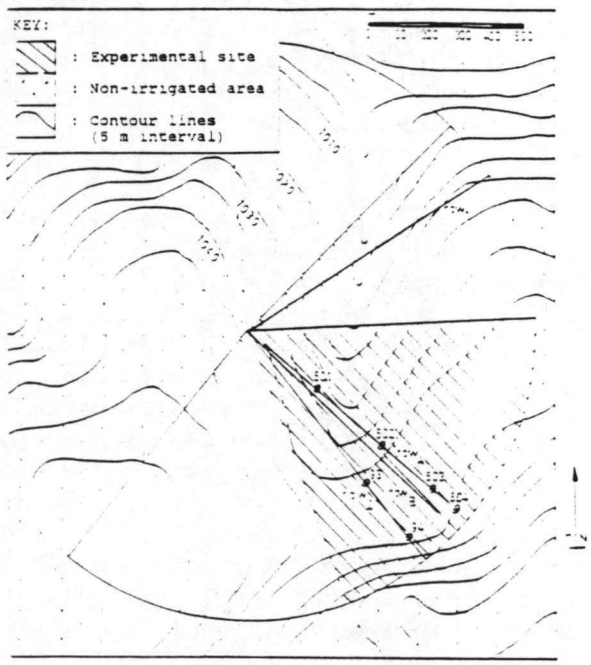


Figure 1 Illustration of the experiment site on "Chailey" farm belonging to the Pioneer Seed Co. at Greytown

As illustrated in Figure 3, the ***CPIP*** model over-estimated runoff slightly and the *Idaho* model underestimated runoff. A perfect model would display a 1:1 relationship, illustrated in Figure 3, between predicted and observed results.

Correlation coefficients were calculated using data collected from fieldwork to confirm these findings. The correlation coefficient between runoff predicted by the *Idaho* model and observed runoff was r = 0.98. The correlation coefficient between observed and predicted runoff by the ***CPIP*** model was r = 0.99. In order to test for systematic over- or underestimation the coefficient of efficiency (Aitken, 1973) was also calculated. This value is always less than unity,

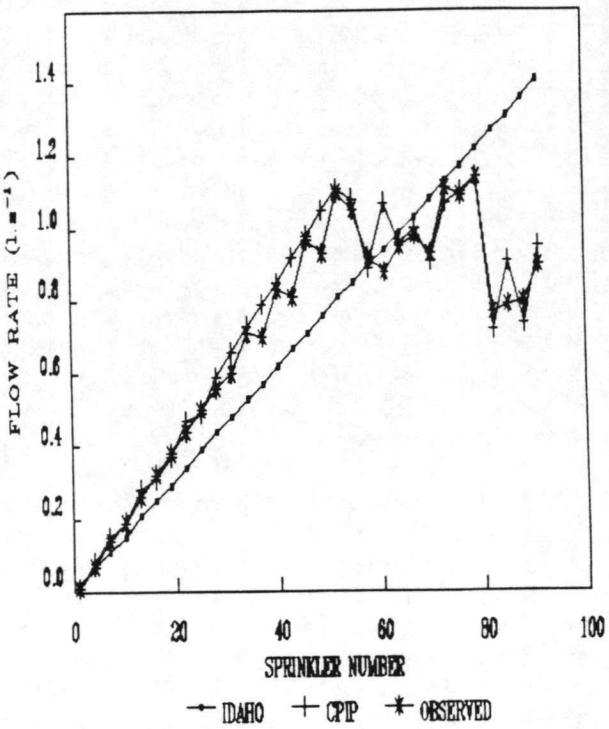


Figure 2 Sprinkler flow rates ($l.s^{-1}$) predicted by the *Idaho* and ***CPIP*** models compared with observed flow rates of the centre pivot on "Chailey"

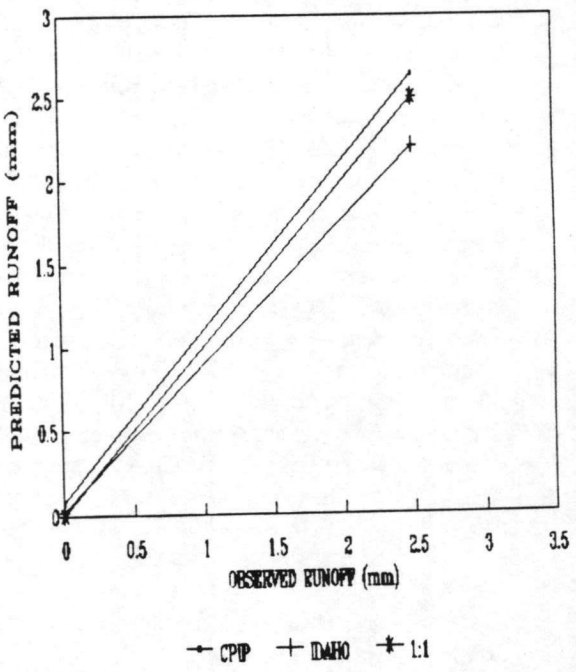


Figure 3 Regression relationships between runoff (mm) predicted by the *Idaho* and ***CPIP*** models and observed runoff on "Chailey" under different grazing and irrigation application conditions

however, the closer the coefficient of efficiency is to unity the more accurate the estimates of runoff. The *CPIP* model with a value of 0.97 opposed to the coefficient of efficiency of 0.93 of the *Idaho* model showed that the latter's results were more biased than those of *CPIP*.

Field results of application uniformity, determined for the "Chailey" centre pivot using the catch can method (Schruer, 1991), ranged from 70.6 to 91.9 depending on operating conditions at the time of irrigation.

These observed application uniformities were generally lower than both the manufacturer's specifications and model predictions, which for the *Idaho* and *CPIP* models were very similar (Table 1). The wide range of application uniformity results obtained in the field may be attributed to the unreliability of the particular centre pivot system on "Chailey", which was prone to leaking and blocked nozzles and pressure variations (Schruer, 1991).

Table 1 furthermore presents predictions, by the *Idaho* and *CPIP* models, of runoff and application efficiency for the centre pivot on "Chailey". The differences in application efficiency predictions between the two models are negligible, as are those of application uniformity. As indicated in Table 1, the *CPIP* model predicted very slightly lower application efficiencies than the *Idaho* model. These slightly lower predictions are attributed to the higher estimations of runoff losses by the *CPIP* model.

Table 1 Runoff (% of application depth), application efficiency (%) and application uniformity at various application depths (mm), as predicted by the Idaho and *CPIP* models (Schruer, 1991)

Model	Application (mm)	Runoff (%)	Application efficiency (%)	Application uniformity
CPIP	10	0.94	85.38	91.76
Idaho	10	0.38	85.82	91.67
CPIP	20	4.24	82.35	91.76
Idaho	20	3.84	82.65	91.67

Conclusions

The objective of this study was to refine an existing centre pivot model, to verify the *CPIP* model performance against results from fieldwork and to compare the performance of the *CPIP* model with that of the *Idaho* model. Fieldwork was aimed at justifying the incorporation of a variable sprinkler spacing option in the *CPIP* model.

Introduction of the variable sprinkler spacing option improved the estimation of sprinkler flow rates and was expected to affect the prediction of runoff losses, application uniformity and application efficiency.

The *CPIP* model showed a slight improvement over the *Idaho* model in the predictions of runoff losses, although runoff was overpredicted. Application uniformities achieved in the field were lower than those predicted by both the *Idaho* and the *CPIP* model. This was attributed to the unreliability of the centre pivot system at "Chailey". Expected application uniformities, as indicated by the manufacturer's specifications, were similar to those predicted by the centre pivot models.

Application efficiency and application uniformity were affected only negligibly in the *CPIP* model despite improved sprinkler flow rate estimations. This is possibly attributed to the two models achieving similar gross application depths and application rates, despite corresponding sprinkler flow rates being different.

The inclusion of a variable sprinkler spacing option requires that each sprinkler spacing be entered into the *CPIP* model input menu. This requires more computer time and the input requirements are more than doubled. In modelling one should assess whether the higher levels of sophistication, requiring more input information and computer time, justify the benefits gained from the improved accuracy. In the case of the variable sprinkler spacing option this does not appear so.

The *CPIP* model was only tested at low infiltration rates and application depths in the field due to the nature of the crop and soil type being irrigated. This model therefore remains to be tested over a range of centre pivot sizes, higher infiltration rates and application depths. A copy of the *CPIP* user manual and a floppy disk containing a PC version of the model are available on request from the second author.

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EVAPORATION AND WIND DRIFT LOSSES DURING CENTRE PIVOT IRRIGATION

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Abstract

Understanding and reducing spray losses are of importance in attempts to increase the efficiency of centre pivot irrigation. In a field experiment conducted over four years, total spray losses between the emitters and the plant canopy were measured and partitioned into wind drift and evaporation losses. Relationships with meteorological factors were investigated. Spray losses expressed as a percentage of water applied are found to be smaller at larger depths of application and should rarely exceed 10%, with approximately equal proportions due to wind drift and evaporation. Meteorological factors which most affect the evaporation component of spray loss are windspeed and vapour pressure deficit.

Introduction

Most of South Africa can be classified as semi-arid to arid. Water is becoming an increasingly scarce resource, requiring optimal management in the national interest. The demand on South African water resources is intensifying, placing increasing pressure on the agricultural sector which at present consumes approximately 60% of available resources. The economic returns per unit of water used in irrigation are often much lower than for some alternative uses (Conley, 1990). Contrary to current opinion, irrigation schemes do not necessarily exhibit above average job-creation advantages. In a recent study by the Department of Water Affairs, approximately 66% of the industrial sectors considered, did better than the estimated labour/capital multiplier for irrigation development of 12.4 persons per R1 million invested (Conley, 1990). The farmer of the future will have to use his quota of water more efficiently by improving the design of the irrigation system, scheduling techniques and his knowledge of crop-water requirements.

During the period 1970-1982 the efficiency considered acceptable for a centre pivot system was estimated at 80%. Around 1982 the shortage of water and the economic situation forced the firms selling centre pivots to improve this as a value of 85% seemed more acceptable.

This paper reports on an investigation done to identify and quantify the spray losses between the emitters on a centre pivot irrigation system and the plant canopy. Meteorological and other factors influencing irrigation losses are identified.

Literature review

Losses during sprinkler irrigation have been the subject of numerous field, laboratory and analytical studies. There are differences in the way evaporation and wind drift losses are defined and also in accuracy of experimental techniques for determination of losses. The term "spray losses", as used in literature, seems to be universally accepted as including all losses during irrigation.

Spray losses have been investigated since as early as the second world war. Christiansen (1942) found losses from a single sprinkler to range from 10% to 40% of the pumped water.

Frost & Schwalen (1955; 1960) made an extensive evaluation of spray losses in Arizona. These authors correlated spray losses to vapour pressure deficit, windspeed, nozzle pressure and nozzle size. The results obtained varied from 3% to 45% loss for a single sprinkler and led to the development of the well-known Frost nomogram. This nomogram estimates spray loss during sprinkler irrigation and is still in use today.

Kranz (1966), as reported by Steiner, Kanemasu & Clark (1983) found spray losses to vary between 3% and 17%. Of these, wind drift losses comprised 36% and evaporation losses 64%.

Clark & Finley (1975) measured spray losses in Texas and found these to be generally less than 10% at a windspeed of less than 4.5 m/s. The result of their study showed that losses were related to windspeed and vapour pressure deficit.

Researchers are in agreement that wind drift loss and evaporation losses cannot be considered a nett loss as these losses offset evapotranspiration losses which would have occurred in an unsprinkled field. Reduced transpiration is attributed to reduced vapour pressure deficit following sprinkling (Kranz, 1966) and increased stomatal resistance due to a film of water on the leaves (McNaughton, 1981).

Steiner *et al* (1983) reported on spray losses under centre pivot irrigation systems. It was concluded that spray losses averaged 15% under strong evaporative conditions. Correlations between spray loss and vapour pressure deficit and a term combining vapour pressure deficit with windspeed yielded coefficients (r) of 0.46 in both instances, with the level of significance at $P < 0.03$. When the wind was parallel to the system no correlation was found betweem spray losses, windspeed, vapour pressure deficit and temperature.

In an effort to measure the evaporation component of the total loss Kohl, Kohl & De Boer (1987) simulated a linear irrigation system in their field layout. This included evaporation from drops drifting through the air over a distance of up to 60 m downwind of the line

source. These authors concluded that (i) measured evaporation loss from smooth impingement spray plates averages 0.9% varying from 0.7% to 1.4%, (ii) measured evaporation loss from coarse impingement spray plates average 0.5% varying from 0.4% to 0.6%, (iii) approximately 40% of the loss occurred from water droplets that did not reach the soil surface within 60 m of the sprinkler lateral, and (iv) calculated losses and measured evaporation values were highly correlated (r= 0.98) for the smooth impingement plate. They further concluded that measured losses were less than the evaporation loss commonly allowed for in the design of irrigation management programs.

It was pointed out earlier by Frost & Schwalen (1955) that losses incurred with an irrigation system (combination of emitters), were only 50% of that of a single nozzle. It is therefore almost impossible to extrapolate the results obtained from single nozzle studies to a centre pivot or any other sprinkler system. The reason for this phenomenon can be ascribed to the high rate of application of the centre pivot system. This forms a dome of water and saturated air which significantly effects the evaporation process.

Materials and methods

Concepts discussed in this study are defined as follows:
Spray loss is the total loss occuring between the emitters and the plant canopy.
Evaporation loss is the evaporation component of the spray loss.
Drift loss is the component of spray loss that is caused by wind drift.
D_{50} —— the volume mean drop diameter in mm specifies that 50% of the total volume of water occurs in drops of D_{50} mm diameter or less.
E_0 —— The rate of total evaporation from an extended surface of a 80 mm to 150 mm tall grass cover of uniform height actively growing, completely shading the ground and not deficient in water or nutrients (De Jager & Van Zyl, 1989).

Data were collected at the experimental farm, Leeuberg, from 1985 to 1989. Observations were made under a centre pivot system (Valley), approximately 195 m in length which irrigated about 12 ha of land. The system was nozzled with a variety of emitters with a pressure variation of 300 kPa for the sprinklers down to 100 kPa for the low-pressure spray emitters. The field was planted to wheat in winter and maize in summer.

Spray losses were estimated by measuring the difference in water volume at the pump, and the volume arriving at the plant canopy.

Water reaching the top of the plant canopy was collected in plastic funnels with an opening of 127 mm diameter. Each funnel (rain guage) was fitted with a plastic top to suppress evaporation. The depth of water thus collected, was measured with a calibrated rain gauge immediately after an irrigation was completed. The funnels were arranged in two rows on the radius at an angle of 3° and a spacing of 9 m. No measure ts were made under the first 25 m of the centre pivot and the collecting funnels were mounted on iron rods continuously adjusted to be above the top of the plant canopy.

The pumped water was measured with a flow meter. The flow meter had been calibrated by the Department of Water Affairs at the calibration laboratory at Jacobsdal.

Evaporation losses were determined by measuring the difference in electrical conductivity of the pumped water and the water collected in the funnels. The pumped water was sampled by drawing samples at the first outlet of the centre pivot. The funnels were sampled immediately after each irrigation.

The losses from a single emitter were measured by simulating the height of a centre pivot through using an iron rod (3.66 m in length) with an emitter placed at its tip. Spray from the emitter was directed onto a p c groundsheet. Calibrated water meters were used to measure the input to the emitter and the run-off fr the groundsheet. A shade cloth approximately 300 mm above the surface of the groundsheet suppressed evaporation from the groundsheet. The drop size distribution was determined by using the flour method. Trays containing about a 25 mm thick layer of plain flour were exposed to the drops from the emitter. The dough balls thus created were dried, weighed and screened. Drop sizes were determined via a calibration formula proposed by Kohl *et al.* (1987).

The measurement of the climatic variables was done with the assistance of the Department of Agrometeorology. The conclusions reached in this paper are based on 79 irrigations applied over a period of 5 years.

Results and discussion

(A) Spray loss from single emitters

Losses measured from the single emitters (Nelson Spray 3 at a pressure of 100 kPa) were, on average, 19% of pumped water. This average loss was for nozzle si ranging from 1.98 mm to 9.32 mm. This range of nozzle sizes is normal on centre pivots beyond span No. 2. The measured losses were found to be highly correlated with the inverse of the exponent of the volume mean drop size D_{50} of the drop size distribution ($r = 0.82$). This was also found to be highly correlated with the exponent of the windspeed ($r = 0.52$). The regression equation describing the combined effect of D_{50} and windspeed on spray loss from a single low pressure emitter was:

$$Y = 108.340 * e^{-D50} + 0.054 * e^{u} - 7.173 \qquad (1)$$

where
Y = percentage loss in pumped water (%)
D_{50} = Volume mean drop size (mm)
u = windspeed (m/s)
The coefficient of determination for this regression equation was high at $R^2 = 0.78$.

Solomon, Kincaid and Bezdek (1985) maintain that drops of small diameter (< 0.7 mm) are very sensitive to windspeed and therefore to wind drift losses, as well as distortion of distribution patterns. The results of this study confirmed this conclusion in that spray losses are inversely proportional to the exponent of volume mean drop size.

(B) Spray losses between emitters and plant canopy
The average loss of irrigation water between emitter and plant canopy was measured as 9.8% of the pumped water. This figure varied with change in operating pressure as shown in Table 1.

Table 1 Variation of average loss with operating pressure.

Operating Pressure (kPa)	Average Loss (%)
>200	10.6
140 - 200	9.4
<140	12.2

The average depth of application for all irrigation was 19.7 mm and the average absolute loss was 1.94 mm. No correlation was found between total losses and either windspeed, vapour pressure deficit or radiation. The correlation of absolute loss with reference evaporation (E_o), from a vegetative surface was somewhat higher but still low at r = 0.33.

Losses expressed as a percentage of pumped water showed similar lack of correlation except that the correlation of losses with application depth was highest and negative at r = -0.45. This correlation with application depth improved at working pressures less than 140 kPa to r = -0.67. Approximately 90% of all emitter-packages sold in S.A. today, operate in this range of working pressure.

Steiner *et al.* (1983) found spray losses to correlate with various climatic variables, but coefficients were so low that only 25% of the variability in their results, could be attributed to climate. It is thus clear from the results of this study that depth of application is the most important variable affecting losses.

Another interesting fact is that the loss under a centre pivot system or combination of emitters is on average only 50% of the loss under a single spray emitter. This confirms the results obtained by Frost & Schwalen (1955).

A possible explanation for lack of significant correlation with any climatic variable, and the fact that a combination of emitters exhibits 50% of the loss measured under a single emitter, is the high application rate under a centre pivot system. Losses are reduced because water is applied in a dome of water saturated air. The microclimate inside the dome varies considerably with the macroclimatic variables existing outside this dome.

(C) Evaporation loss
Evaporation loss is a component of the spray l between the emitter and plant canopy. The average loss of irrigation water due to evaporation was measured as 5% of the pumped water. It was further established that under the first span of the centre pivot, the evaporation losses were consistently higher than for span number two and three. This can be ascribed to the smaller drop size (D_{50} = 1.8 mm compared to D_{50} = 2.1 mm) produced by the smaller nozzles on the first span. The results of the first 3 spans are given in Table 2.

The influence of depth of application and of climatic variables upon evaporation loss were investigated. Correlation results are given in Table 3 and equation 2.

$$Y = 3.86 + 0.0014X_1 + 1.1311X_2 - 0.0089X_3 \quad (2)$$

where Y = Evaporation loss as % of pumped water
$X_1 = e^{\text{windspeed(m/s)}}$
X_2 = Vapour pressure deficit (kPa)
X_3 = Depth of application (mm)
The coefficient of determination of this equation was high at $R^2 = 0.77$ with the level of significance at P = 0.0001

(D) Wind drift losses
As previously explained, this component was also estimated to be 5% of the pumped water or 50% of the spray loss. This was calculated as the difference betv total spray loss and evaporation loss.

Table 2 Evaporation losses measured under the first 3 spans of a centre pivot.

Span No	Evaporation loss
1	8.5%
2	5.8%
3	4.8%

Table 3 Correlation coefficient (r) of evaporation loss with depth of application and climatic varaibles.

Variable	r
Depth of application	-0.61 (p = 0.03)
$e^{windspeed}$	0.77 (p = 0.002)
Vapour pressure deficit	0.49 (p = 0.04)

Conclusions

It is concluded that:

(i) Average losses under centre pivot irrigation should rarely exceed 10% of the pumped water if the emitter package is properly designed and irrigation is carried out day and night. This will be true for conditions where windspeed does not exceed 6 m/s.

(ii) The components of the spray loss of 10% consist of wind drift losses at 5% and evaporation losses also at 5% of pumped water.

(iii) From the results obtained with single nozzles it is clear that drop size has an important effect on spray loss. If the proportion of drops of < 1 mm diameter in the drop size distribution of the emitter package exceeds approximately 2%, the resultant percentage of spray loss due to evaporation and wind drift will increase substantially.

(iv) Depth of application is the variable effecting irrigation spray loss most and it should always be as large as possible and preferably more than 25 mm per irrigation.

(v) Meteorological factors influencing the evaporation component of spray loss are windspeed (59%) and vapour pressure deficit (24%).

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GENERAL PRINCIPLES AND PRESENT APPROACH TO IRRIGATION DEVELOPMENT BY THE GOVERNMENT OF SOUTH AFRICA

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ABSTRACT

Irrigation development has gone through different stages in the history of South Africa. At present, economic realities make it very difficult to justify new irrigation development and the risk to such new development is relatively high both for the State and the farmer. Principles involved in determining the feasibility of new irrigation developments are discussed and the basic approach to government support of irrigation development is explained.

Introduction

Irrigation has been practised in South Africa for more than 300 years. With those early irrigation projects, planning centred mainly around the technical aspects and little attention was paid to financial or economic studies.

The main reason for the development of irrigation projects in the past was to develop specific areas or to create job opportunities. Although these motives are still valid, other motives are currently also valid. It is true to say that both the motives for irrigation development and the accompanying nature of problems have changed with time and have become more complex.

At present no irrigation development should take place without proper studies and planning, and even then some projects carry risks which cannot be taken into account during the planning stage.

Irrigation development requirements at various levels

Where government was involved in irrigation development in the past, most times it was based on the assumption that irrigation development was economically justifiable and that it would serve a useful purpose in realising socio-political aims such as job creation, development of rural areas, stimulation of local economic activities and the development of the country's infrastructure. However, various important changes during the past ten years have begun to seriously curtail irrigation development. In this regard reference is made to a dramatic rise in costs of capital goods relative to a small rise in producer prices (Figure 1), the fact that the most cost effective developments have been completed and the fact that the government has laid increasing emphasis on privatization. With regard to privatization, for example, government no longer provides loans for irrigation boards and financing is done by the Landbank. The consequence of all these factors is that it has become increasingly difficult for irrigation development to be economically viable for the farmer. Proper irrigation planning is the only answer to ensure viable irrigation development.

The need for proper irrigation planning manifests itself at three levels:

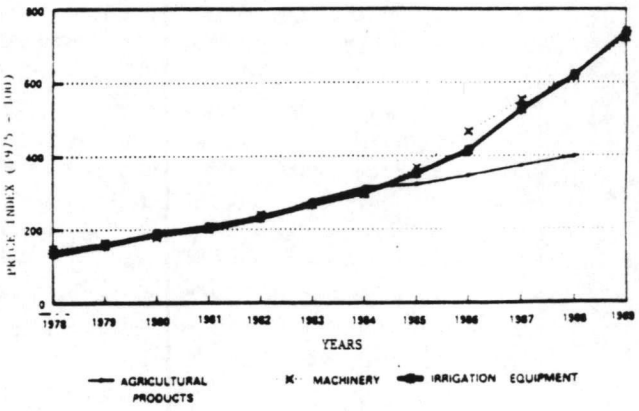


Figure 1 Price index for agricultural products, machinery and irrigation equipment (Abstract of Agricultural Statistics, 1990).

a) Government: An urgent need has evolved to obtain more clarity on the long term policy that should be pursued with irrigation development. The role that irrigation should play in self-sufficiency of food supply for South Africa is central to this. Coupled to a needed long term policy is a policy regarding state aid for irrigation. The role that should be played by irrigation subsidies should be addressed as well as the role of special aid to irrigators during times of water shortage, worsening markets and other problems.

b) Individual farmers: Due to the increasing gap between prices of inputs and products, the difference between survival and ruin of a farmer often lies in proper planning, especially of cash flow. If unrealistically high yields are built into planning and these do not materialize, the survival of the business becomes impossible.

c) Commercial companies: The future of companies who serve the irrigation industry is directly linked to those of the irrigation farmers. When sound planning by farmers lead to financially viable farming enterprises, good business is done while struggling farmers do not make good customers. Proper planning ranging from long term

government strategies right down to sound farmer planning, is the foundation of a healthy irrigation industry.

General principles applied in government planning of irrigation projects

The broad goal pursued in planning new projects is that any new project should be technically and economically viable both in the short term and in the long term. Since technical problems are not a real concern, only economic considerations will be discussed. Feasibility studies are conducted roughly in accordance to the principles laid down in "Guide to the economic evaluation of irrigation projects" (Bergmann & Boussard, 1976) and are carried out in phases of increasing detail.

Typically, a feasibility study will start off with an exploratory investigation involving generally available information, experience and common sense to form a broad picture of possibilities and obstacles. A positive result will indicate the start of another phase of investigation using broadly based techniques to gather more information but without much detail. This is conducted by a multi-disciplinary team consisting of engineers, soil scientists, agriculturalists and economists of the Department of Agricultural Development, operating as an "Irrigation Action Committee" (IAC). IAC's are decentralized and stationed at seven agricultural regions. A centralized "Irrigation Investigation Committe" (IIC) is available to give aid to the seven IAC's and is empowered to hire suitable consultants when required.

From a government's point of view, any new irrigation development must be a good investment of taxpayers' money, with as low a risk attached to it as possible. To ensure a good investment, it is required that a benefit : cost ratio greater than 1 must be realized. The benefit : cost ratio (R) is calculated as follows:

R = (Nett present value of project - nett present value without project)/(Nett present value of capital cost of project)

A value of R greater than 1 is an indication that more money will be generated by the project than money put into it. This, of course, is the indicator that is of importance to government when a new project is considered. However, it is not the only criterion.

Normally, new irrigation projects are undertaken by irrigation boards who get financing from the Landbank under a government guarantee. The money lent from the Landbank is repaid by individual irrigation farmers through water rates levied by the irrigation board. The ability of individual farmers to pay their water rates therefore determines the risk that the state runs in supplying a guarantee for the loan and the state has to use that ability as a second criterion in deciding to implement a new project.

During a feasibility study great emphasis is laid on an analysis of the expected cash flow of farmers after implementation of the project. If it is a small project with only a few irrigators, the cash flow of each individual is analysed. In large projects irrigators are divided into representative groups and cash flow for a typical farm in each group is analysed. Figure 2 shows the annual (surplus) cash flow and Figure 3 the cumulative cash flow for a typical farm in a project with good prospects. A sensitivity analysis (Figure 4) shows that parameters such as product price, carrying capacity, water rates and production can vary by more than 20% from the values assumed in the analysis without causing the nett present value of the project to become negative. Such a project can be supported by government with reasonable confidence.

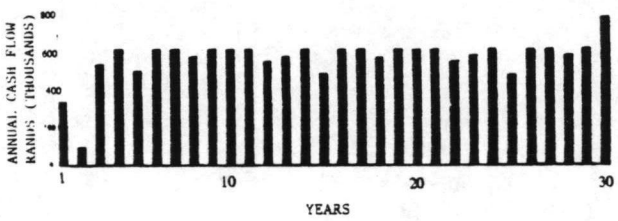


Figure 2 Annual cash flow for a successful irrigation project (Agriplan, 1991).

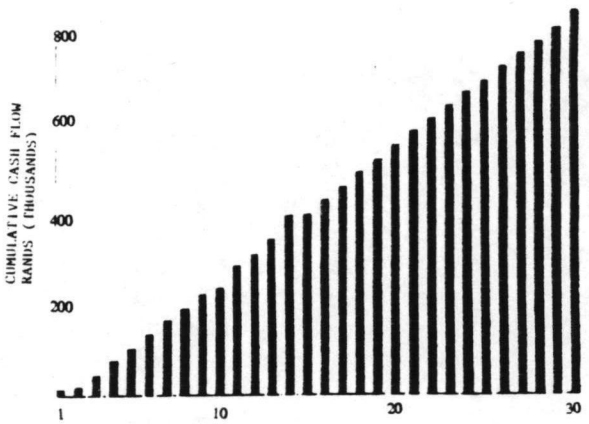


Figure 3 Example of cumulative cash flow for a successful irrigation project.

An example of a project that can hardly be justified economically is illustrated in Figure 5 and Figure 6. Figure 5 shows that a typical farmer will only achieve a positive cumulative cash flow after ten years. Furthermore, the sensitivity analysis (Figure 6) shows that if either prices or the exchange rate varies by more than 10% from the values used in the analysis, the nett present value of the project becomes negative. Given an uncertain market or volatile exchange rate, the risks for such a project may be too high and government may decide not to support it. The problem in decision making is that neither price nor the

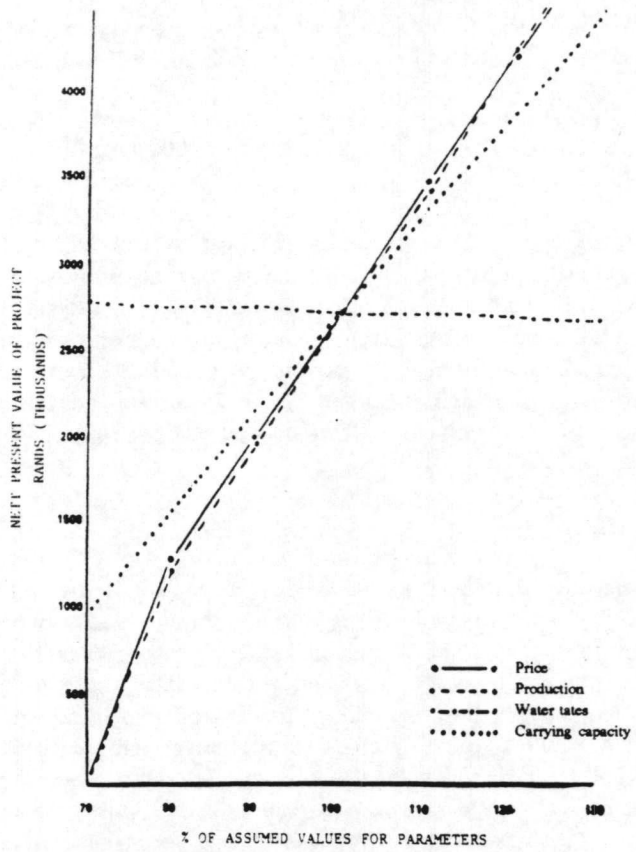


Figure 4 Sensitivity analysis of key factors for an irrigation project with a low risk (Agriplan, 1991).

exchange rate can be forecast with any degree of confidence and decisions have to be made subjectively. In such a case, the attention of the farmers must be drawn specifically to the period of difficult financial circumstances that may lie ahead. Detailed analysis of the project is necessary in such a case.

Monitoring of irrigation projects is essential to ensure the correct implementation of the plan and timeous reaction to problems. In the past, apart from the normal extension service, government left irrigators to their own devices after implementation of the project.

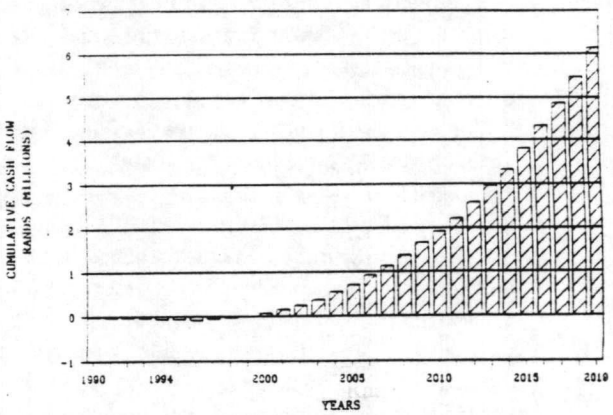


Figure 5 Cumulative cash flow of an irrigation project with a high risk (Agriplan, 1991).

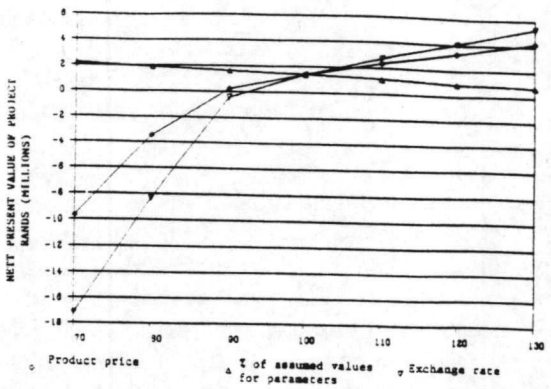


Figure 6 Sensitivity analysis of key factors for an irrigation project with a considerable risk (Agriplan, 1991).

In some cases, the financial position of farmers did not develop according to plan due to lower than expected yields, salinization of soils or lower producer prices. In the absence of feedback through a monitoring programme, the state was normally faced with a hopeless situation by the time difficulties were brought to its attention. Government has therefore recently decided that State funded irrigation projects should each be subjected to a monitoring program and that this will be a prerequisite for future financial assistance.

Conclusion

The irrigation industry in South Africa has undergone significant changes in its cost structure during the past ten years. This factor, plus a greater emphasis on privatization, led the government to pay much more attention to feasibility studies than in the past.

Feasibility studies are aimed at analysing the benefit : cost ratio as well as the expected cash flow of typical farms in the projects.

Monitoring of the development of projects after implementation is important and government has now decided to implement monitoring programmes for new and even existing projects.

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VERANDERDE BENADERINGS IN DIE KEURING VAN LAND VIR BESPROEIINGSONTWIKKELING

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Abstract

Assessment of land suitability is an essential and primary step in the development of irrigation land. During the past 25 years much experience has been gained. Several land suitability systems for irrigation planning purposes are used throughout the world. In South Africa, earlier systems did not adequately consider the potential of soil to successfully produce crops. This paper reviews progress in South Africa over the last 25 years in inventorizing and mapping natural land features which determine yield production under irrigation. These include soil and climate features as well as factors to be considered prior to land cultivation (topography and natural vegetation) and criteria concerned with the selection of water application methods (soil permeability, salt content, irrigation water quality, etc.). This review focuses attention on a number of selected approaches only.

Inleiding

Die keuring van land vir besproeiingsontwikkeling is 'n uiters komplekse en veeleisende taak wat samewerking van verskeie vakspesialiste en die uitvoer van talle hoogs gespesialiseerde ondersoeke ten opsigte van grond, klimaat, terrein, ekonomiese lewensvatbaarheid, ingenieursaspekte, ens. vereis. 'n Deeglike kennis van die omgewing van 'n potensieel besproeibare gebied is noodsaaklik vir beide ekonomiese en tegniese redes. Die koste verbonde aan die ontwikkeling van land vir besproeiing is enorm en vereis deeglike raming van die risiko en voordele verbonde aan die beplande ontwikkeling. Die stand van kennis en uitgangspunte rakende die keuring van land vir besproeiingsontwikkeling in die Republiek van Suid-Afrika word onder andere bespreek deur Cass (1980), Irrigation Planning Staff (1980), Hensley & Laker (1980), Dohse (1982), Eloff & Dohse (1982), Schoeman (1987), Bester & Liengme (1989) en Turner & Scotney (1990). Hierdie voordrag konsentreer op enkele van die belangrikste veranderings wat die afgelope 25 jaar by die keuring van land vir besproeiing deur owerheidsinstansies in die RSA plaasgevind het.

Veranderde benaderings ten opsigte van die keuring van land vir besproeiing

Die grond as medium waarop besproeiingswater toegedien word, en waaruit dit deur plante opgeneem word, behoort waar moontlik so gekies te word (Schoeman, 1987), dat

* so min as moontlik water verlore gaan deur afloop en onnodige diep perkolasie onder besproeiing met die betrokke besproeiingstelsel,
* water so maklik as moontlik onttrek kan word deurdat so 'n groot grondvolume as moontlik deur water en wortels binnegedring word,
* vry watervlakke selde sal ontstaan,
* voortdurend genoegsame plantvoedingstowwe teenwoordig is in die regte verhoudings tot mekaar, terwyl
* die grond in 'n toestand geskik vir voortgesette besproeiing bewaar word.

Nie alle gronde beantwoord aan hierdie beskrywing van 'n ideale medium nie. Gronde wat oorweeg word vir besproeiingsontwikkeling moet gekeur word met die oog op funksionele eienskappe wat betrekking het op die besproeiing. Omdat sommige grondeienskappe, soos beskikbare waterhouvermoë, infiltrasie en deurlatendheid, nie maklik en vinnig meetbaar is nie, word soveel as moontlik gebruik gemaak van eienskappe wat wel maklik bepaalbaar is en wat gevind is om goed met sulke eienskappe te korreleer (Schoeman, 1987).

Grondopnames vorm derhalwe die basis waarvolgens voorgestelde Staats- en Raadbesproeiingsontwikkeling geëvalueer word. Sodoende word verseker dat slegs gebiede met 'n hoë waarskynlikheid op sukses, ontwikkel sal word.

Verkenningsgrondopnames

Die doel met verkenningsgrondopnames is om 'n voorlopige aanduiding te verkry of daar wel besproeibare gronde in 'n betrokke gebied is en om spesifieke gebiede uit te wys waar verdere detail ondersoeke uitgevoer behoort te word. Opnames van hierdie aard verskaf voldoende inligting vir finale besluitneming ten opsigte van of daar voortgegaan kan word met die beplanning van 'n voorgestelde besproeiingsprojek en of die besproeiingswater enigsins aan 'n betrokke gebied verskaf behoort te word.

Tot en met die vroeë sestigerjare is verkenningsgrondopnames uitgevoer op skaal van nagenoeg 1:24 000 deur toetsgate te grawe op 'n ruitsisteem van nagenoeg 300 m x 300 m. Waar die onderliggende rots of ondeurdringbare lae dit toegelaat het, is hierdie toetsgate tot 'n diepte van twee meter gegrawe. Die grondopname van gebiede aan weerskante van die Oranjerivier vanaf die voorgestelde Torquaydam tot by die samevloeiing met die Vaalrivier, was een van die laaste verkenningsopnames wat volgens hierdie metode gedoen is (Bruwer, 1961).

Sedert 1965 het die beskikbaarheid van lugfoto's en

goeie kwaliteit 1:50 000 topokadastrale basiskaarte, tesame met 'n afname in beskikbare mannekrag en die arbiedsvereiste wat deur 'n ruitsisteem van profielgate daargestel is, bygedra dat hierdie metode van verkenningsgrondopname laat vaar is vir 'n *ad hoc* tipe van opname waar verteenwoordigende grondprofielgate verspreid deur die opnamegebied gegrawe is. Hierdie profielgate is gewoonlik 1.8 m diep gegrawe, of minder waar harde rots of 'n verharde laag teëgekom is. In geval van baie diep grond is die dieperliggende horisonte deur middel van 'n grondboor ondersoek. Alle grondprofiele is deeglik ondersoek en beskryf soos uiteengesit deur Loxton (1966). Grondseries is gedefinieer deur die verantwoordelike grondkundige waarna grondgrense met behulp van 'n grondboor gekarteer is. Finale grondgrense is daarna oorgedra na die basiskaart wat in skaal kon varieer van 1:50 000 tot 1:100 000. Hierdie metode is vir die eerste keer gebruik tydens die verkenningsgrondopname van die Oranjerivier Besproeiingsprojek (Van Rooyen, Dohse & Burger, 1968).

Terselfdertyd is 'n verkenningsgrondopname van die Tugela opvanggebied aangepak en afgehandel (Van der Eyk, MacVicar & De Villiers, 1969). Hierdie opname het 'n prototipe van 'n eie Suid-Afrikaanse grondklassifikasiesisteem ingesluit. Verskeie grondopnames daarna het gelei tot 'n groeiende bron van kennis wat tot die ontwikkeling van die Binomiese grondklassifikasiesisteem (MacVicar, De Villiers, Loxton, Verster, Lambrechts, Merryweather, Le Roux, Van Rooyen & Harmse, 1977) gelei het. Hierdie stelsel is met groot sukses die afgelope 20 jaar by die keuring van grond vir besproeiing gebruik.

'n Tweede uitgawe het onlangs verskyn (Grondklassifikasiewerksgroep, 1991). Hierdie tweede uitgawe maak die klassifikasie en kartering van gelyksoortige, natuurlike, min of meer eenvormige grondliggame moontlik. Die arbitrêre gekose klasse (gewoonlik tekstuur) van die eerste uitgawe (MacVicar, *et al.*, 1977) het veroorsaak dat eenvormige grondliggame gereeld kunsmatig verdeel word. Grondseries wat in die eerste uitgawe veral op grond van tekstuur gebaseer is, het die meerderheid van hierdie arbitrêre klasse uitgemaak. Derhalwe is die seriekategorie uit die tweede uitgawe gelaat en vervang met die grondfamilie, 'n hoër kategorie as die serie, die laagste kategorie van hierdie tweede uitgawe van die grondklassifikasiesisteem. Die tweede uitgawe is reeds met groot sukses deur die Navorsingsinstituut vir Grond en Besproeiing tydens die verkenningsgrondopname van die Riviersonderendvallei gebruik (Oosthuizen, Geers & Nell, 1990).

Detailgrondopnames

Die stelsel van keuring vir Staats- en Raadbesproeiingskemas wat deur Louw en ander ontwikkel was (Louw, 1967) en gebruik was sedert die jare vyftig tot ongeveer 1970, was besonder gerig op die keuring van grond vir vloedbesproeiing. In hierdie stelsel is profielgate op 'n ruitsisteem (meestal loodreg op die dreinasierigting) van nagenoeg 150 m x 150 m gegrawe. Elke profielgat se posisie is presies deur 'n landmeter bepaal waarna dit deeglik deur 'n grondkundige beskryf en grondmonsters van opeenvolgende horisonte geneem is vir die bepaling van pH, weerstand en vry karbonate. Elke profielgat is in 'n sogenaamde profielwaarde geklassifiseer (gewoonlik op grond van oorsprong, byvoorbeeld ligte alluvium, swaar kolluviale gronde, ens.) en na voltooiing van die basiskaart deur die landmeter, is grondgrense deur ekstrapolasie ingetrek. Hierna is elke profielgat ook volgens sy geskiktheid in een van vyf besproeiingswaarde klasse verdeel en dié klasse deur ekstrapolasie te kaart gestel. Volgens hierdie stelsel word gronde in een van vyf klasse na gelang van hul geskiktheid vir permanente besproeiingsgebruik, gegroepeer (Figuur 1). Eienskappe waarop veral klem gelê is, was gronddiepte, deurlatenheid (soos bepaal deur struktuur, tekstuur, graad van beperkendheid van onderliggende lae), waterhouvermoë en die teenwoordigheid van nadelige soute (soos bepaal deur the pH en weerstand van die versadigingspasta).

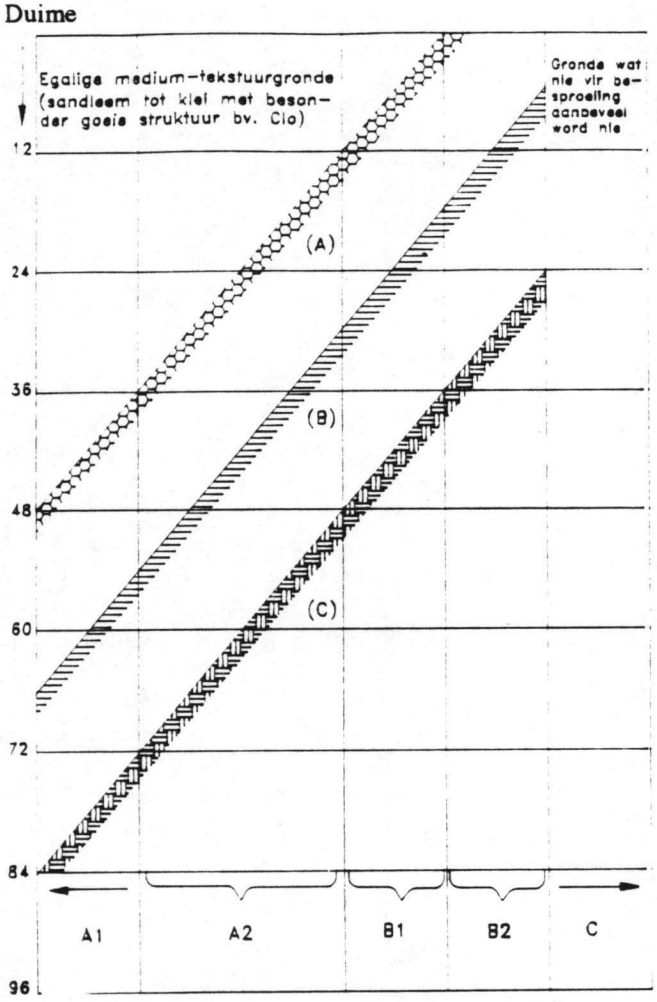
Hierdie stelsel van evaluering was met aansienlike sukses aangewend, en gronde wat later probleme opgelewer het, was gewoonlik daardeur uitgewys as B2 en of C-gronde. (Dohse 1978; Dohse & Bruwer, 1980; IKD Werkspan 1980(a); IKD Werkspan 1980(b)).

Min of meer gelyktydig met die ingebruikneming van die Binomiese grondklassifikasiesisteem (MacVicar, *et al*, 1977), ongeveer in 1972, is ekonomiese faktore, die invloed van klimaat en die terreinmorfologiese eienskappe ook ingebring in die evaluering van nuwe besproeiingskemas (Verster & Stofberg, 1974; Besproeiingsbeplanningspersoneel, 1974; Irrigation Planning Staff, 1980). Terselfdertyd het meer gesofistikeerde chemiese ontledings meer algemeen in gebruik geraak en is waterkwaliteit ook deeglik in ag geneem (Du Plessis, 1974). Tydens die detailgrondopname van gedeeltes van die Groot Visrivier (Dohse, Geers, Smith-Baillie, Duckitt & Hartmann, 1974) is gronde gekarteer deur gebruik te maak van die sogenaamde besproeiingsgrondtipe (MacVicar, 1976). Hierdie stelsel was 'n aansienlike verbetering op die vyfklasstelsel van Louw (1967) en het gebruik gemaak van vier belangrike grondlae in terme waarvan elke profielgat in 'n betrokke besproeiingsgrondtipe verdeel kan word. Riglyne vir die identifikasie van hierdie besproeiingsgrondtipes word volledigheidshalwe in Bylaag 1 gegee.

'n Ernstige tekortkoming van hierdie stelsel was dat dit nie die grondkundige gelei het om 'n besluit oor die besproeibaarheid van die karteringseenhede te neem nie aangesien dit bloot beskrywend en ontledend van aard was. Verder het die groot aantal (nagenoeg

570) besproeiingsgrondtipes wat tydens bovermelde grondopname (Dohse *et al.*, 1974) geïdentifiseer is, die evaluasie daarvan aansienlik bemoeilik. Hierdie stelsel het nooit daarna byval gevind nie en is in die laat sewentiger jare laat vaar.

In die huidige bestel, soos reeds genoem, word ekonomiese sowel as fisiese kriteria (grond, terreinvorm en klimaat) gebruik om die geskiktheid



(A) Deurlatend: L1,F1, verweerde rots, C11

(B) Half-deurlatend: deur wortels gepenetreer, gebarste L3 of F3, L2, F2, halfverweerde rots, C12

(C) Ondeurlatend: nie deur wortels gepenetreer nie, soliede rots, C13, soliede F3, massiewe gesementeerde C3, W.T.

Die simbole L, F, C1, C en WT dui onderskeidelik kalkbank, dorbank, klei, gesementeerde laag en watertafel aan. Die nommers wat na die simbole volg dui mate van deurlatenheid vir water en wortels aan.

Figuur 1 Diagram wat die diepte- en onderliggende materiaalfaktor in die klassifikasiestelsel van Louw (1967) illustreer.

van land vir besproeiingsontwikkeling te bepaal (Irrigation Planning Staff, 1980). Afhangende van die ingewikkeldheid van die grondpatroon en die beskikbaarheid van geskikte basiskaarte, varieer die opnameskaal van 1:5 000 tot 1:20 000. Profielgate word nog steeds op 'n ruitsisteem met digtheid van nagenoeg 1:2.2 ha gegrawe, beskryf en gemonster. In gebiede met 'n eenvoudige grondpatroon kan hierdie digtheid dienooreenkomstig aangepas word (1:4 ha) en kan daar in die plek van profielgate gebruik gemaak word van 'n voertuiggemonteerde hidrouliese grondboor (Oosthuizen & Dohse, 1980). In sulke gevalle word modale profielgate in die vernaamste gronde gegrawe, beskryf en gemonster vir volle chemiese ontleding.

Vir elke profielgat/waarnemingspunt word die volgende inligting aangeteken:

(i) 'n deeglike beskrywing van die direkte omgewing van die profielgat/waarnemingspunt;

(ii) 'n volledige morfologiese beskrywing;

(iii) monsters word van elke horison geneem vir pH en weerstand bepalings; of in die geval van 'n modale grondprofiel vir 'n volle ontleding;

(iv) op die grondkaart word die grondserie en ander belangrike grondeienskappe vir besproeiing (bv. tekstuur, geaardheid en diepte van beperkende lae, klipperigheid, mikrorelief, ens.) aangetoon. Elke karteringseenheid word in die kaartlegende en meer volledig in die gepaardgaande verslag beskryf;

(v) die indeling van alle karteringseenhede in voorlopige landklasse deur gebruik te maak van onder andere grondeienskappe, terreinvorm, klimaat en plantegroei. Ontwikkelingskostes, byvoorbeeld ontbossing, dreinering, ameliorering, ens. word vir elke voorlopige landklas bereken;

(vi) aan elke voorlopige landklas word verwagte opbrengste onder besproeiing toegeken en tesame met ontwikkelingskostes, gebruik om 'n ekonomiese waarde vir elke voorlopige landklas te bereken. Voorlopige landklasse word daarna op grond van eenvormigheid van ekonomiese waarde in ongeveer vyf finale landklasse gegroepeer. Bogenoemde inligting word gebruik om gronde wat wel geskik is vir besproeiingsontwikkeling te selekteer. Alle gronde waar ondervinding in die verlede getoon het dat daar 'n hoë waarskynlikheid van ondoeltreffende waterverbruik (in terme van verbrakking, versuiping, oormatige waterverlies en diep perkolasie, ens.) bestaan, word nie vir besproeiing aanbeveel nie.

In 'n poging om riglyne neer te lê vir die besproeibaarheid van gronde van die Vrystaatstreek, doen Eloff (1984) aan die hand dat 'n effektiewe diepte van 900 mm tot op 'n beperkende laag vir normale besproeiingspraktyke voldoende behoort te wees, maar

dat die diepteperk moontlik tot 600 mm verlaag kan word vir spilpunt- en drupbesproeiing. Hy wys daarop dat tekstuuruiterstes (< 10% en > 40% klei), sowel as gronde met 'n sterk struktuur, bogemiddelde bestuursvereistes stel. Bylaag 2 toon 'n groepering van grondvorms volgens hul besproeibaarheid soos voorgestel deur Eloff (1984), vir die Vrystaatstreek. In 1986 word riglyne deur die Navorsingsinstituut vir Grond en Besproeiing daargestel vir keuring van grond langs die Oranje- en Visrivier (MacVicar, 1986). Hiervolgens word swakker gronde (vlakker as 900 mm tot op 'n matige beperkende laag en vlakker as 1 200 mm tot op 'n sterk beperkende laag), en kleigronde, doelbewus deur die norme uitgesluit aangesien daar geredeneer word dat voldoende oppervlaktes geskikte gronde wel langs hierdie riviere voorkom sodat dit nie nodig of wenslik sal wees om problematiese gronde met duur water wat elders aangewend kan word te besproei nie.

Dit is duidelik dat streng norme feitlik deurgaans in die verlede voorgestel is by die gebruik van openbare water, en dat deur al die pogings gesamentlik daarin geslaag is om aan te toon hoe 'n probleemvrye grond behoort te lyk, en watter gronde problematies is (Schoeman, 1987). Volgens Schoeman (1987) is 'n tekortkoming van beide die vyfklas stelsel van Louw (1967) en latere stelsels dat beperkings wat wel aanwesig mag wees in gronde wat goedgekeur word, nie aangedui word nie. Voorts maak die Oranjeriviernorme van 1986 (MacVicar, 1986), in 'n poging om so eenvoudig as moontlik te wees, geen onderskeid tussen probleemvrye en marginale, dog geskikte gronde nie. In 1987 slaag Schoeman (1987), met 'n redelike mate van sukses, om die gronde van die Vrystaatstreek in vyf geskiktheidsklasse, met afnemende geskiktheid vir besproeiing, te verdeel. Hy gebruik vier fisiese parameters, naamlik effektiewe diepte, grondtekstuur, struktuur en growwe fragmente, twee chemiese parameters, naamlik natriuminhoud en soutinhoud en twee landskapkenmerke, naamlik topografie en behoefte aan dreinering.

Bylaag 3 toon kriteria aan wat Schoeman (1987) voorstel vir die indeling van gronde in een van vyf klasse, met afnemende geskiktheid vir besproeiing van klas 1 tot klas 5. Hierdie vyf klasse kan kortliks as volg opgesom word.:

Klas 1 - Gronde met geen of min beperking op volgehoue produksie onder besproeiing.

Klas 2 - Gronde met matige beperkings op volgehoue produksie onder besproeiing.

Klas 3 - Gronde met ernstige beperkings op volgehoue produksie onder besproeiing.

Klas 4 - Grond wat as gevolg van baie ernstige beperkings marginaal is vir volgehoue produksie onder besproeiing.

Klas 5 - Grond wat nie geskik is vir volgehoue produksie onder besproeiing nie.

Beperkings word aangedui deur een of meer simbool uit 'n lys van simbole (Bylaag 3) in afnemende volgorde van belangrikheid na die klas te skryf, byvoorbeeld Klas 3 ed, gv. Die mees ernstige beperkings wat in 'n grond of landskap teenwoordig is, bepaal die klasplasing. So byvoorbeeld, word 'n grond wat origens geen beperkings besit nie, maar 1.8 cm ol (+) kg^{-1} Na in die bogrond bevat, in Klas 4 geplaas.

In 'n onlangse dokument, stel Turner & Scotney (1990) volledige minimum riglynvereistes vir alle aspekte van die keuring van land vir besproeiingsontwikkeling voor.

Slotopmerking

* Aansienlike vordering is gemaak met die keuring van land vir besproeiingsontwikkeling in die RSA die afgelope 25 jaar.
* As gevolg van die ingewikkeldheid van die sisteem (veranderlikheid van die bestuursfaktor, aanpasbaarheid van gewasse, relatiewe skaarsheid van grond en water), kan al die pogings om kriteria daar te stel, vanaf Louw (1967) tot die huidige, slegs as breë riglyne dien en is dit belangrik dat navorsing sal voortduur om gronde wat reeds onder besproeiing geplaas is, te monitor ten einde verbeterde kriteria moontlik te maak.

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Bylaag 1 Riglyne vir die identifikasie van besproeiingsgrondtipes (MacVicar, 1976).

Guidelines: When to define a new irrigation soil type

1. Preliminary items:

(a) Each pit should be 180-250 cm deep, when rock does not intervene.

(b) The nature of the underlying rock (basalt, shale, sandstone, etc.) must be noted when it is encountered.

(c) Pits should usually be sited at a density of about 1:2.2 ha or on a 150 m grid.

2. Four important irrigation layers:

(a) *Overburden* (Bolaag): Observe the topsoil (that layer at the top which is more than 20 cm thick) and note those characteristics which reflect permeability (texutre, structure). Then proceed down the profile until a boundary is found below which there is a layer of significant lesser permeability. This is the lower boundary of the overburden. The character of the overburden is that of its least permeable part.

(b) *Restricting layer* (Beperkende laag): Because of a higher clay content, a stronger structure or because it is rock, or for any other reason, the restricting layer is less permeable (lower hydraulic conductivity) than the overburden and would almost certainly lead to waterlogging if water were applied to the soil at too fast a rate.

(c) *Deep subsoil* (Diep ondergrond): This is unconsolidated material which lies between the restricting layer and bedrock. It is frequently more permeable than the restricting layer. It usually needs to be described only in general terms, with emphasis on that part which restricts water movement.

(d) *Underlying rock* (Onderliggende rots): This is found either beneath the deep subsoil, or beneath the overburden when it is classed as the restricting layer.

3 Guidelines

3.1 *Guidelines for the overburden:*

(a) Thickness classes (cm)
0-60
60-90
90-120
more than 120

(b) Texture classes:
coarse less than 6% clay
medium less than 6% clay
fine less than 6% clay
coarse 6-15% clay
medium 6-15% clay
fine 6-15% clay
15-25% clay
25-35% clay
more than 35% clay (sandy)
more than 35% clay (very high clay, very heavy, very fine, very silty)

(c) Free lime classes:
Absent
Present (isolated nodules)
Abundant (abundant nodules and/or powder)

3.2 *Guidelines for the restricting layer:*

(a) Colour
Red prominent
Other

(b) Structure classes (in the dry state):
Strong angular blocky + prismatic + moderate prismatic
Moderate angular blocky + strong subangular blocky + moderate subangular blocky
Apedal + weak blocky

(c) Texture classes:
Loams (roughly less than 35% clay)
Sandy clays (roughly more than 35% clay, sandy)
Fine clays (roughly more than 35% clay, clayey)

(d) Free lime classes:
Absent
Present (isolated nodules)
Abundant (abundant nodules and/or powder)

(e) Rock classes:
Unweathered or only slightly altered rock
Weathered basalt/dolerite/diabase
Weathered sandstones (flat)
Weathered sandstones (tilted)
Weathered shales (flat)
Weathered shales (tilted)
Weathered granite, schist, migmatite
Limepan (consolidated)
Limepan (partly consolidated)
Ironpan (consolidated)
Ironpan (partly consolidated)
Other (specify)

3.3 *Guidelines for the deep subsoil:*

(a) A general description is needed giving colour, texture, structure.

(b) To distinguish types of the basis of the deep subsoil, apply the guidelines given in 3.2 to the least permeable part of the deep subsoil.

3.4 *Guidelines for stoniness:*

Rock outcrops and large piles of stones or boulders must be mapped out as non-irrigable land. However, there is irrigable land of which there are stones on the surface which pose a hazard to implements or problems in seedbed preparation. These must either be

removed or, if left, a more rapid depreciation on implements and probably lower yields must be accepted. It must be stressed that this land is definitely capable of being worked for irrigation.

Two classes:

Insignificant stoniness.

Significant stoniness (describe briefly: separate different kinds of stoniness if markedly different kinds occur).

3.5 *Guidelines for microrelief:*

There is some microrelief such as large dongas which must be mapped out as non-irigable land. However, there are lesser gullies, dunes and other forms of unevenness which simply make land more expensive to prepare for surface irrigation.

Two classes:

Insignificant unevenness,

Significant unevenness (describe briefly: separate different kinds of microrelief if markedly different kinds occur).

3.6 *Guidelines for watertables:*

An area found to contain a watertable should be separated off as a separate type, a note being made of the depth to the watertable.

3.7 *Guidelines to overall depth*:

This is the depth to rock (either the restrictive layer as in Mispah or the underlying rock). Usually it will not be necessary to use this criterion in addition to the foregoing when defining soil types. Where found in a pit rock will be recorded. This criterion may be used at a later stage to deal with watertable problems. Should the need arise to use overall depth in soil type classification, the guidelines in 3.1 (a) should be followed.

Bylaag 2 Tentatiewe indeling van grondvorms vir besproeiing (Eloff, 1984).

Maklik besproeibaar	Spesiale maatreëls vir lae voghouvermoë	Besproeibaar indien diepte voldoende is	Spesiale maatreëls vir lae infiltrasie en lae vogbeweging en versuiping	Moeilik besproeibaar
Leemsand-klei	Sand			
Kranskop Magwa Inanda Griffin Clovelly Hutton Oakleaf Shortlands Dundee Inhoek	Constantia Shepstone Vilafontes Lamotte Clovelly Hutton Oakleaf Fernwood Dundee	Nomanci Mayo Cartref Glencoe Avalon Bainsvlei Glenrosa Swartland Pinedene	Arcadia Milkwood Longlands Westleigh Kroonstad	Champagne Rensburg Willowbrook Bonheim Tambankulu Katspruit Sterkspruit Valsrivier Estcourt Houwhoek Wasbank Mispah

Bylaag 3 Grondklasse vir besproeiing in die Vrystaatstreek (Schoeman, 1987).

GRONDE EN LANDKENMERKE \ GRONDKLASSE	GESKIK MET TOENEMENDE GRAAD VAN BEPERKING				NIE GESKIK
	1	2	3	4	5
1. Algemene beskrywing van klas volgens graad van beperkings, enkel of gesamentlik	min of geen beperkings	matige beperkings	ernstige beperkings	baie ernstige beperkings	beperkings sluit ontwikkeling uit
2. Grondvorms	Hutton Clovelly Oakleaf Shortlands Dundee	Hutton Clovelly Oakleaf Shortlands Dundee Pinedene Avalon Bainsvlei	Hutton Clovelly Oakleaf Shortlands Dundee Pinedene Kroonstad Westleigh Arcadia	Hutton Clovelly Glenrosa Valsrivier Swartland Sterkspruit Kroonstad Westleigh Arcadia Bonheim Mayo Milkwood	Hutton Mispah Glenrosa Valsrivier Swartland Sterkspruit Katspruit
3. Effektiewe grond-diepte					
(a) waar die tekstuur die van sand is (< 10% klei)					
(i) tot op sagte kalk, gruis saproliet, dorbank	-	> 900	600-900	300-600	< 300
(ii) tot op hardebank kalkreet, harde rots, digte klei	-	> 1 200	600-1200	300-600	< 300
(b) waar die tekstuur sandleem en fyner is					
(i) tot op sagte kalk, gruis, saproliet, dorbank	> 900	600-900	300-600	200-300	< 200
(ii) tot op hardebank kalkreet, harde rots, digte klei	> 900	> 900	500-900	300-500	< 300
4. Tekstuur					
(a) van A-horison	leemsand sandleem sandklei-leem leem	sand leemsand sandleem sandklei-leem leem	sandklei kleileem klei	klei slikklei slikklei-leem slikleem slik	tekstuur aileen diskwalifiseer nie in grond vir besproeiing nie
(b) van B-horison	leemsand sandleem sandklei-leem leem	sand (nie grof) leemsand sandleem sandklei-leem slikleem	sandklei kleileem klei slikkleileem slik	klei slikklei sand (grof)	
5. Struktuur					
(a) van B-horison	struktuurloos swak blok matig blok (droog)	struktuurloos swak blok matig blok (droog)	struktuurloos swak blok matig blok (vogtig)	struktuurloos swak blok matig blok sterk blok matig prismaties sterk prismaties	sterk prismaties matig prismaties sterk blok (vogtig)
6. Growwe fragmente					
(a) klippe >75 mm deursnit	< 5	5-15	15-35	35-65	> 65
(b) gruis 2-75 mm deursnit	< 15	15-35	35-55	55-70	> 70
(c) rotsdagsome (afstand van mekaar in m)	> 40	20-40	15-20	5-15	< 5

7. Natriuminhoud					
(a) in boonste 300 mm (enige van die volgende)					
(i) cmol(+)kg^{-1} Na/100g grond	< 0.5	< 0.5	0.5-1	1 - 2	> 2
(ii) UNP	< 5	< 5	5-8	8-15	> 15
(iii) NAV vers. ekstrak	< 5	< 5	5-8	8-15	> 15
(b) in B-horison (enige van die volgende)					
(i) cmol(+)kg^{-1} Na/100g grond	< 0.5	0.5-1	1 - 2	2 - 3	> 3
(ii) UNP	< 5	5-8	8-15	15-20	> 20
(iii) NAV vers. ekstrak	< 5	5-8	8-15	15-20	> 20
8. Soute					
(a) in B-horison (slegs grond wat nie voorheen besproei in nie) mS/m (vers. ekstrak)	< 200	< 800	800-1200	1200-1600	>1 600
(b) sigbare soutpresipitaat op oppervlakte of teen profielgatwande (slegs gronde wat nie voorheen besproei is nie): persentasie van gebied wat geaffekteer is	< 10	10-20	20-35	35-50	> 50
9. Topografie					
(a) helling (%)	0 - 2	0 - 4	0 - 6	0-10	>10
(b) risiko van vloedwatergevaar (erosie, verspoeling, slikafsetting)	min of geen; beskerming onnodig	laag; beskerming teen redelike koste behoort effektief te wees	betrekklik hoog; beskerming duur maar redelik seker van sukses	baie hoog; beskerming duur en/of onseker van sukses	te hoog
10. Dreinering					
(a) waarskynlikheid dat dreinering nodig mag wees					
(i) bogronds	laag	laag-hoog	hoog	hoog	hoog
(ii) ondergronds	geen	laag	hoog	hoog	hoog
(b) uitvoerbaarheid van ondergrondse dreinering	-	maklik	redelik	moeilik	onpraktries

Lys van simbole om die beperkings in grondklasse 2 tot 5 mee aan te dui

ed	effektiewe diepte
Sa	tekstuur sanderig
Cl	tekstuur kleierig
Si	tekstuur hoog in slik
pr	prismatiese struktuur
vp, vr	blokstruktuur (kyk Algemene simbole,
vr	Binomiese Sisteem)
ab	abrupte oorgang
gc	vergleyde klei
ka	hardebank kalkreet
db	dorbank
so	verweerde rots (saproliet)
sf, sr	klippe (kyk Algemene simbole, Binomiese Sisteem)
gv	gruis
R	rots of rotsdagsome
na	alkaliniteit
sa	soute
he	helling
vl	vloedgevaar
E	geërodeerde toestand
dr	dreinering nodig

WATER RESOURCES, ECONOMICS AND THE FUTURE OF IRRIGATION IN SOUTHERN AFRICA - A PERSPECTIVE

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Abstract
Irrigation development in South Africa is subject to water resource constraints and the need for investment to follow competitive advantage. Greater social benefits may derive from investments in dryland farming or other sectors. Irrigation development should be guided by market forces. The major regional opportunities for irrigation lie outside South Africa whose competitive advantage is its management skills which should be exploited at high-potential new sites outside South Africa or in improving efficiencies on existing South African schemes. Irrigation efficiencies may be improved when new farming systems are established to cater for resettled black farmers.

Introduction

The desire to promote economic development in South Africa's less developed regions has given rise to many proposals for investment in irrigation to support intensive agriculture. The Development Bank of South Africa (DBSA) alone has received dozens of applications for financial assistance for such projects. These proposals have to be seen in the context of the broader economic problems facing South Africa. These can be summarised as the need to find a development path than can generate and sustain economic growth and the need to address the interrelated problems of poverty and unemployment.

The need for job creation has been recognised for some time, although the urgency of addressing it is becoming ever clearer (Ligthelm & Van Niekerk, 1990). In South Africa, as elsewhere, large irrigation works have in the past been undertaken as part of socio-economic upliftment programmes. The Department of Water Affairs has noted (DWA, 1986) that:

"The construction of several large government irrigation schemes was successful in achieving social aims, mainly the combating of the poor-white problem at a time when there was a need for rapid development of non-industrialised South Africa and when there was little competition for water. A need for similar solutions in certain sectors of the population still exists today."

It is understandable in this context, that agriculture and specifically irrigation agriculture should be seen as a potential contributor to the process of creating jobs. A report for the President's Council (President's Council, 1987) singled out the possibility of using irrigation development as a means to create jobs, noting that "... irrigation farming is generally more labour-intensive than other forms of farming (and) the construction of irrigation schemes in itself provides many job opportunities."

While irrigation may be a vehicle both for job creation and for broader development, this kind of proposal often fails to take account of the constraints under which it takes place. The success of the schemes referred to above was based on heavy state subsidies. Generally, water has been delivered to the farm boundary at minimal charge, making irrigation a profitable enterprise - for the farmer but not necessarily for society at large (RSA, 1984).

The objectives of this paper are a) to highlight some development constraints based on DBSA experience and b) to identify of some of those areas in which the scarce technical, human and water resources can be matched for the greatest benefit.

The resource constraint

South Africa's water resources are limited. According to the Department of Water Affairs, "relative to increasing demand, water is already scarce in certain regions of the country and within the foreseeable future, water will be scarce in most regions" (DWA, 1986).

There is a basic quantitative limitation - South Africa is in overall terms a relatively arid country (for instance Falkenmark's (1989) positioning of SA with other African countries). Perhaps more important than the simple quantitative limit to the resource is its highly unequal and variable distribution in both space and time. This, when combined with factors such as topography, means that the cost of making water resources available to the user is relatively high.

There is a hierarchy of systems by which water can be made available, with progression up the hierarchy determined essentially by scarcity. This can be characterised as follows, beginning with the simplest and cheapest systems:

a) run of river extraction (gravity);
b) groundwater extraction;
c) run of river extraction (pumping);
d) impoundment and local transfer;
e) impoundment and interbasin transfer.

At each level of the hierarchy, the cost of a unit of water may be as much as an order of magnitude more than at the previous level. These cost factors have obvious implications for how the available water resources are actually used. If the value of the water in a particular application is less than the cost of supplying it, that water is not available for use in

economic terms.

There are many examples of the practical implications of the resource constraint. In quantitative terms, one of the most striking examples is in the field of groundwater exploration. In the Springbok Flats and other areas of the Transvaal, irrigation has effectively been based upon short term "resource mining". Investments were made in capital equipment in excess of the capacity of the ground water resource to support them on a sustainable basis. This is causing serious problems as was highlighted by Truter (1991) who noted that: "The growing draft on underground sources and their resulting reduction is now increasingly affecting the economy, the agricultural economy in particular."

Topography and variability also impose costs on the extraction of water resources which can preclude the development of irrigation in otherwise promising areas. A recent study of irrigation potential in the basin of the Umzimvubu river (the third largest in South Africa) noted that one of the major constraints to using the large water resource, most of which currently flows to the sea, is that: "The land suitable for irrigation is very often situated in scattered areas and/or elevated above the source of water as to be not viable for irrigation" (BSC 1990).

In this context, it is important to recognise that an investment in a water resource project may not be the most appropriate way of protecting the user against the effects of shortage. "The acceptance of greater variability in water supply will as a rule make more water available at a lower cost. The possibility of carrying over products and capital reserves instead of scarce and expensive water for periods of shortage must always be considered as an alternative" (DWA 1986).

Competition for resources

Even where water is available and its use can be justified in economic terms (i.e. the value of using it is greater than the cost of providing it) there are often competing uses for the water. In this case, its allocation should ideally be made on the basis of relative economic merit, i.e. opportunity cost.

As South Africa develops further, the competition between different water users will become more acute. In this context, it is important to identify the main users, namely:

a) primary (human consumption),
b) industrial (including electricity generation and mining),
c) irrigation,
d) forestry,
e) conservation, and
f) waste disposal (it may be economic to allow a river to be polluted and import water from elsewhere!)

If the value of water for these different uses is considered, it is clear that irrigation is by no means a high value user, principally because of the large volumes it requires. A few examples illustrate the competition that is already occurring.

Primary needs

In the KwaNdebele region of the Transvaal, there are clear limits to the extent of dryland farming that can be practised and it has been suggested that irrigation development may provide opportunities for some of the hundreds of thousands of people who have moved to the area in recent years.

A review of the water resources of the region (TPGP, 1991) showed however that they are insufficient for such needs. The projected primary consumption requirements are such that any irrigation development that is commenced today would probably be increasingly constrained within ten or fifteen years to allow water to be diverted for primary consumption. To maintain potable supplies, existing sources of raw water from the Elands river are already having to be augmented by transfers from other sources or by the use of water allocated for irrigation.

(On a larger scale, the same conflict is also evident in the context of the Vaal Basin with extensive inter-basin transfers already occurring and the Lesotho Highlands scheme currently under construction to ensure the maintenance of supplies for primary and industrial users.)

Conservation

Conservation has for many years been seen as one of the least valuable uses for water. There is however a growing body of opinion to the contrary. While the economic basis for allocating water for conservation purposes has not yet been formalised, the Department of Water Affairs has identified water for environmental management as "a major competing water demand" (DWA 1986).

In many cases, the allocation decision has effectively already been taken. There is thus a consensus that, in areas like the Eastern Transvaal, it is more important to allow some water to run through the Kruger National Park than to use it for irrigating the additional available arable land in the region (Chunnett Fourie 1990).

Forestry

Another competitor for irrigation is the forest industry which may in many cases be a more appropriate user of water resources than irrigation agriculture. At present, the use of water for forestry is arbitrarily restricted by the permit system which controls forest planting (RSA, 1972).

The sole consideration of this system is the impact of afforestation on water availability with broader conservation objectives being dealt with separately. While afforestation is a consumptive activity in water

resource terms, the arbitrary restriction of forest development to limit its impact on runoff is being questioned (Bosch, 1989). The issues are of some relevance to irrigation.

Forestry is arguably an efficient activity in terms of water resources. It requires no major construction works to capture and store the resource nor infrastructure to convey the water to where it is to be used. It is also not seriously affected by rainfall variability. It also appears to be efficient in economic terms.

Indicators such as the cost per job created and the number of hectares required to create one job, suggest that forestry may compare well with irrigated crops. A review of water resource related development opportunities in the Transkei portion of the Umzimvubu river basin, which examined both forestry and irrigated agriculture, supported this. (The review is summarised in Table 1). Since the investment required for irrigation development is shown to be considerably more than that for forestry (if major new water supply infrastructure is required), it is suggested that, in a broader economic sense, an increase in the share of water allocated to forestry should be considered.

Given the debate about the desirability of extending afforestation, there is a need for a definitive economic study which focuses on the opportunity cost of water consumption to guide policy formulation as the permit system has tended to direct arguments away from this fundamental issue (Anon, 1990).

Table 1 Forestry versus irrigation (Umzimvubu River Basin, Transkei),

	Hectare/ Job Opportunity	Water Demand/ha Mm^3	Investment/ Job
Irrigation			
Annual crops	3 - 17	5 000	(1)50 - 100 000
Tree crops	0,5 - 3		
Forestry			
Field only	13,5	1 000	(2)10 000
Field and process	6,3		

Sources:
BSC 1990 and
(1) DBSA projects and Department of Water Affairs estimates
(2) SA Forestry Council estimate (1985 figure)

Irrigation efficiency

One immediate consequence of the increasing competition for water resources is that there is a dire need for greater efficiency in relatively low value uses - such as irrigation. Many existing schemes use water sub-optimally, encouraged by a tariff system that ignores the economic value of water. One estimate suggests that nearly 40% of water released from government dams is wasted (Kirkwood, 1988). In the Western Cape, Burger (1989) notes a disturbing 30 per cent gap between actual production and what can be expected with the use of current technology. Inefficient irrigation is a problem which has been recognised internationally for many years and was the subject of intensive discussion at the 1977 World Water Conference in mar de Plata, Argentina (ODI, 1977). Inefficient management has been associated internationally with the need for extensive, repeated rehabilitation works (World Water, 1989). However, some commentators attribute such inefficiencies to cost-cutting approaches adopted in initial projects to achieve acceptable rates of return (World Bank, 1990).

A related problem in a South African context is the under-utilisation of existing infrastructure such as the Orange River Development and Pongolapoort water schemes. This is due to many factors - institutional and political as well as economic - but it demonstrates the complexity of turning an irrigation concept into a viable working project.

Opportunities for the future

Some of the constraints to the use of water for irrigation have been outlined above. However, t do not mean that there are no opportunities for further irrigation development, but that development will have to be carefully focused in areas where there is a clear advantage to using scarce water resources for this purpose. There are in addition the broader social needs mentioned in the introduction which highlight opportunities for improvement in existing irrigation activities.

Aside from these domestic opportunities, some recognition also needs to be given to the fact that in the broader Southern African region, there are other countries with high potential for the development of irrigated agriculture.

High value crops

Given South Africa's relatively scarce and expensive water resources and the range of competing uses, it would appear logical to focus on the irrigation of high value crops. This situation is similar to that in many other Third World countries. In Brazil for instance, a recent review (FAO, 1990) compared irrigation projects with each other, and with rainfed options. It concluded that production of basic commodities (wheat, maize and cotton) would only be viable if irrigation was either very cheap or very efficient and that the focus for irrigation should thus be on high value crops. This had implications not just for the type of irrigation but also for the size of units, their location and the organisation of markets since the more valuable produce was often sensitive to transport distances and marketing delays.

Very similar considerations can be expected to apply in a South African context. Any new development should thus be guided by a good understanding of market opportunities and their limitations. Political reform may open new external market opportunities through, for instance, South Africa's accession to international conventions as well as by the removal of trade sanctions. It is important however that such opportunities be carefully identified and their exploitation planned to avoid risky, speculative investments in costly irrigation infrastructure.

Focus on small farmers

As already indicated in the introduction, there are growing pressures within the economy for strategies to deal with the related problems of poverty and unemployment as well as to the broader issue of achieving a fairer distribution of South Africa's wealth. In this context, considerable attention has been focused on agriculture, largely in the context of the land question.

Christodolou & Vink (1990) demonstrated that black smallholder farmers can make a substantial contribution to mainstream agriculture in South Africa if they are provided with an appropriate support package and given access to land.

Agriculture is widely regarded as one of the most efficient channels for job creation in terms of jobs created per rand invested. Because of the high capital cost, it is not clear that this benefit does accrue in irrigation projects. This was demonstrated by Van Niekerk (1987) who analysed the labour multiplier (jobs generated per million rand invested) of a (run of river) irrigation project and found that it "does not seem to hold above-average job creation advantages".

This was confirmed by Christodolou & Vink who report that the capital cost of establishing small irrigation farmers is more than an order of magnitude higher than for dryland farming. An economic input-output analysis of a case study recently conducted in the Southwest Free State also suggested that the backward linkage employment multiplier for the rest of agriculture is roughly twice that for irrigation. (Kirsten & Van Zyl, 1990)

These findings are again similar to those from the Brazilian study (FAO Investment Centre, 1990) where high capital cost, public irrigation schemes were found unlikely to be viable for the production of basic commodities by small farmers. The Brazilian conclusion - that irrigation investments could only be justified if there were clear social benefits to compensate for the economic costs incurred - equally applies to South Africa.

Efficient management and technology choice

Given the high costs and limited economic returns from irrigation, it seems unlikely that South Africa will see the construction of any major new irrigation projects (with the possible exception of the Komati River project which may be viable given the extensive existing infrastructure in the Eastern Transvaal).

One specific opportunity which is going to arise, however, derives from irrigation management problems and the new focus on small farmers identified above. Given increased opportunities to gain access to land, it is probable that during the 1990s, there will be a rapid growth in the number of black smallholders. Should this occur in currently irrigated areas, there may be opportunities for irrigation management to be improved as support systems are established to cater for these new farmers. This will however require the development of an approach to irrigation appropriate to these farmers. Much of this will of necessity revolve around institutional, financial and other management issues rather than irrigation technology as such since these are widely recognised to be the critical factors for the success of small farmers.

There will however be a need to develop and promote the use of appropriate technologies. Marais has already drawn attention to the need to review the irrigation technologies adopted:

"Computer controlled systems are generally installed to reduce labour and advance management. This does not create work, nor does it assist in the education of black farm managers. Centre pivot irrigation also reduces the labour requirements and the old method of hand moveable irrigation pipes may yield the same results for lower capital outlay" (Marais, 1986).

He also calls for support for small scale irrigation using appropriate, if modern, drip irrigation technology. Here he correctly notes that one of the most important requirements will be for training and marketing support rather than simply technical inputs which is in line with DBSA and international experience.

Other opportunities

In a rapidly changing Southern Africa, there is a clear need for regional specialisation. Any strategy for the development of South Africa which ignores the needs - and opportunities - in the broader region is unlikely to succeed. The region offers South Africa the prospect of creating an economy of a scale large enough to be significant (if only marginally so) in global terms; further, economic failure in the broader region will inevitably impact on South Africa itself through migration and general instability as well as a shrinking of markets for South Africa's goods and services.

Should market opportunities be found, it would thus be inappropriate for major new irrigation development to occur in the physically least favoured areas. In this sense, the major regional opportunities for large-scale irrigated agriculture appear to lie outside South Africa's borders. In regional terms, Mozambique has

probably the largest resource. The Zambezi and its flood plains can already be commanded with limited additional off-field capital expenditure and there are a number of other river basins where large tracts of irrigable land are situated in close proximity to major rivers (DNA, 1985).

South Africa's main competitive advantage in the region is arguably its management skills. This advantage could perhaps best be exploited at high-potential new sites outside South Africa - or in improving efficiencies on existing South African schemes with a focus on high value crops. Similarly, South Africa's well developed industrial and commercial infrastructure could best be deployed to service the regional needs of irrigated agriculture as well as to exploit off-field linkages internally - as exemplified by the wine industry.

Conclusion

Irrigation in South Africa will be constrained by the overall shortage of water resources and by competition with other users. Further development in the sector will thus necessarily have to focus on increasing efficiencies and finding high value "niches" which can justify the allocation of the resource to them.

The rural transformations which are expected to occur over the next decade should give many more black farmers the opportunity to enter the agricultural sector. There will be an opportunity to use this transition to improve irrigation management.

In the Southern African region, there are many opportunities for expanding irrigated agriculture which are not as constrained by the water resource limits as is the case in South Africa. The irrigation industry and profession should focus their attention on serving this regional sector since it will provide broad benefits to the region and to South Africa.

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CALC : A LAND USE CLASSIFICATION SYSTEM PARTICULARLY SUITED TO IRRIGATION PLANNING IN DEVELOPING AREAS

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Abstract
CALC, the Comprehensive Agricultural Land Classification system is an empirical system of rating land according to easily identifiable soil and land characteristics. The system was devised as an aid to agricultural planners who are faced with soil taxonomic base maps that are too complex or land capability and irrigability maps that are often mutually incompatible and provide insufficient pertinent detail. The principal advantages of CALC are its simplicity and emphasis on practical soil and land factors of direct concern to planners and end users. It is particularly useful in developing regions where access to laboratories and trained pedologists may be limited. The system is designed specifically for use at a field scale of no more than 1:10 000. Both capability, which considers the agricultural quality of the land, and its susceptibility to erosion and irrigability, which considers additional factors specifically relating to irrigation potential, are covered by the system. Seven capability classes and five irrigability classes are recognised. The field data are recorded in a code form with such factors as slope, effective depth, permeability and texture being rated. The mechanism of allocation of a coded land to a specific capability or irrigability class is primarily by means of a preset hierarchy network or spider diagram. CALC can be calibrated for different regions according to local knowledge and conditions. The system has been used to classify more than 4 000 ha of land in the Ciskei, and has been tested in other parts of southern Africa.

Introduction

CALC, the Comprehensive Agricultural Land Classification system is an empirical system for rating land according to easily identifiable, practically applicable soil and land characteristics. The system has been devised primarily as an aid to development planners, agriculturalists and irrigation engineers - who are required to effectively utilize soil surveys, but are often lacking in sufficient interpretative skills. Much of the detail contained in pedological surveys is superfluous to such workers, whilst other important information is lacking, especially that on land characteristics. Land use capability surveys, on the other hand, whilst usually more applicable to development planning, are mostly deficient in soil profile detail, particularly with regard to those factors of importance in irrigation design (Copeland, 1987).

CALC is intended to overcome these shortcomings and, in addition, provide a readily usable system applicable to Third World situations where access to laboratories and fully trained surveyors is often limited.

The aim of this paper is to describe the working of the CALC system and to indicate its usefulness in development planning.

The CALC system

The objective of CALC is to provide a meaningful land evaluation system that is both easy to survey for the field worker and easy to interpret for the end user. It is practically orientated and comprises the identification and assessment of those factors considered most important to the safe utilization of land and to those that define most accurately the potential of land for irrigation development.

The CALC assessment of a land is divided into two portions, namely capability and irrigability. The system defines capability classes and irrigability ratings. Capability appraises a land according to its intensity of use limitations (i.e. hazards of use) and its general agricultural quality (FAO, 1976). Irrigability enlarges this analysis to consider other factors more relevant to the intrinsic value of the land for irrigation development.

CALC has been formulated to appraise as few factors as possible in order to simplify the survey and rating process, but it has also been the intention to so choose a mix of factors with specific areas of description that would produce a reasonably accurate picture of the quality of the land for development. The layout of the CALC coding and classification system has also been arranged to promote relatively easy usage.

Land Use Capability

As this paper concerns irrigation development *per se*, capability will be referred to mainly where its relevance as part of the irrigability rating code requires expansion. However, a brief description of the rationale behind a land use capability classification, the capability classes, their usage and a definition of non-arable land is required (Conex, 1978).

Land use capability, which is used primarily for planning at a scale relevant for farm or project development, at no more than 1:10 000, is important in the following areas:

- the identification and removal from farming of

unsuited land
- the estimation of a value of land for development, purchase, disposal etc
- as an indicator of the intensity of cultivation that can be safely permitted, crop rotation planning
- as a cautionary indicator for soil conservation planning and mechanical protection implementation.

CALC uses a seven class land capability system: classes I to IV being arable, classes V and VI being grazing land, at best, and class R is reserve or non agricultural land.

Figure 1 describes the use intensity and constraints to use of the seven classes.

CLASS	USE SYSTEM	USE INTENSITY	CONSTRAINTS TO USE
I	Arable	High	Minimal
II	Arable	Moderate	Moderate
III	Arable	Limited	Strict
IV	Arable	Low	Severe
V	Grazing	Use intensity will depend on stocking rate assessment, which is based on vegetation quality and land conditions.	Wet land but generally has good quality grazing. Marginal agricultural land. Often poor quality rough grazing.
VI	Grazing		
R	Non-agricultural reserve land.	Specific requirements of allocated use.	Sensitivity of ecosystem.

Figure 1 Summary of capability class use recommendations, use intensity and constraints to use.

In general, lands that are permanently wet, have prohibitive problems with regard to ease of cultivation, have slopes greater than 16% and have effective depths less than 250 mm, are classified as non-arable. Other non-arable situations can be easily deduced from the spider diagrams. Most non-arable lands automatically downgrade to class VI, unless permanently wet which become class V, or if agriculturally of little value, class R. Class R, which describes "reserve" land comprises mainly sheet rock, ravines, hillocks or mountainous terrain.

Irrigability

The CALC irrigability rating gives the planner a broad indication of the suitability of a particular land for irrigation development. Five ratings are recognised from high potential to very low. Figure 2 describes the increasing limitations to use of the five ratings.

The irrigability rating is designed as an extension of the land use capability assessment. In most cases the lower the capability class, the less suitable the soil will be for irrigation. This is because factors such as slope and subsoil drainage are not only indicative of erosion

IRRIGABILITY RATING	IRRIGATION POTENTIAL	COMMENTS
1	HIGH	SUITABLE FOR ALL TYPES OF IRRIGATION PRACTICES. CAPABLE OF A SUSTAINED HIGH LEVEL OF PRODUCTIVITY.
2	MODERATELY HIGH	DECREASING FLEXIBILITY IN DESIGN; DECREASING NUMBER OF CROP VARIETIES; DECREASE IN YIELD POTENTIAL; INCREASING IRRIGATION COSTS; INCREASING MANAGEMENT PROBLEMS; INCREASING HAZARDS
3	MODERATELY LOW	
4	LOW	
5	VERY LOW	
NI	NON IRRIGABLE	UNSUITABLE FOR IRRIGATION UNDER NORMAL CIRCUMSTANCES.

Figure 2 Summary of irrigability rating values and rating implications.

sensitivity and agronomic quality, but are also important factors in irrigation potential. In addition, land characteristics such as slope and micro-relief have to be considered in the engineering side of irrigation design.

The capacity of a soil to store and release water, and its drainage characteristics are also important irrigation criteria, but are not covered sufficiently in the capability code. The irrigability assessment therefore extends this code to take cognisance of these extra aspects of the soil profile to give a more complete irrigation picture. The available water capacity of a soil depends primarily upon depth and texture, with other interrelated characteristics such as structure and the nature of the sand fraction also being important. In addition, soils should be freely draining through and beyond the main rooting zone of the crop. This is defined by the drainage of the restricted rooting zone. All these factors are therefore included in the irrigability rating assessment.

Lands that are defined as being non-arable should also be regarded as non-irrigable. Most lands over 12% are considered to be non-irrigable, except where the soils are very deep and well drained and are not too light in texture.

The CALC approach as a planning tool

The basis of the CALC system is a land description code, which is usually compiled *in situ*, and which is

followed by the systematic conversion of that code into land assessment groupings, either capability or irrigability.

The main advantage of this approach is that it systematically examines and rates all the principal parameters involved in land to a particular class. Land use planners and developers quickly get a feel for such a system and the limited number of classes and coding factors encourage ready communication in a common language (Ivy, 1977).

However, whilst the capability classes and irrigability ratings with their derived mapping boundaries are useful tools in overall planning and communication, the basic code with all its readily identifiable data recorded systematically in a standard structure is the most important unit for detailed planning and design (Goemans, 1977).

The CALC assessment of a piece of land is considered from two aspects, namely its soil properties and its physiography, i.e. its physical land features, with the basic code structured in a fashion logical to both compilation and to class derivation. Figure 3 shows the manner in which it is arranged:

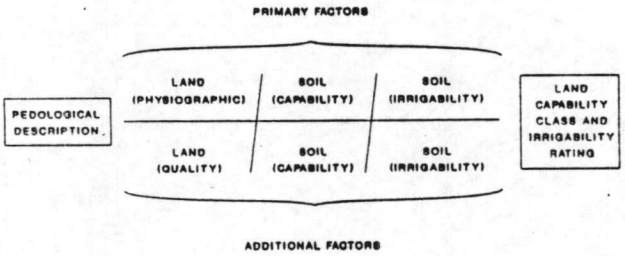


Figure 3 Arrangement of CALC code showing standard structure.

The code is read from left to right and from top to bottom. The order is the same employed in the "spider" diagram used for specifying the class or rating.

The CALC code is usually compiled in the field at a specific point within the area of interest. The soil pit or auger site is the specific description point, not only for soil properties but also for the physiography. Thus the planner will firstly examine the pit and rate the profile factors before observing the surrounding terrain, noting its condition and filling in the remainder of the code.

An example of the code is shown in Figure 4. The factors employed in the compilation of the code are described in tabular form in Figure 5 and in detail in the following section.

Note that although the whole code will be completed for any land survey, the first part of the code only is used for capability classing and only the second half for irrigability rating. The irrigability rating can thus

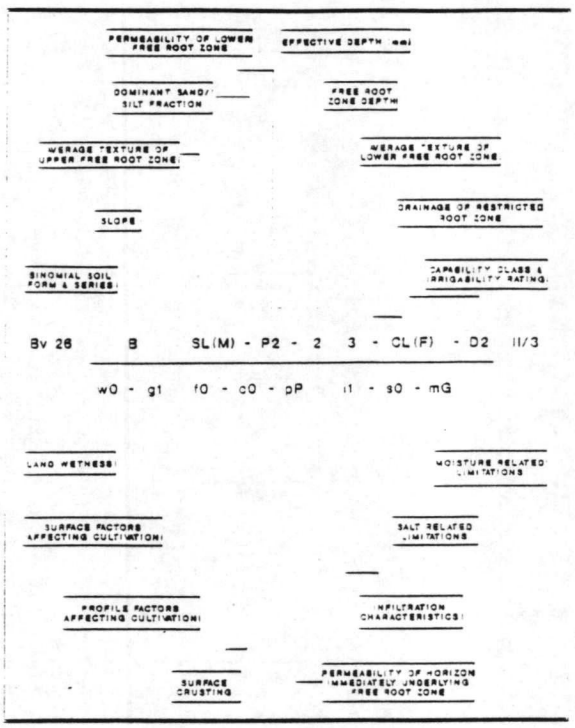


Figure 4 CALC code example showing layout of capability and irrigability factors.

be expressed separately, or can be combined with the capability code, e.g. II/3, the latter expression giving a broader picture of the development potential of the land.

As a suffix to the CALC code, it is useful to append a pedological description code, should the surveyor have the expertise and access to a laboratory. This is non-diagnostic, but will help expand the assessment of the soil to those planners with a pedological background (Macvicar, *et al.*, 1977).

Principal definitions applicable to CALC

CALC does not follow strict pedological soil horizon delineations; it may also average out texture and other physical characteristics across some pedologically defined horizon changes. With regard to irrigability, the purpose of CALC is to simplify the job of the irrigation designer, clearly grouping together the salient soil features into useable, understandable categories. New profile definitions have therefore been adopted in order to avoid confusion and to describe more clearly these useable categories. Figure 6 shows the layout of the profile divisions as specified by CALC.

The following summaries describe the profile definitions as used in CALC:

Free Root Zone (FRZ)

The FRZ describes that portion of the solum in which the majority (±75%) of plant roots occur or, in

CALC : PRIMARY REQUIREMENTS FOR CODING

SLOPE

A1	0 - 1%
A2	1 - 2%
B	2 - 4%
C	4 - 8%
D	8 - 12%
E	12 - 16%
F	16 + %

DOMINANT SAND/SILT FRACTION

(F)	Fine
(M)	Medium
(C)	Coarse
(T)	Silt (more than 30%)
(nb.	non diagnostic symbol)

EFFECTIVE DEPTH (mm)

1.	Exceeds	-	1 250
2.	1 250	-	1 000
3.	1 000	-	750
4.	750	-	500
5.	500	-	250
6.	below		250

AVERAGE TEXTURE OF LOWER FREE ROOT ZONE

(as for upper free root zone)

AVERAGE TEXTURE OF UPPER FREE ROOT ZONE

S	Sand
LS	Loamy Sand
SL	Sandy Loam
SCL	Sandy Clay Loam
L	Loam
CL	Clay Loam
SC	Sandy Clay
C	Clay
V	Vertisol

PERMEABILITY OF LOWER FREE ROOT ZONE

p1	Very rapid
p2	Good permeability
p3	Restricted permeability

FREE ROOT ZONE DEPTH (mm)

(as for effective depth)

DRAINAGE OF RESTRICTED ROOT ZONE

DD	FRZ equals effective depth
D1	Drainage free to slightly impeded
D2	Drainage moderately impeded
D3	Drainage severely impeded to impermeable

CALC : ADDITIONAL REQUIREMENTS FOR CODING

LAND WETNESS

w0	No wetness evident
w1	Seasonally wet
w2	Permanently wet

PROFILE FACTORS AFFECTING CULTIVATION

f0	None evident
g	Gravel/stones
r	Rocks
h	Concretions/hardpan

SEVERITY

1.	Hindering
2.	Severely restricting
3.	Prohibiting

PERMEABILITY OF HORIZON IMMEDIATELY UNDERLYING FREE ROOT ZONE (Only applicable when effective depth is < 750 mm)

p0	No pronounced change, similar to or slightly slower than free root zone
pl	Markedly slower than free root zone or impermeable
pP	Effective depth more than 750 mm

SALT RELATED LIMITATIONS

s0	No problem evident
sX	Evidence of salinity
sZ	Evidence of sodicity

SURFACE FACTORS AFFECTING CULTIVATION

f0	None evident
b	Boulders/outcrops
a	Anthills
k	Micro-relief
e	Erosion features

SEVERITY

1.	Hindering
2.	Severely restricting
3.	Prohibiting

SURFACE CRUSTING

c0	None evident
c1	Slight
c2	Pronounced

INFILTRATION CHARACTERISTICS

i1	Rapid to moderate
i2	Moderate to slow
i3	Slow to very slow
iV	Vertic condition

MOISTURE RELATED LIMITATIONS

m0	None evident
mE	Leached E horizon
mG	Gleyed material
mP	Plinthite

Figure 5 CALC coding factors.

situations where only shallow rooted plants are present, where it can reasonably be expected that relatively unimpeded rooting will take place. Where the FRZ is less than 250 mm, it becomes synonymous with the Upper Free Root Zone (see below). The FRZ is, to a certain extent, an artificial horizon but at the same time it is a portion of the soil that is of great practical importance.

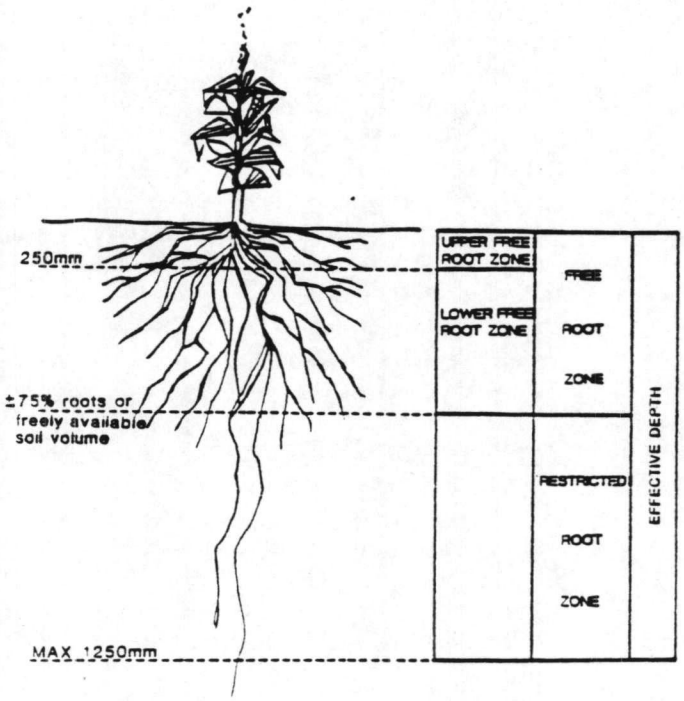


Figure 6 The root profile definitions as applicable to CALC.

Whilst some roots will penetrate below the FRZ, this zone constitutes the major area of root activity where, under normal conditions conducive to good plant growth, the principal nutrient reserves and the major water reservoir are found.

The FRZ excludes horizons where periodic water-logging occurs, and also leached and eluviated horizons where they occur above impervious layers, or highly compacted horizons. The FRZ will also extend a relatively short distance into infertile horizons such as regic sand, some alluvia and gravel layers. In most cases, however, it is an horizon of impeded drainage/ aeration that will limit the extent of the FRZ.

The FRZ is also of principal concern to irrigation planners as it constitutes the normal soil depth used by engineers for water storage calculations. That part of the solum located beneath the FRZ, termed the Restricted Root Zone, can be of great importance in dryland cropping, as it may be capable of retaining useful volumes of water accessible to the deeper plant roots.

The FRZ is itself divided into a surface horizon, the Upper Free Root Zone, and the portion of the FRZ that underlies this, the Lower Free Root Zone.

Upper Free Root Zone (UFRZ)

This surface horizon has a maximum depth of 250 mm, by definition, and therefore encompasses partly or wholly the A horizon (orthic, melanic etc). The UFRZ is, *inter alia*, the most weathered portion of the solum, it is the zone of maximum biological activity, is subject to rain-splash impact compaction and surface erosion, is the principal tillage zone and is the fertilizer/agricultural chemical incorporation zone.

Whilst the drainage characteristics of deeper horizons may finally regulate the overall water intake rate of a soil, the UFRZ will act as the intake and transmission throttle and significantly affect the soil's infiltration rate. This has important connotations with regard to both erodability and irrigability.

It is distinguished from the remainder of the FRZ by virtue of the above distinctive characteristics and also because it is usually eluviated and somewhat lighter in texture than the Lower Free Root Zone (see below), and may be subjected to further separation from deeper horizon types by, for example, the effects of ploughing which will be compounded over time.

Lower Free Root Zone (LFRZ)

This horizon comprises the remainder of the FRZ and constitutes the bulk of the useful volume of most arable soils.

Restricted Root Zone (RRZ)

The RRZ underlies the FRZ, up to a maximum depth of 1 250 mm by definition. The RRZ whilst having significantly fewer roots than the FRZ, must nonetheless comprise soil or soil-like material that can accommodate the passage of the deeper occurring plant roots. The term restricted refers to the limited usefulness of this soil horizon rather than its physical strictures.

The RRZ, whilst being of great importance in a dryland cropping situation, is also important in irrigation in that it constitutes the drainage channel or throttle, regulating the passage of water to depth.

A slowly draining RRZ will not be favourably disposed to over-irrigation, and will be detrimental to irrigation if a leaching fraction is required, unless artificial drainage is envisaged. Excessively rapidly drained horizons, whilst included in the RRZ are also not desirable as they imply, firstly, a low water holding capacity and, secondly, in drought situations they may rapidly transmit scarce water to depths unavailable to most plant roots.

The RRZ will include, to some extent, those horizons excluded from the FRZ as a consequence of the different role or function as defined for the former horizon. Thus some exploratory or tap roots will penetrate into horizons showing signs of waterlogging

including gleyed or plinthic horizons, down cracks in compacted horizons, and deeply into infertile sands and unconsolidated parent material. The penetration of these roots and their access to the moisture retained therein, requires that some cognisance be taken of these horizons.

Some penetration into horizons such as pedocutanic, lithocutanic, soft plinthic, etc can be expected, and significant penetration into regic sand, alluvial and apedal material will be found. E horizons can be included within the RRZ (but not the FRZ).

Effective depth (ED)

The ED describes the total depth of the solum available to plants as a reasonable growth sustaining medium. It therefore comprises the FRZ and the RRZ together and is confined by the definition of the latter, where 1 250 mm is the maximum, or limiting depth.

Factors employed in the CALC code

Primary requirements for Coding

The primary requirements for coding are recorded above the code line and for the purpose of the CALC system are considered the principal elements characterising and evaluating the land for capability and irrigability.

Slope

Slope is of paramount importance in any land use classification system. This is so principally because of the strong correlation between slope and erosion susceptibility and the implied necessity for mechanical land protection etc., but also because of the additional costs in cultivating and irrigating such land. The steeper the slope, the fewer the options available with regard to irrigation system and the higher the implied pumping costs, pipe class ratings etc.

Lands over 16% slope are considered to be non-arable, although lands over 12% slope require considerable precautions to be taken in their cultivation. In general and where soils are free draining, the best arable/irrigable lands will be those found on shallow slopes. The irrigability rating further divides the A slope lands into A1 with slopes of 0-1% and A2 with slopes of 1-2%, in order to evaluate more accurately land for irrigation development.

Slope assessment is carried out using either ortho-photo maps or an Abney level on site in conjunction with the necessary air-photo interpretation analysis.

Soil Texture

There are eight soil textural classes recognised by CALC (see table in Figure 5) which are further combined to give four textural groups (see Figure 7 and 8). An additional grouping for vertic soils is included which is warranted because these soils have distinctive physical characteristics which may be different to those indicated by the textural classes into which they may naturally fall.

Texture is assessed using finger assessment *in situ*. This system can produce good results, but practice with reference to local soils to get the correct "feel" is important before surveyors undertake their field work.

For capability, texture is assessed for the UFRZ, primarily for erodibility evaluation, and for irrigability, the texture of the LFRZ is taken, primarily for moisture retention estimation.

The dominant sand/silt fraction of these two horizons is also assessed at the same time. Whilst being non-diagnostic this analysis is helpful to end-users in estimating possible moisture retention/release characteristics, infiltration rates, etc.

Soils with high silt fractions (over 30%) are treated outside the "main stream" of the CALC analysis. This is because they are usually less common than the other categories, are easily confused with clayey soils during finger assessment, and have distinct physical characteristics which tend to distort the textural groupings they would otherwise fit into. Silty soils frequently have low infiltration rates, crust easily, and are erodible but also have good moisture retention and release properties.

Where soils have over 30% silt content, the suffix "T" is added after the textural grouping.

The silty type soils, where they do occur, are accommodated in the principal textural categories as follows:

Textural Grouping	Silty Soil Type included	Silty soil Abbreviation
(S)	-	-
(LS.SL)	Silt	Z
(SCL.L.CL)	Silty loam/silty clay loam	ZL.ZCL
(SC.C)	Silty clay	ZC.

Permeability of the Lower Free Root Zone

Permeability can be defined as the ability of the soil to transmit air and water, cf. infiltration rate which is the rate at which water enters the surface of the soil, and drainage which is the rate that it leaves the soil profile. CALC assesses the permeability of the LFRZ only. With regard to the horizons above and below the LFRZ, the infiltration rate is assessed for the UFRZ, and the drainage rate for the RRZ.

Unfortunately, there is no ready practical means of measuring the permeability of soil horizons *in situ* under natural conditions. The most appropriate method is by evaluation and interpretation of soil morphology, substantiated where necessary and if possible by investigation of, for example, the clay mineralogy. In the field a great deal can be inferred with regard to permeability by observing colour and structure in relation to soil texture and, for example, the presence of mottles above horizons suspected of having poor permeability, iron/manganese concretions etc.

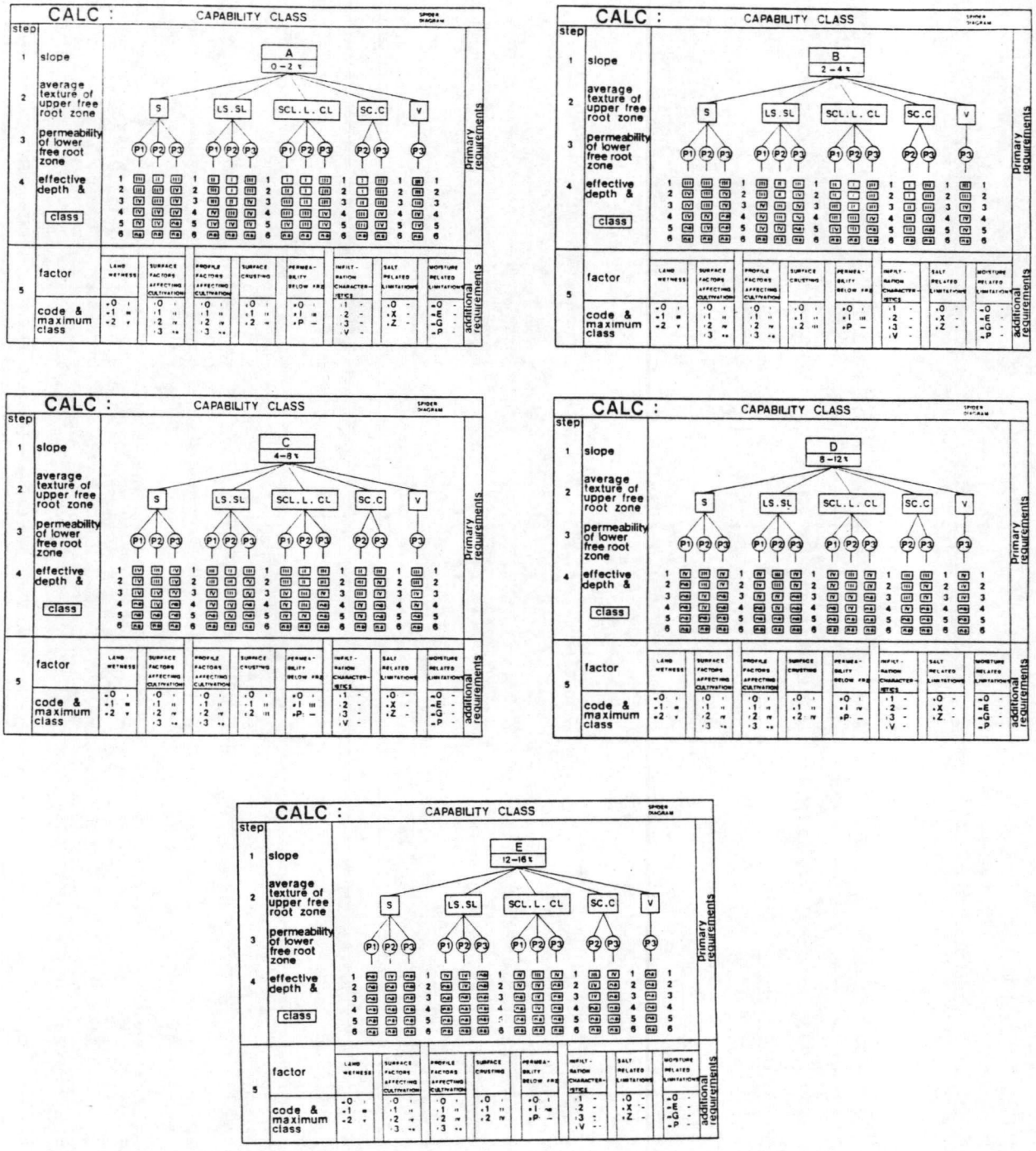


Figure 7 Spider diagrams for the conversion of CALC codes into capability classes. Five spider diagrams apply, corresponding to the five slope groups, A to E.

Permeability assessment can be seen therefore to befairly subjective and dependent on the experience of the field surveyor. For this reason, the CALC permeability categories have been kept to a minimum, the allocation process being thus simplified as the categories are broad and exclusive with little "overlapping".

CALC recognises three degrees of permeability, viz:

P1 Very rapid permeability
P2 Good permeability
P3 Restricted permeability

Depth

For the purposes of the CALC classification system, depth is considered only for the FRZ and for the ED of the full soil profile (down to a maximum depth of

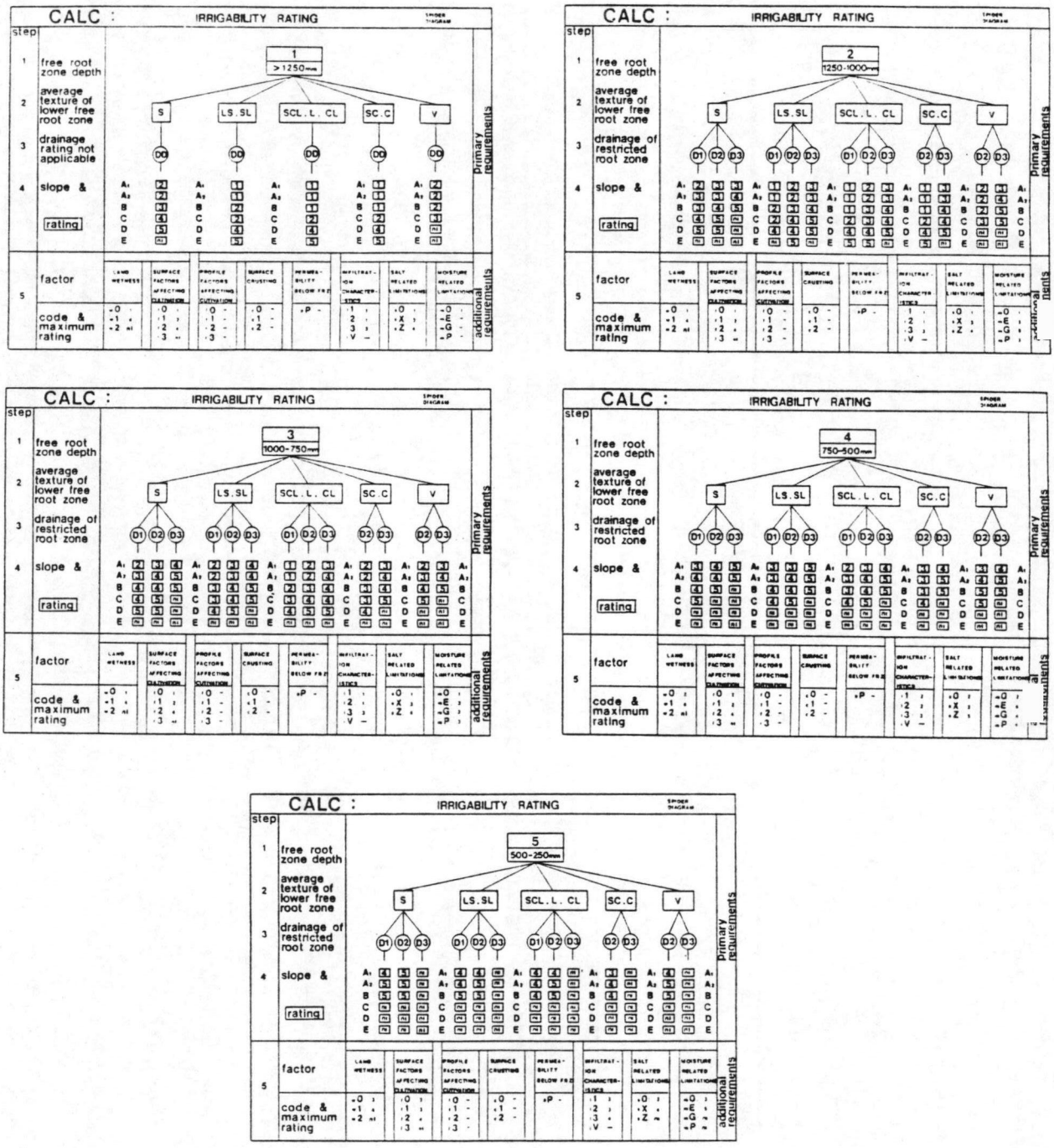


Figure 8 Spider diagrams for the conversion of CALC codes into irrigability ratings. Five spider diagrams apply, corresponding to five depth groups, 1 to 5.

1 250 mm).

Six depth groups in steps of 250 mm are identified. These relatively narrow depth bands have been chosen in order to increase accuracy for irrigation design.

Soils with a FRZ less than 250 mm are classified as non-arable and non-irrigable.

Depth has obvious importance with regard to both capability and irrigability. Effective depth, used in capability assessment, will better describe the usefulness of a soil profile to supply water to plants in a dryland situation, whilst the FRZ, which is indicative of the most productive portion of the soil, is that most applicable to irrigation design.

Drainage of the Restricted Root Zone

The drainage characteristics of a soil describe the ease of passage of water through and out of the plant-useful soil profile and into the strata below. It therefore automatically implies saturated flow.

The drainability of a soil is important in irrigation potential assessments because slowly draining soils will favour the formation of a temporary or fluctuating water table, especially when rain may follow an irrigation cycle, and also where salinity amelioration is required, free passage out of the profile or saline water is necessary for successful leaching.

There are three drainage rates described by CALC:

D1 free to slightly impeded, implies no problem to irrigation development.

D2 moderately to severely impeded, problems may arise if leaching is indicated and wide irrigation cycles with heavy applications will be a problem, with most orchard crops not thriving.

D3 severely impeded to impervious, will usually result in definite yield reduction under intensive irrigation development, and artificial drainage will be required in most situations.

Soils with severely restricted drainage are also usually prone to erosion.

Where the FRZ is limited by the presence of an E horizon, the permeability of the horizon immediately below the E horizon should be taken for the purposes of the rating exercise.

Additional Requirements for coding

The additional requirements for coding are recorded on the bottom of the CALC code. Although in themselves they may be of great importance in land evaluation, they are considered supplementary to the primary assessment characteristics.

Land Wetness

Susceptibility to waterlogging for extended periods is catered for by the land wetness rating. Lands that remain wet for much of the rainy season are coded W1. These lands should not be confused with those having heavy soils or sub-soils where drainage is slow and may take some days to dry out after periods of wetting. The W1 soils are frequently found in slope-break situations where surface and sub-surface drainage rates are reduced. Hydromorphic characteristics are usually found in the soil profile.

The W2 category is reserved for those soils that are, by and large, permanently wet. This wetness may be due to their position in the drainage sequence or to close proximity to springs, rivers etc.

Factors affecting cultivation

Several factors within the soil profile or on the surface or both may act to reduce the value of a land for arable usage. Stones, gravel, etc may cause problems for cultivation as may dongas, rills, etc which may also limit the size of lands to uneconomic units.

The severity ratings vary from hindering to prohibiting, the latter describing a situation where reasonable cultivation activities are prevented from being carried out.

Surface Crusting

The tendency of a soil to crust, which can normally be seen during the field survey or inferred from the textural analysis, is important in that susceptible soils are more prone to erosion, frequently have low infiltration rates and may tend to inhibit seedling emergence.

Permeability of Horizon immediately underlying the Free Root Zone

Should the horizon immediately underlying the free root zone have a markedly slower permeability, or drainage rate, the soil may be downgraded. This situation is only considered for land capability, which may be classified separately from irrigability - where the drainage of the restricted root zone constitutes an equivalent factor. A marked change in the permeability of an underlying layer will usually predispose a soil to waterlogging and erosion sensitivity. This factor only applies to soils shallower than 750 mm, and specifically caters for duplex type soils.

Infiltration characteristics

The infiltration rate is a vital consideration in irrigation planning, but also has significance in the hydrological characterisation of a catchment and is a factor in soil erodibility.

The infiltration rate of a soil is unfortunately difficult to measure and is also susceptible to marked changes through the course of a season and with varying cultivation and irrigation practices.

For these reasons, CALC rates the infiltration rate qualitatively, with three groupings: "rapid to moderate", "moderate to slow" and "slow to very slow" for most soils, and a special grouping for "vertic" soils with their distinct infiltration properties.

For most situations, the surveyor will have to make a subjective assessment, based on visual appraisal, of the crusting potential of the soil and the texture of the surface soil.

Salt Related Limitations

Salinity or sodicity problems may have a major impact on the agricultural quality of a soil, especially with regard to irrigation, where salts are being imported and cation concentrations in the soil solution affected. Sodium salt accumulation may also have a drastic effect on the soil structure.

CALC does not attempt to quantify the salt problem and only makes allowance for the inclusion of an indicator, stating that evidence of sodicity or salinity has been found.

Should a salt problem be suspected, soil samples should be taken for quantification at a laboratory. The results of this analysis should be used to give a final rating of the potential of the land for development.

Moisture Related Limitations

A soil exhibiting signs of impaired permeability or drainage has limited value as an irrigation soil. This is due to the fact that the irrigation development will probably mean an increased overall moisture regime for these soils that have already shown that they are not well adapted, from an agricultural point of view, to their existing moisture conditions.

Such evidence as an E horizon, gleying or plinthite are all indications that perched water tables are not infrequently present, aeration is poor and drainage will be slow. In many cases an artificial sub-surface drainage system will improve these soils, but for the purpose of the CALC classification, they are downgraded and accepted as poor to very poor irrigation soils. Should two or more of these limiting factors be expressed in the soil profile, then the symbols should be included together in the code, e.g. MEG.

Interpretation of land evaluation codes using spider diagrams

The "spider" or hierarchy-network diagrams are used as the means of interpreting the land code and of translating it into land capability classes and irrigability ratings.

Two sets of spider diagrams are applicable to the evaluation exercise. Five correspond to the five slope groups for the capability classes, as in Figure 7, and five to the specific soil depth groups for the irrigability ratings, as in Figure 8. Capability classes in Roman numerals and irrigability ratings in Arabic numerals are identified.

The spider diagrams are designed to be read in five sequential steps - corresponding to the evaluation code. The "primary requirements" comprise the first four steps, and the "additional requirements" a composite final step.

The primary requirements channel the code into a particular class or rating. The additional requirements may not change this first approximation, or they may downgrade it accordingly. Classes and ratings cannot be upgraded through this fifth step.

Where a class or rating is downgraded due to an additional factor, the symbol for that factor should be appended to the code as a suffix e.g. IIIw/4 m.

For capability classing, the spider diagrams commence with slope, they then consider the texture of the UFRZ, the permeability of the LFRZ and effective depth, before adjusting the class, if required, according to the additional factors.

For irrigability rating, the spider diagrams commence with the FRZ depth, they then consider the texture of the LFRZ, the drainage of the RRZ and the slope of the land before adjusting the rating, if required, according to the additional factors.

It should be noted that any land not meeting the minimum requirements shown in the spider diagrams, is automatically downgraded to non-arable or non-irrigable land. The abbreviation "na" means non-arable under normal circumstances, and "ni" means non-irrigable under normal circumstances.

Examples of the derivation of capability and irritagility classes and ratings using the coding system are shown in Figure 9.

SITE	PEDOLOGICAL CODE	CALC CODE	CLASS	RATING
PIT1	Hu 16	C / LS(C)-P1-1 / 1-SCL(C)-DD w0-e2 / f0-c0-pP / i1-s0-m0	IVe	4e
PIT2	Oa36	A1 / SC(T)-P2-3 / 4-C(T)-D2 w0-f0 / f0-c1-pP / i2-s0-m0	II	3
PIT3	Lo21	B / SL(M)-P1-4 / 5-SCL(M)-D2 w0-f0 / f0-c0-p1 / i1-s0-mP	IV	NIm

Figure 9 Examples of CALC codes, classes and ratings in standard presentation format.

Conclusion

The CALC system has been devised in an attempt to extend, using practical and relatively easy to measure parameters, the usefulness of land evaluation type surveys and especially the assessment of irrigation suitability.

In order to accommodate the requirements of irrigation planners, CALC has re-defined the soil profile according to terms directly applicable to design. These factors are expressed in code form, from which capability classes and irrigability ratings can be derived fro demarcation purposes.

CALC can be considered as either an alternative to or as augmenting pedological or other surveys, and

should be seen as a field scale tool for agricultural development planners and irrigation engineers.

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THE ROLE OF GEOGRAPHIC INFORMATION SYSTEMS IN ESTIMATING IRRIGATION WATER REQUIREMENTS FOR PLANNING IN DEVELOPING REGIONS OF SOUTHERN AFRICA

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Abstract

There has recently been a surge of interest in using the techniques incorporated in commercial geographic information system (GIS) software packages for natural resource planning in developing regions. The estimation of irrigation water requirements and the associated water resources have inevitably fallen into this category. The temptation to use commercially available GIS software packages for estimating and then mapping irrigation water requirements in Southern Africa has been given further inpetus by recent studies which have produced detailed long term mean rainfall (Dent, Lynch & Schulze, 1989), temperature and evaporation (Schulze & Maharaj, 1990) images covering Southern Africa. The applicability of using overlays of long term mean evaporation and rainfall images to estimate crop water requirements from irrigation is investigated in this paper. The assessment is based on the results of a study by Dent, Schulze & Angus (1988), in which crop water requirements from irrigation were estimated for a range of crop and soil conditions. The abovementioned study used daily water budgeting from representative rainfall stations at each of 712 homogeneous rainfall regions in Southern Africa. The paper concludes that in the supplementary irrigation areas it is necessary to move considerably beyond the capabilities of present day commercial GIS packages. Daily soil moisture budget modelling is required to estimate crop water requirements for supplementary irrigation in the more humid developing areas of Southern Africa.

Introduction

There are several roles which geographic information system (GIS) software may play in the estimation of monthly irrigation requirements for planning purposes. The aim of this paper is to enhance appreciation of the range in sophistication, appropriateness and accuracy of these roles. The factors which have prompted this study are;

(i) the increase in supplementary irrigation practices (Co-ordinating Committee for Irrigation Research, 1986), especially in the more humid eastern regions of southern Africa as anticipated by Midgley (1983) and Green (1984);

(ii) the increased use of micro-computer based GIS software;

(iii) the publication of surfaces of long term median monthly rainfall estimates by Dent, Lynch & Schulze (1989) and long term mean monthly evaporation estimates by Schulze & Maharaj (1990);

(iv) the publication of a research report on crop water requirements for irrigation planning by Dent, Schulze & Angus (1988).

The latter report provides the basis for a quantitative comparison of two of the techniques mentioned in this paper. Estimates of monthly crop water requirements for planning based on long term mean monthly evaporation and median monthly rainfall are compared with those of Dent *et al* (1988) who based their estimates on daily soil water budgeting. The estimation of irrigation requirements for planning purposes is used as an example in this paper. The discussion on the role of GIS software is however, also appropriate for many applications in water resources and environmental analyses which involve long time series of daily climatic data.

Trends in the interaction between GIS software and models

The role of GIS software in estimating irrigation requirements for planning purposes will be discussed with the aid of Figure 1. It is reasonable to assume that in time the combination of GIS and modelling will be capable of addressing an increasing portion of the problem of estimating irrigation requirements, as shown in Figure 1.

At present much of the effort in GIS applications is being focused on the mechanisms illustrated in Role 1. This situation is understandable, yet regrettable. In Role 1, the model is an existing map, for example of rivers, altitude contours, roads, land use, soils or cadastral boundaries. It is necessary to examine briefly the origins of GIS development to appreciate the reasons for this confinement of effort to Role 1. In the main GIS development has been driven by city planning and engineering applications involving road, electricity and water reticulation networks. In these endeavours the model or information source is the map, from which features are digitised and entered into the GIS.

The primary functions of GIS software have not altered substantially over the past five years. Th are capture, storage, extraction, basic manipulations, for example, sorting, searching, overlaying, buffering, excluding and finally displaying of spatial information. The functions have nevertheless improved in speed, user friendliness and quality of display. Direct interpolation modelling as mentioned in Role 2, Figure 1 is a more recent development in many GIS packages.

The modelling techniques referred to in Roles 3 and are not included in commercial GIS software at present. The major marketing forces behind develop

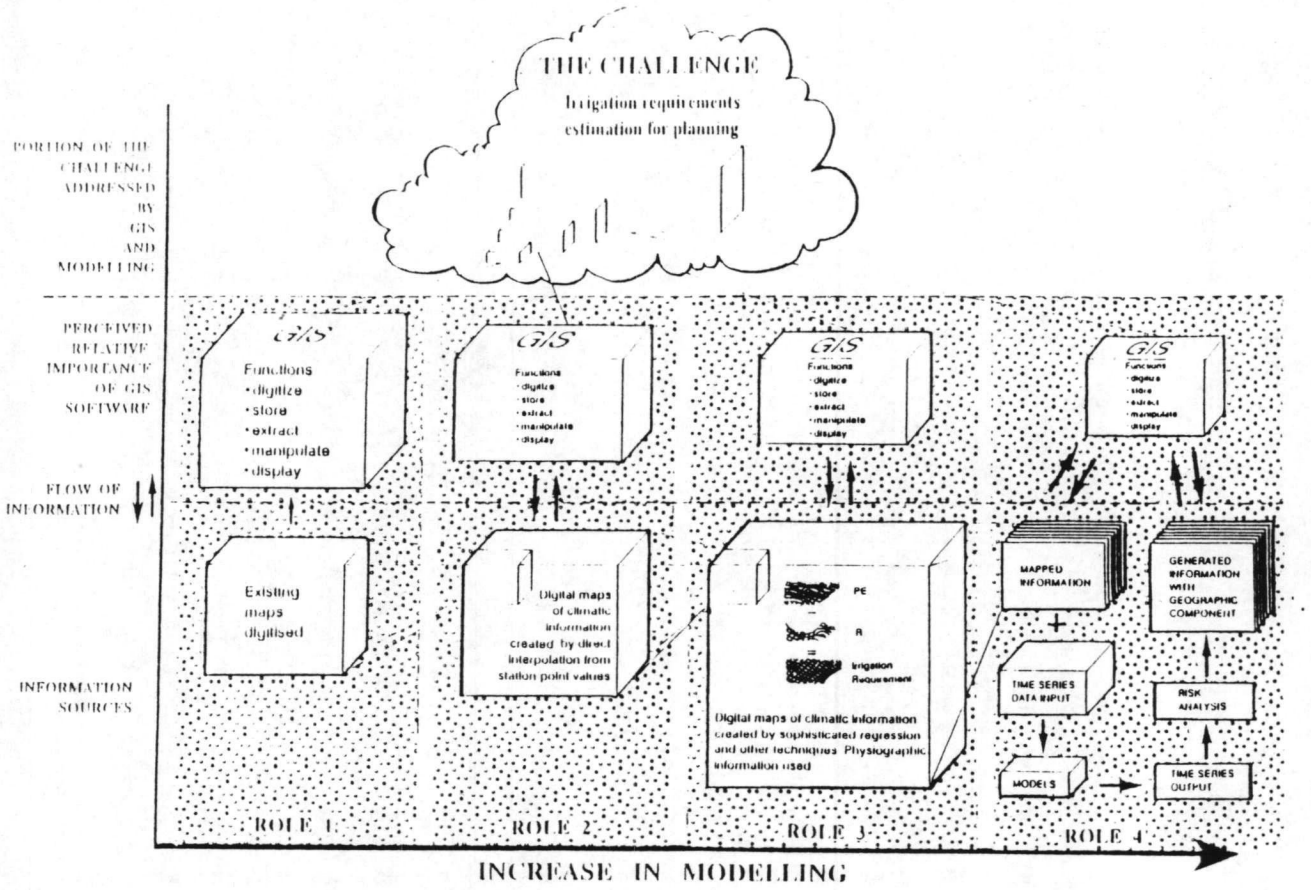


Figure 1 Trends in the interaction between GIS and modelling.

ments in GIS software, mentioned earlier, will probably ensure that this remains so. The quantum leap in complexity and the limited market for these modelling techniques will play a decisive role in this regard. In addition, modelling which produces the type of information indicated in Role 3 and Role 4 is of a level of sophistication which is generally beyond the capability of most users of GIS software. However, the information provided by these modelling techniques is vital to the future use of GIS software in water resources and environmental planning and management.

If the use of GIS is confined to Roles 1 and 2 as shown in Figure 1 then it will suffer limited use in irrigation planning in particular, and water resources and environmental planning in general.

It is encouraging to note that there are some organisations and research leaders who have recognised this. They have therefore concentrated much effort on modelling to generate information as illustrated in Roles 3 and 4 of Figure 1. These researchers view GIS software as an ideal tool for extracting, displaying and performing standard manipulations on the information input to and output from models. This enhances greatly the display and interpretation of the model generated information. The estimation of monthly irrigation requirements for planning purposes is the example chosen in this paper to illustrate the potential interaction between modelling and GIS. The model employed by Dent *et al* (1988) to generate estimates of monthly irrigation requirements, *inter alia* from daily time series of rainfall data, is described briefly in the following section.

Modelling irrigation requirements

A soil moisture budgeting model, based on the concepts of the ACRU model (Schulze, 1989), was developed by Dent *et al* (1988) to estimate possible crop water requirements under irrigated conditions. This model catered for daily rainfall, interception, stage of growth of crop, actual evapotranspiration, crop rooting depth and soil texture. Irrigation water was applied when the soil moisture reached 50 per cent of the plant available moisture (PAM), where PAM was defined as the moisture held in the root zone between field capacity and wilting point.

The monthly summations of such water applications and the change in soil moisture storage between the first and last day of the month constituted the crop water requirement from irrigation. These values for

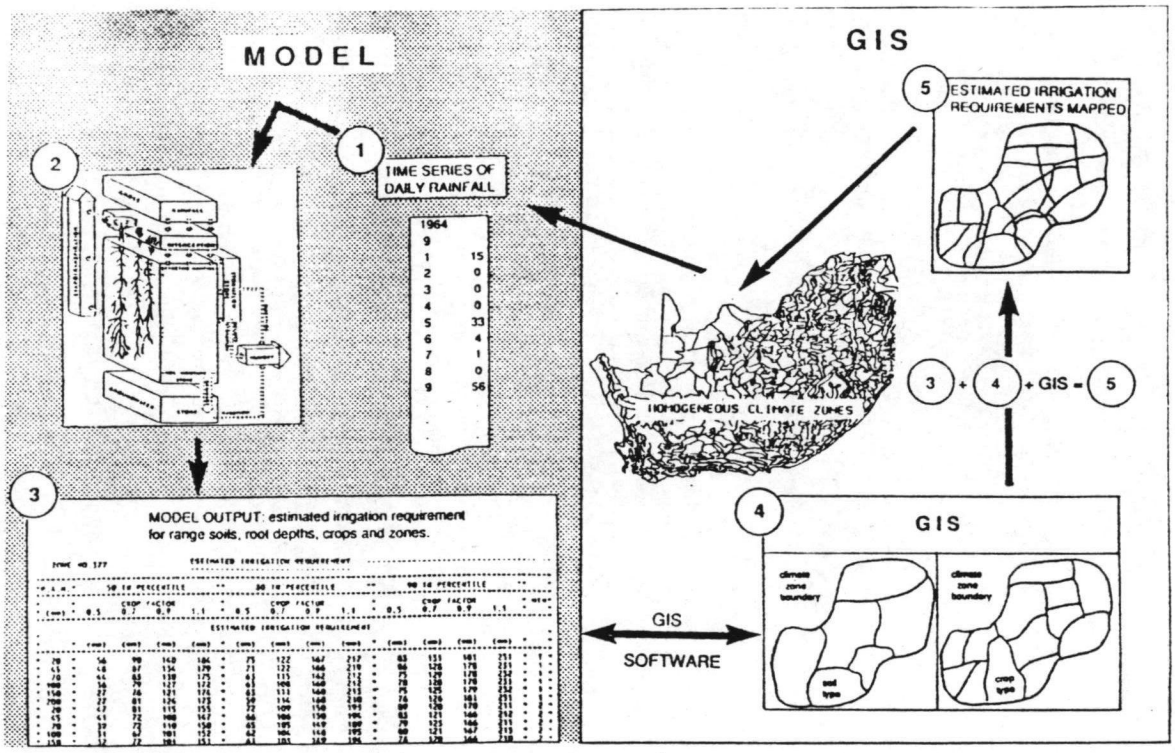


Figure 2 An example of the interaction between GIS and modelling as depicted in Role 4 of Figure 1.

the entire daily rainfall record at each station, were ranked and the 50, 80 and 90 percentile values were extracted for each month.

In the study by Dent *et al* (1988) this model was run using daily rainfall data at each of 712 climate zones and for a range of PAM and crop factors and for each month of the year. A portion of the output from the above procedure is presented in Figure 2.

Comparison of irrigation estimates

The irrigation requirements estimates produced by the model described above and which could be used in Role 4 (Figure 1) were compared with the results from a Role 3 type estimation procedure. The estimates at each of 65 rainfall stations within the climate zones listed in Table 1 were used in the comparison. The zones referred to are those designated by Dent *et al* (1988). The months of January and July and a number of locations throughout the country were selected to show the general applicability of the findings presented in Table 1 and discussed below.

The differences between estimates using the two methods range from approximately 2 per cent in the dry areas and seasons to approximately 100 per cent and sometimes much more in the wetter areas. All forms of the simplistic estimating procedure presented in Figure 1 as Role 3 yield results which are very different from the modelled estimates. If one assumes that the daily moisture budgeting methodology yields more realistic results, then the unacceptability of the Role 3 approach is apparent.

Interaction between GIS and modelling: an example

An example of the interaction between GIS and modelling as depicted in Role 4 of Figure 1 is presented in Figure 2. The example is an application of the procedure developed by Dent *et al* (1988). Steps 4 and 5 shown in Figure 2 could be performed manually. However if the table in Step 3 as well as Steps 4 and 5 were linked to a GIS then the speed and ease of the procedure would be enhanced considerably.

Conclusions

The primary objective of this paper was to examine the role of GIS software in the estimation of irrigation requirements in developing regions in southern Africa. Several possible roles were presented and the quantitative performances of the two most advanced roles were compared. In the wetter areas of southern Africa there are marked differences, in the estimated monthly irrigation requirements, between the two techniques. It is reasonable to assume that the method which involves daily water budgeting provides the more realistic estimates. The method of subtracting the long term median monthly rainfall from the

Table 1 Comparison of irrigation requirements estimates for planning.

	Climate zone	JANUARY								JULY							
		$\frac{(PE-R)-IR_{50}}{IR_{50}}$ x100 (%)	$\frac{(PE-R)-IR_{90}}{IR_{90}}$ x100 (%)	$\frac{(PEMAX-R)-IR_{50}}{IR_{50}}$ x100 (%)	$\frac{(PEMAX-R)-IR_{90}}{IR_{90}}$ x100 (%)	$(PE-R)-IR_{50}$ (mm)	$(PE-R)-IR_{90}$ (mm)	$(PEMAX-IR_{50})$ (mm)	$(PEMAX-IR_{90})$ (mm)	$\frac{(PE-R)-IR_{50}}{IR_{50}}$ x100 (%)	$\frac{(PE-R)-IR_{90}}{IR_{90}}$ x100 (%)	$\frac{(PEMAX-R)-IR_{50}}{IR_{50}}$ x100 (%)	$\frac{(PEMAX-R)-IR_{90}}{IR_{90}}$ x100 (%)	$(PE-R)-IR_{50}$ (mm)	$(PE-R)-IR_{90}$ (mm)	$(PEMAX-IR_{50})$ (mm)	$(PEMAX-IR_{90})$ (mm)
Western Cape	33	-2	-5	10	7	-7	-16	32	23	-46	-83	572	119	-7	-36	80	51
	34	0	-6	17	9	1	-19	49	29	-306	-143	1076	147	-25	-55	86	56
	35	0	-3	12	9	-1	-11	37	27	-910	-225	1113	87	-73	-117	89	45
	36	0	-2	12	10	0	-5	35	30	-108	-103	322	59	-25	-63	74	36
	50	0	-1	10	9	-2	-4	32	30	21	-17	111	43	10	-12	52	30
	51	0	-4	13	9	-1	-11	38	28	28	-2	96	51	16	-1	55	38
	52	1	-5	19	11	3	-17	55	35	33	-12	144	62	15	-8	65	42
Eastern Cape	133	22	17	38	32	61	49	105	93	37	21	63	44	30	19	51	40
	134	23	16	42	33	59	42	106	89	37	12	81	48	32	13	70	51
	135	-8	-19	22	7	-17	-46	45	16	-1	-19	46	19	-1	-19	36	18
	141	-4	-11	19	10	-9	-28	45	26	19	2	59	36	14	1	46	33
	142	-1	-8	22	14	-3	-20	54	37	21	-12	98	45	10	-8	48	30
	143	32	21	55	42	78	55	133	110	62	38	87	59	54	39	75	60
	144	21	6	50	31	39	13	91	65	29	10	62	38	22	9	47	34
Transkei	185	28	-5	101	49	43	-10	155	102	17	8	37	26	17	9	36	28
	186	18	-4	80	47	30	-8	136	98	10	0	29	18	10	0	31	21
	243	27	-7	119	60	38	-14	168	116	16	9	34	26	16	10	34	28
	259	30	-34	275	89	26	-58	234	150	25	13	48	33	25	14	49	38
	261	32	-1	105	53	46	-3	150	101	25	15	43	32	27	18	45	36
	263	17	-22	204	103	18	-34	214	162	15	4	39	26	16	4	43	31
Northern Cape	318	36	17	73	48	89	48	180	139	37	35	51	49	44	42	61	59
	319	37	12	75	43	88	35	180	127	38	38	52	52	43	43	58	58
	320	37	22	70	52	103	70	196	163	42	42	56	56	48	48	64	64
	321	33	19	66	48	92	59	182	149	39	39	52	52	44	44	60	60
	322	36	20	69	49	97	62	184	149	43	40	59	56	47	45	65	63
	323	30	18	52	38	84	56	147	119	36	36	49	49	42	42	58	58
Eastern OFS	348	63	26	139	84	107	57	235	185	61	61	77	77	58	58	73	73
	349	77	34	167	102	110	64	240	194	56	49	78	69	53	48	73	68
	350	57	27	150	102	85	49	224	188	52	45	72	65	46	42	63	59
	353	66	14	186	95	83	25	232	174	57	50	77	70	52	48	70	66
	354	80	9	226	97	87	16	246	175	48	39	66	56	44	38	60	54
Western Natal	368	80	-16	498	177	35	-16	219	168	52	35	74	55	42	32	60	50
	369	105	22	370	179	74	26	259	211	51	32	83	60	48	34	79	65
	370	56	-5	262	121	52	-7	244	185	36	32	53	48	39	35	57	53
	371	102	-30	678	168	42	-36	278	200	55	44	72	61	53	46	70	63
	372	82	23	274	152	73	30	244	201	67	62	87	81	69	66	90	87
	373	77	10	251	119	62	13	203	154	51	43	73	64	45	40	63	58
	375	95	19	268	125	110	36	311	237	67	66	84	83	81	80	102	101
	377	82	30	204	117	104	53	259	208	67	67	85	85	84	84	107	107
	401	114	6	545	219	53	5	256	208	46	30	74	55	41	30	66	55
Zululand	415	12	-20	132	66	15	-34	162	113	30	-14	122	47	19	-13	77	45
	418	26	-26	217	87	21	-34	171	116	19	-30	167	57	9	-23	77	45
	419	27	-20	169	70	27	-31	169	111	40	5	102	51	27	4	70	47
	420	38	-13	163	65	40	-22	171	109	35	17	73	51	28	16	59	47
	423	19	-18	117	49	23	-33	143	87	31	13	65	42	25	12	53	40
	424	26	0	121	76	34	0	159	125	31	1	78	38	23	1	60	38
	425	25	-24	192	78	20	-33	160	107	16	-23	146	63	8	-17	72	47
	426	-1	-27	116	58	-1	-39	121	83	16	-24	104	34	8	-19	54	27
Eastern Transvaal	642	64	9	163	75	73	16	186	129	51	49	66	64	49	48	63	62
	647	-80	-93	886	266	-21	-65	230	186	42	31	64	51	35	28	54	47
	649	59	12	223	127	56	16	212	172	57	50	77	70	55	51	75	71
	650	65	15	200	110	68	23	210	165	48	46	66	64	50	49	68	67
	651	100	0	341	120	60	0	204	144	61	58	80	76	51	49	66	64
	652	60	-39	448	111	28	-47	210	135	29	22	47	40	28	23	47	42
	656	61	27	144	91	87	48	204	165	57	54	75	72	57	55	75	73
Northern Transvaal	681	41	-5	198	102	37	-7	182	138	49	43	70	63	46	42	65	61
	682	43	1	145	73	49	2	164	117	37	37	51	51	35	35	48	48
	684	49	-10	195	78	44	-15	175	116	54	51	72	69	52	50	70	68
	694	1	-46	268	95	1	-66	201	134	33	28	51	45	31	27	49	45
	695	-28	-77	558	108	-12	-103	234	143	19	0	50	26	18	0	48	30
	696	-247	-163	763	273	-79	-121	244	202	52	18	95	52	38	17	70	49
	697	24	-23	239	110	21	-33	210	156	44	32	68	54	43	34	66	57
	698	32	-7	176	93	35	-11	190	144	45	42	63	60	45	43	63	61
	699	46	9	128	70	67	17	186	136	51	50	68	66	55	54	74	73
	701	7	-43	234	79	6	-66	194	122	36	33	53	50	33	31	49	47

where:

PE = estimate of monthly mean potential evaporation (mm)

R = median monthly rainfall (mm)

IR_{50} and IR_{90} = estimated monthly irrigation requirements from Dent *et al* (1988), which are not expected to be exceeded on 50 and 90 per cent of occasions respectively (mm)

PE MAX = maximum monthly potential evaporation, estimated at 110 per cent of the mean PE (mm)

evaporation should therefore be avoided in preference to the daily moisture budgeting approach. This means the GIS software should be used in Role 4. Given the rainfall and evaporation surfaces the simplicity of the approach outlined as Role 3 makes its adoption tempting. Role 3 however, does not account for the important dimension of time and the variability of rainfall at the daily time step.

For the reasons given earlier it is unlikely that the time series modelling required in daily moisture budgeting will be incorporated in commercial GIS software in the foreseeable future. A more probable scenario is that bridging programs will be developed by researchers to export GIS based input to models and to import the information generated by these time series models into the GIS. The function of the GIS will then be to store, extract, manipulate and display the results speedily and in a variety of spatial forms.

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THE USE OF A CROP SIMULATION MODEL TO EVALUATE OPTIMAL IRRIGATION STRATEGIES FOR WHEAT IN ZIMBABWE

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Abstract
Most wheat in Zimbabwe is grown during the dry winter under irrigation. Consequently, production strategies should be directed towards maximizing water use efficiencies within the constraints of land and water availability. The determination of optimal irrigation strategies is therefore essential for the efficient use of the limited water supplies during this time of year. The crop simulation model CERES-Wheat was modified and tested under Zimbabwean conditions and then used to evaluate irrigation options that had the dual and apparently antagonistic aims of: 1. maximizing net returns per unit of applied water per unit area; and 2. maximizing net returns per unit area of crop produced. In spite of these two antagonistic aims, the use of the Pareto multicriteria optimization technique enabled the identification of irrigation strategies that gave feasible, non-inferior combinations of profit per unit applied water and profit per unit area. The irrigation treatments used to form the basis of the Pareto optimal curve were analyzed in order to provide a basis for recommending deficit irrigation to farmers.

Introduction

Wheat in Zimbabwe is predominantly grown with sprinkler irrigation during the relatively dry, cool winter months by large scale commercial farmers. On most farms, available water resources limit the area of land that can be irrigated, and often there are competing demands for water (e.g., early establishment of summer crops). Furthermore, the costs of irrigation are escalating, both in terms of capital and energy costs. The adoption of more efficient irrigation methods is therefore of prime importance, and considered by Longmire, Ngobese & Tembo (1986) as one of the main factors that will contribute to greater what production in Zimbabwe.

Traditionally, farmers have tended to be liberal in their application of water to wheat, as indicated by surveys carried out by Whingwiri (1985) and Longmire *et al.* (1986). However, line source experiments carried out by MacRobert & Mutemeri (1987, 1988) showed that wheat exhibited a typical curvilinear water production function for yield. Maximum yields were achieved with the application of 548 to 596 mm water ha^{-1}, whereas maximum water use efficiencies (i.e., grain yield per mm applied water) were obtained at water applications of 350 to 400 mm.

In situations where land is the limiting resource for an irrigated crop, the economic objective is to irrigate at a level where the marginal net return from applying a unit of irrigation equals the marginal cost of applying a unit of water (Heerman, Martin, Jackson & Stegman, 1990). Thus, the optimal irrigation depth is equivalent to that which maximizes the gross margin or net returns per unit area (NRha). This depth is often near that for maximum yield, particularly where water is cheap. On the other hand, in cases where water supply limits the area of crop that can be grown, the economic criteria for determining the amount of water to apply are the maximization of the average net return per unit of water applied per unit area produced (NRmm) (Heerman *et al.*, 1990) and the maximization of profit with respect to the total area put into production (English & Orlob, 1978). In this case, the optimal irrigation depth is usually less than that required to achieve maximum NRha, and therefore implies deliberately subjecting a crop to water deficits. James (1988) referred to this method of irrigation as "deficit irrigation".

The problems of deficit irrigation management lie firstly in determining the sequence and amounts of irrigation that will maximize net returns per unit of water (NRmm), and secondly in evaluating the risk associated with allowing the development of soil water deficits. Irrigation farmers may be quite concerned with risk (English & Orlob, 1987), and therefore, even though they may appreciate the economics of deficit irrigation, they may tend to favour irrigation schedules that maximize NRha rather than NRmm. The determination of irrigation regimes that have the dual aim of maximizing both NRha and NRmm was therefore the aim of this study.

Materials and methods

Stegman, Musick & Stewart (1983) recommended the use of computer simulation to evaluate deficit irrigation options. The CERES-Wheat crop simulation model (Ritchie & Otter, 1984; Godwin, Ritchie, Singh & Hunt, 1989) was therefore selected for this purpose, based on the fact that it is well documented and conforms to the Decision Support System for Agrotechnology Transfer developed by the International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT, 1989).

CERES-Wheat Version 2.00 was validated against experimental data from deficit irrigation experiments conducted by MacRobert & Savage (1991) and on unpublished data of J F MacRobert. Although

simulated grain yields compared fairly well with measured grain yields, CERES-Wheat V.2.00 was unable to account for the hastening of crop development as observed under water deficient conditions. Plant temperature is known to increase under conditions of water deficits (Wiegand & Namken, 1966). Consequently, the CERES-Wheat source code was modified so as to increase daily thermal time when total root water uptake declined below 1.5 times the potential plant evaporation, as follows:

$$DTT = DTT * (1.50 - 0.50 * SWDF2) \quad (1)$$

where DTT = daily thermal time (°C day),
SWDF2 = 0.67 * TRWU/EP1,
TRWU = total root water uptake, and
EP1 = potential plant evaporation.

Based on unpublished data of J F MacRobert, and supported by a report by Morgensen & Talukder (1987), in which kernel growth rates increased under water deficit stress, the relative kernel growth rate factor (RGFILL) was made to increase under conditions of water deficits as follows:

$$RFGILL = RGFILL * (1.25 - 0.25 * SWDF1) \quad (2)$$

where SWDF1 = TRWU/EP1.

In order to evaluate the effect of irrigation sequence and amount on the yield of wheat, 304 possible irrigation regimes were established during the 1990 growing seasons. Combinations of irrigations of either 50, 30 or 25 mm were utilized, and the return intervals were varied so as to cover a range of total

Table 1 Profile characteristics of the three soils used in this study.

Layer (mm)	LL	UL	SATSW	EXTSW	INSW	WR
			$m^3\ m^{-3}$			
			ART			
0 - 125	0.220	0.348	0.400	0.128	0.275	1.00
126 - 375	0.260	0.390	0.407	0.130	0.345	0.70
376 - 625	0.300	0.406	0.432	0.106	0.345	0.40
626 - 875	0.250	0.370	0.412	0.120	0.345	0.20
876 - 1375	0.260	0.370	0.417	0.110	0.360	0.10
Average	0.262	0.378	0.415	0.116	0.344	-
			GLEN			
0 - 125	0.106	0.235	0.260	0.129	0.165	1.00
126 - 375	0.105	0.235	0.265	0.130	0.190	0.80
376 - 625	0.134	0.256	0.292	0.122	0.190	0.60
626 - 875	0.138	0.260	0.306	0.122	0.190	0.30
876 - 1375	0.141	0.260	0.304	0.119	0.240	0.10
Average	0.129	0.252	0.291	0.123	0.206	-
			KUTS			
0 - 250	0.029	0.119	0.176	0.090	0.050	1.00
251 - 500	0.035	0.117	0.168	0.082	0.085	0.75
501 - 750	0.035	0.126	0.168	0.091	0.085	0.60
751 - 1000	0.040	0.136	0.172	0.096	0.085	0.30
1001 - 1250	0.036	0.143	0.191	0.107	0.140	0.10
Average	0.035	0.128	0.175	0.093	0.089	-

LL = Lower limit of plant extractable soil water
UL = Upper limit of plant extractable soil water
SATSW = Saturated soil water content
EXTSW = Plant extractable soil water content (UL-LL)
INSW = Initial soil water content
RW = Root growth weighting factor

water applications from 80 mm to 690 mm. The majority of irrigation treatments were such that the total applied ranged from 250 to 450 mm. A 50 mm irrigation is common for many irrigation schemes in Zimbabwe on soils with plant extractable soil water contents of >0.10 m^3m^{-3}, whilst 30 mm irrigation applications are used widely on irrigation schemes primarily designed for tobacco and which are usually associated with sandy soils. An 85% irrigation efficiency was applied to all irrigation treatments.

The modified CERES-Wheat version was run with these 304 irrigation treatments on three soil types (Table 1): ART, characterized by deep (1.38 m), clay soil; GLEN, characterized by deep (1.38 m), sandy clay soil; and KUTS, characterized by moderately deep (1.25 m), sandy soil. The first irrigation at each site was applied on 15 May, which has been shown to be an optimum sowing date for wheat in Zimbabwe (MacRobert, 1991).

Actual weather data from the Agricultural Research Trust (ART) Farm, Harare (altitude 1 500 m), for 1990 were used for the simulations on the ART soil, while actual weather data from Wooler Farm, Glendale (altitude 1 150 m, and temperatures generally warmer than ART Farm), for 1990 were used for the simulations of the GLEN and KUTS soils. No rainfall was received during the winter of 1990 at either ART or Wooler Farm.

Daily solar radiation was measured at ART Farm only. Estimates of solar radiation at Wooler Farm were made from a weighted average cloud cover index with the following formula:

$$I = Q_o * (0.742 - 0.050 * C) \quad (3)$$

where I is the daily total solar radiant density ($MJ\ m^{-2}$), Q_o is the daily total incoming solar radiant density in the absence of an atmosphere ($MJ\ m^{-2}$), and C is the weighted average daily cloud cover index (Octals). This approximation for solar radiation was developed on ART Farm over three seasons and the regression equation used had an $R^2 = 0.786$. The genetic coefficients used in the simulation for cv. Sengwa were:

P1V (Vernalization sensitivity factor) = 0.5
P1D (Photoperiod sensitivity factor) = 2.0
P5 (Duration of linear grainfill period) = 9.0
G1 (Kernel number from stem weight factor) = 6.0
G2 (Potential kernel growth rate) = 1.1
G3 (Potential dry weight of a single stem and ear) = 3.5

Once all treatments had been simulated, the NRha and NRmm was calculated for each, based on the following assumptions:

1. A net harvested grain price of ZW$ 484.80 t^{-1}, the current price of "A" grade wheat in Zimbabwe for 1991.
2. Input costs per unit area for all other factors other than irrigation (e.g., seed, fertilizer and tractor operating costs) were assumed constant for all treatments, and were set at a total of ZW$ 1 000.00 ha^{-1}. This may not be entirely correct, for a deficit irrigated crop with a lower potential yield than a fully irrigated crop may warrant lower fertilizer inputs. Nevertheless, it was considered prudent to be conservative and weight the costs against the deficit irrigation treatments.
3. Irrigation costs, which include pumping costs, repairs and maintenance and labour, but not depreciation, were set at ZW$ 1.00 mm^{-1}, based on actual cost data accumulated by the Agricultural Research Trust. It could be argued that irrigation frequency may influence this cost, but it was considered too difficult to estimate unit irrigation costs based on irrigation frequency.

The NRha was calculated as the product of yield and net price, less the constant costs and the irrigation cost. The NRmm was calculated as NRha divided by the total irrigation water applied.

The Pareto dual criteria optimization technique, as presented by Osyczka (1984), was used to select those treatments that combined high NRha and high NRmm. Pareto optimization is a multicriteria optimization technique which evaluates multiple objective functions and produces a set of non-inferior solutions, i.e., solutions for which there is no way of improving any one criterion without worsening at least one other criterion. Such a set of solutions, when applied to this deficit irrigation problem would yield those treatments on the frontier of profit maximization, and thereby provide a range of optimal irrigation options for farmers.

Results and discussion

The first modification to CERES-Wheat (Equation 1) reduced the systematic root mean square error ($RMSE_s$) of the model for days to physiological maturity (Table 2). This improvement is illustrated in Figure 1.

The second modification to CERES-Wheat (Equation 2) marginally improved both the $RMSE_s$ and the unsystematic root mean square error ($RMSE_u$) for grain yield when compared to the original version (Table 2). The observed and predicted grain yields using the modified version are shown (Figure 2). At low yield levels, the modified CERES-Wheat tended to under-predict, whilst at high yield levels, the model tended to over-predict, although to a lesser extent than the original version.

The modified version was able to adequately simulate the soil water balance as illustrated by a comparison of observed and simulated soil water contents of two treatments from MacRobert & Savage (1991) (Figure 3).

Of the 304 simulated irrigation treatments, only five, seven and 18 treatments on the ART, GLEN and

Table 2 Comparison of average observed and predicted grain yields, and days from germination to physiological maturity of 25 wheat irrigation treatments in Zimbabwe from MacRobert & Savage (1991) and J.F. MacRobert (unpublished data), using the original CERES-Wheat V.2.00 and that modified according to details specified in the Materials and Methods section.

	Grain yield ($t\ ha^{-1}$)		Physiological maturity (days after sowing)	
Observed	5.77			
S.E.	1.433			
	Original	Modified	Original	Modified
Predicted	6.25	6.14	128	122
S.E.	2.017	1.982	2.4	4.96
$RMSE_s$	0.662	0.564	6.66	2.22
$RMSE_u$	0.653	0.647	2.21	2.33
I of A¶	0.997	0.997	0.966	0.996

¶ Index of Agreement (Willmott, 1982)

KUTS soils, respectively, showed a negative net return per unit area (NRha) (data not shown). This shows that, in most instances, wheat irrigation would be profitable regardless of the irrigation sequence or total amount of water applied. However, a wide range of NRha's were obtained for any given total water application, particularly between 150 to 400 mm total irrigation (Figure 4). Thus, for any given total water application within this range, timing of irrigation had a significant impact on yield and consequently also on profit. This would be expected, and has been observed in wheat irrigation experiments conducted in Zimbabwe (MacRobert & Savage, 1991).

On each soil type, those treatments that were established and then given no further irrigation were the worst treatments in terms of NRha or NRmm. However, referring to Figure 2, the model tended to underpredict yields in the very low yield range, and this may partly explain the poor performance of those treatments. Treatments which were irrigated beyond establishment, but which had irrigations terminated before grain-filling, also performed poorly, but both NRha and NRmm improved as the timing of the last irrigation approached the early grain-fill stage. Thus, in most cases, for a given quantity of water, it was better to schedule a deficit regime from emergence through to maturity than to initiate a frequent regime and then terminate irrigations prior to grain-filling.

One of the worst treatments on the GLEN and KUTS soils in terms of a low NRmm for a relatively high total water application of 320 mm was one in which a 50 d return period was imposed between 25 and 75 d after sowing (das) followed by five irrigations of 50 mm at 10 d intervals. An analysis of similar treatments with differing return periods at this stage indicated that a return period of greater than 25 d after the 25 das irrigation made a large detrimental impact on yield and consequently also on NRha and NRmm.

Finally, before progressing to the optimal irrigation regimes, low positive NRha's and NRmm's were achieved with as little as 150 to 175 mm applied water. On the ART soil, these were typified by establishment irrigations of 60 mm, followed by 30 mm irrigations at 20, 65 and 80 das, or establishment irrigations of 50 mm, followed by 25 mm irrigations at 20, 50 65 and 80 das. On the GLEN and KUTS soils, low NRha's were achieved with 50 mm at establishment, followed by 25 mm irrigations on a 20 d return period through to 105 das.

The scatter of points from treatments on the GLEN soil that achieved an NRha >$ 1 000 and an NRmm >$ 3.00 are shown (Figure 5).

Those treatments joined by a solid line represent the Pareto optimal curve, and any treatment on this curve represents a feasible, non-inferior irrigation regi whereby NRha cannot be improved without decreasing NRmm. On all three soil types, the aims of maximizing net returns per unit of applied water per unit area and of maximizing net returns per unit area tended to be antagonistic. The circled point to the upper right of the Pareto curve in Figure 5 represents the irrigation treatment that would maximize both NRha and NRmm, and therefore represents desirable technology, which, under the circumstances of this exercise, was not obtained.

Of the 304 treatments simulated, only seven made up the Pareto optimal curve at GLEN. At ART, five points composed the Pareto optimal curve, while at KUTS, only four points made up the Pareto opti curve (Figure 6). This indicates the critical nature of irrigation timing in determining profits from wheat production, and emphasizes the necessity of establishing a scheduling system to assist farmers in sequencing irrigations, particularly deficit irrigation regimes.

The potential profits from wheat irrigation were higher on the ART soil than the GLEN and KUTS soils, and this may have been due to the different sets of weather data used. ART was cooler than Wooler Farm in 1990, and this reduced potential evaporation rates and favoured longer crop growth. Such differences in wheat yield potential between sites of high and low altitude have been observed previously in Zimbabwe (Cackett & Wall, 1971).

The seasonal soil water depletion patterns of the two treatments on the GLEN Pareto optimal curve that the highest NRmm are shown (Figure 7), illustrating

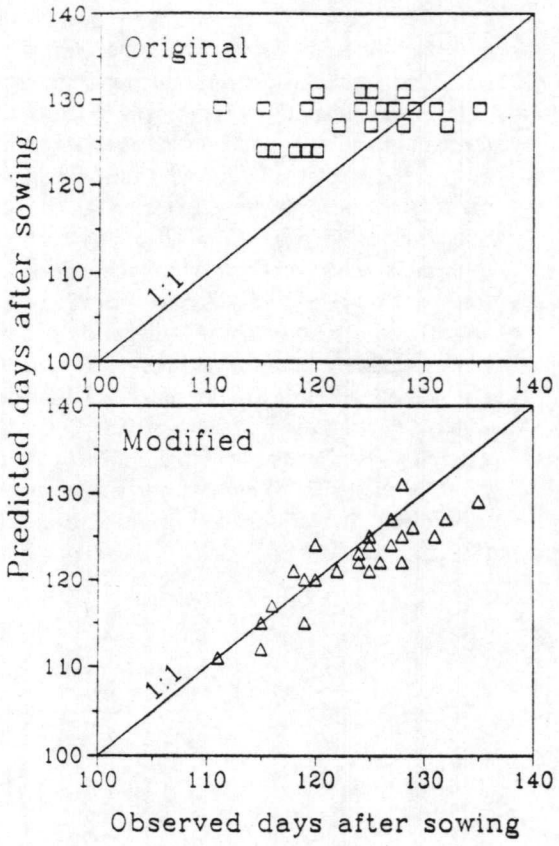


Figure 1 The comparison of predicted and observed days from germination to physiological maturity of wheat for the original and modified CERES-Wheat model.

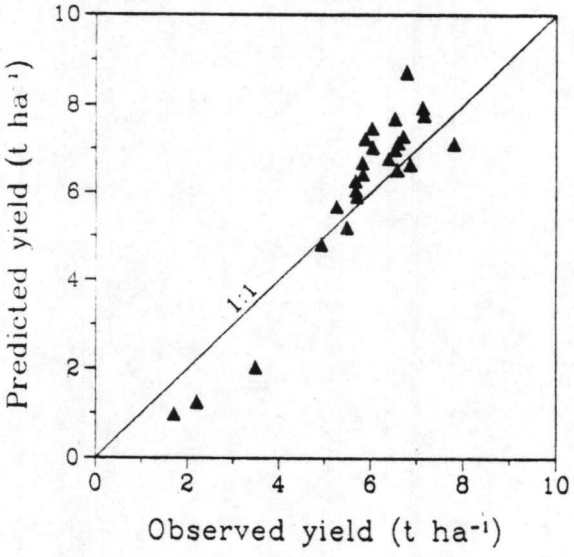


Figure 2 The comparison of simulated and observed grain yields of wheat using a modified CERES-Wheat model as specified in the text.

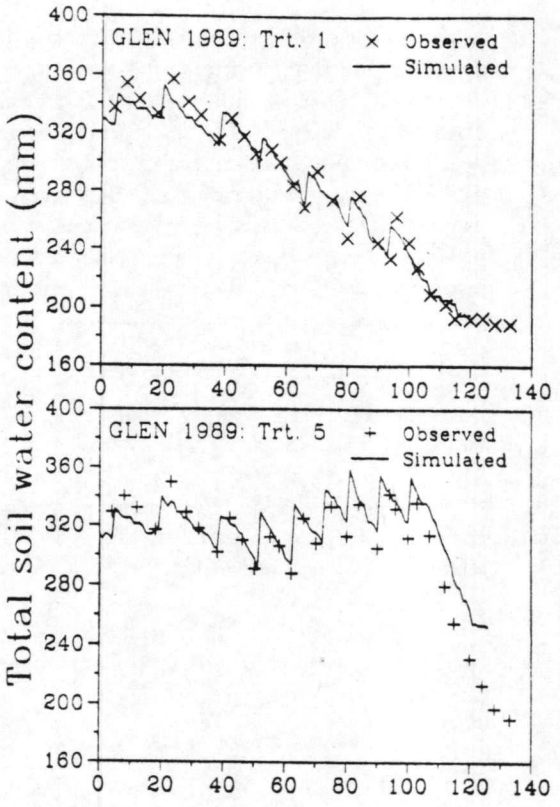


Figure 3 The comparison of simulated and observed total soil water contents (summed over a profile depth of 1.38 m) using a modified CERES-Wheat model.

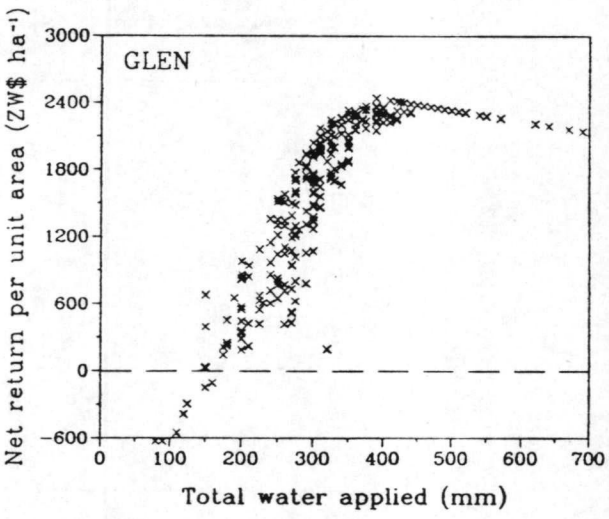


Figure 4 Simulated net returns per unit area of wheat as a function of total irrigation water applied on the GLEN soil.

some problems associated with such a simulation exercise.

The treatment that achieved the highest NRmm was one which received its first irrigation after establishment at 45 das. On the face of it, this appears acceptable. However, results from irrigation timing

trials on wheat by MacRobert (1989) showed that such a delay in the first irrigation after establishment had a detrimental effect on tiller production and yield. The same set of trials indicated that an irrigation at 28 das was beneficial over a range of total water applications. This apparent inability of CERES-Wheat to account for this effect of a delayed irrigation after emergence needs to be investigated further, and appears to be primarily associated with tillering and early root development.

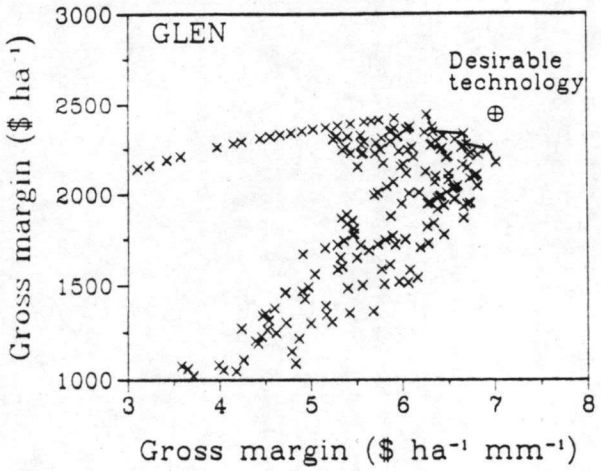


Figure 5 Scatter diagram of irrigation treatments on the GLEN soil that achieved net returns > ZW$ 1 000.00 ha^{-1} and > ZW$ 3.00 ha^{-1} mm^{-1}. Also shown, as the solid line joining points on the upper right of the scatter, is the Pareto Optimal Curve.

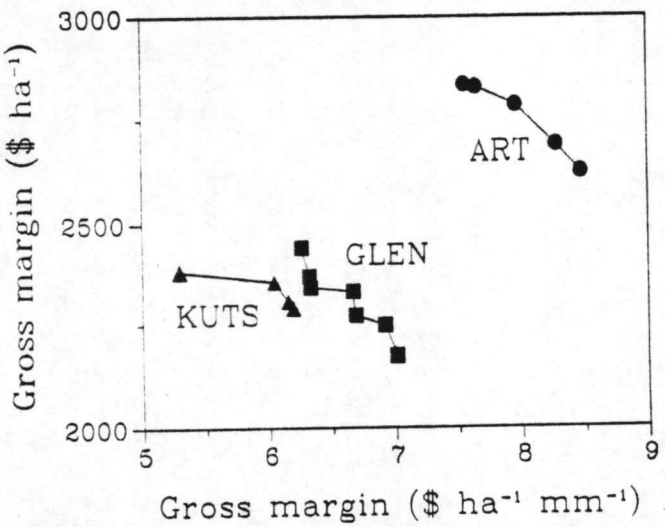


Figure 6 Pareto optimal curves for the ART, GLEN and KUTS soils.

The treatment with the second highest NRmm had an irrigation at 25 das, but thereafter, prior to each irrigation, the plant extractable soil water was depleted by nearly 80% (Figure 7). This appears to be a somewhat risky situation, in that in the event of an irrigation pump break down, particularly if it occurred early in the season, soil water levels would rapidly reach critically low levels, and yields would be drastically affected. Perhaps a better deficit irrigation treatment would be the one illustrated in Figure 8.

In this regime, the soil water is gradually depleted through the season, and only reaches a very low level of plant extractable soil water near maturity. This particular treatment was characterized by a 25 mm irrigation at 25 das, followed by five irrigations of 50 mm spaced at 16d intervals. This particular treatment was not on the Pareto optimal curve but was close to it. The soil water depletion pattern of the treatment that produced the highest NRha at GLEN is also shown (Figure 8). For most of the season, soil water depletion did not exceed 50% of the total plant extractable soil water, which conforms to the concept of 50% allowable root zone water depletion used for scheduling irrigations for near maximum yield (Stegman *et al.*, 1983).

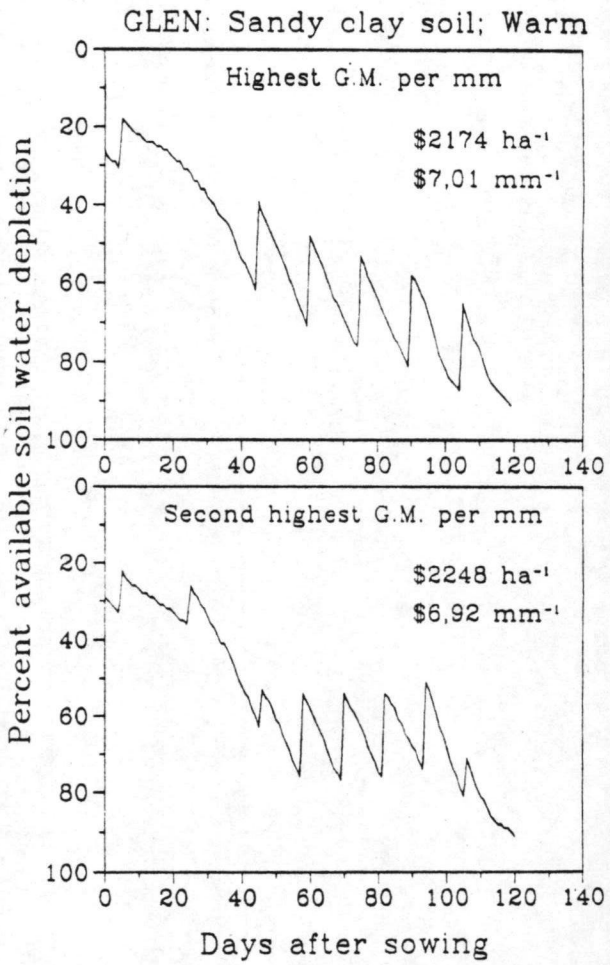


Figure 7 Seasonal soil water depletion patterns of the two treatments on the GLEN soil that achieved the highest net returns per unit area per unit water applied.

In comparing the potential profits from two treatments in Figure 8, the deficit irrigated treatment can achieve a total profit substantially in excess of the high NRha treatment, if one considers the total areas that could be produced from a given supply of water.

The soil water depletion patterns for the highest NRmm treatments on the ART and KUTS soils are illustrated in Figure 9.

The ART soil required less irrigation to achieve maximum NRmm than the KUTS soil, and of the three sites, KUTS gave the lowest maximum NRmm. Similarly, the KUTS soil required a greater total irrigation amount than the other soils for the maximum NRha treatment (data not shown). These differences were probably due to both soil and climatic differences, for KUTS had sandier soils of lower water holding capacity than GLEN and ART, and the temperatures and potential evaporation at KUTS and GLEN were greater than at ART.

The characteristic feature of all the optimal deficit irrigation treatments was that at crop maturity, very little plant extractable soil water remained. This could pose problems to the preparation for and establishment of subsequent crops. In particular, in the absence of early summer rains, pre-irrigation may be warranted, water depletion pattern on the GLEN soil and the cost of this should perhaps be allocated to the wheat, thereby negating the apparent economic benefits of deficit irrigation. However, from discussions with farmers who are already employing deficit irrigation, it is apparent that in any case they tend to pre-irrigate or return their soils to near the upper limit of plant extractable soil water when they establish early sown summer crops. They therefore do not consider this as a cost associated with the wheat. Furthermore, some have argued that where they have a limited supply of water, the water saved by deficit irrigating wheat can be profitably applied to the early establishment of summer crops. This point is corroborated by Morris (1989), who, in a macro-economic analysis of wheat production in Zimbabwe, concluded that during times of drought both farmers and the nation as a whole are better off if water is used to establish early crops of tobacco, coton and maize rather than for wheat.

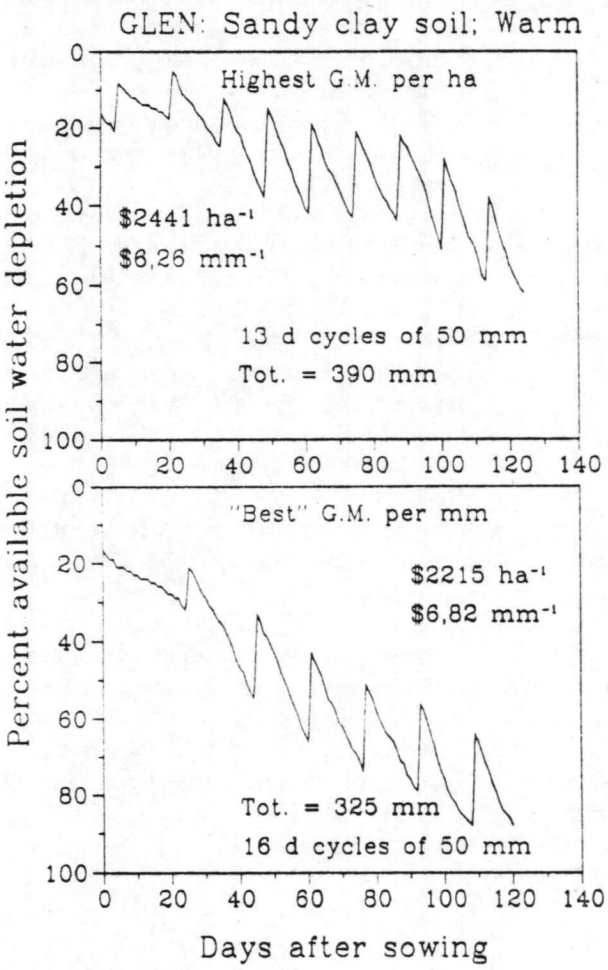


Figure 8 Seasonal soil water depletion patterns of A The irrigation treatment that achieved the highest net return per unit area, and B. The treatment considered best in terms of combining high net returns per unit area per unit water applied and an acceptable soil.

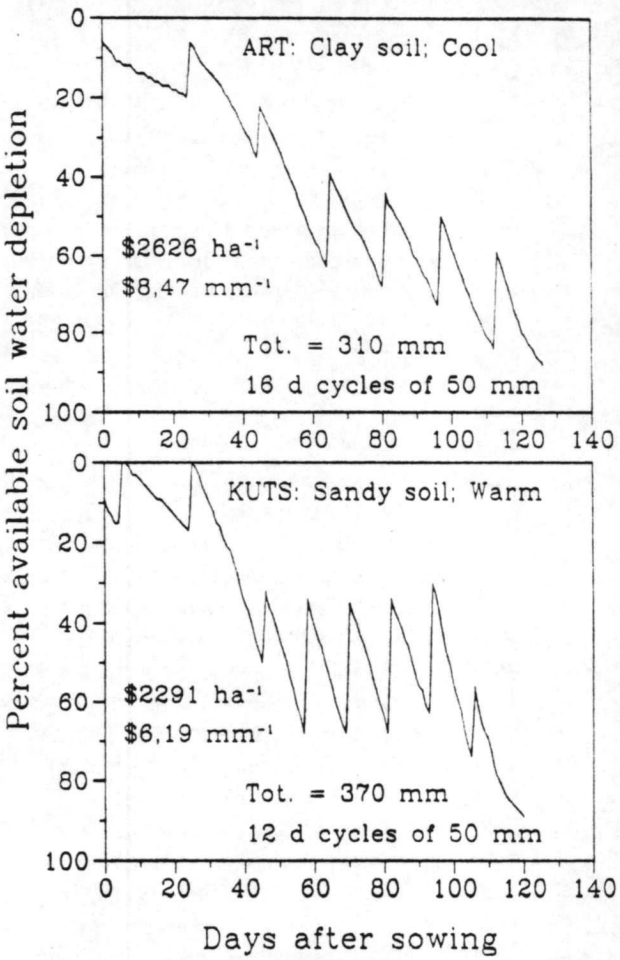


Figure 9 Seasonal soil water depletion patterns of the irrigation treatments that achieved the highest net returns per unit area per unit water applied on the ART and KUTS soils.

Morris also pointed out that if irrigation efficiencies of wheat were improved through better scheduling of irrigations, the value of irrigation applied to wheat would rise and potentially equalize the value of water applied to the early establishment of summer crops.

Conclusion

The use of the CERES-Wheat crop simulation model coupled with the Pareto multicriteria optimization technique has been shown to be a useful tool for evaluating potential optimal irrigation strategies. However, solutions determined from this technique still need to be evaluated in terms of the seasonal depletion of soil water to ensure that undue risks were not inherent in the optimal solution. Optimal deficit irrigation strategies were characterized by a gradual depletion of soil water content from establishment through to maturity, such that by maturity, little soil water remained in the profile. This technique could be further employed to evaluate real-time scheduling methods for irrigation of wheat, and to evaluate the variance of treatment yields through multi-year simulations.

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AN EVALUATION OF THE SEASONAL WATER USE OF SPRING WHEAT AS PREDICTED WITH THE BEWAB IRRIGATION MODEL

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Introduction

The main aim of irrigation scheduling models is to facilitate the decision-making process of determining when and how much water to apply during the growth cycle of a crop. In order to make scientifically based decisions, water balance modellers make use of irrigation timing criteria which differ widely in degree of sophistication, depending on the availability of quantitative information on factors such as irrigation, rain, potential evapotranspiration, ground cover, available water in the soil at field capacity, soil water content and growth developmental phases. Baird, Gallagher & Reid (1987) grouped these applied models into four categories: (1) simple input-output models, (2) potential deficit models, (3) actual deficit models, and (4) phasic models which use estimated deficits.

It is rather difficult to classify the BEWAB irrigation model into one of the described categories because it is a pre-plant instructive rather than a response model and as such, most of the mentioned factors are incorporated as historical functions. The total amount of irrigation water needed for a target yield, or the crop water demand, is calculated with an empirical water production function. The estimated irrigation demand is then apportioned over the crop growth season according to an idealized daily crop water demand function. The BEWAB crop water demand function is described in detail by Bennie, Coetzee, van Antwerpen, van Rensburg & Burger (1988).

The unique characteristics of the single line source irrigation technique developed by Hanks, Keller, Rasmussen & Wilson (1976), suited the field testing of the BEWAB model perfectly. The model-prescribed irrigation rates for a gradient of target yields and the actual irrigation rates of the line source could be synchronized by choosing appropriate distances from the line source.

The aim of this paper is to compare the predicted crop water demand of the BEWAB model with the actual evapotranspiration of wheat over a wide range of water application levels and specific target yields created under a line source experiment.

Materials and methods

The line source experiment formed part of a water-nitrogen interaction trial (Figure 1) conducted with wheat (*Triticum aestivum* L. cv. SST66), planted on a soil of the Shorrocks Series (Macvicar, De Villiers, Loxton, Verster, Lambrechts, Merryweather, Le Roux, Van Rooyen & Harmse, 1977) at Roodeplaat during the 1989 season. The actual irrigation scheduling programme was predetermined with the BEWAB model. Six water application levels were used to verify the crop-water use performance of the model.

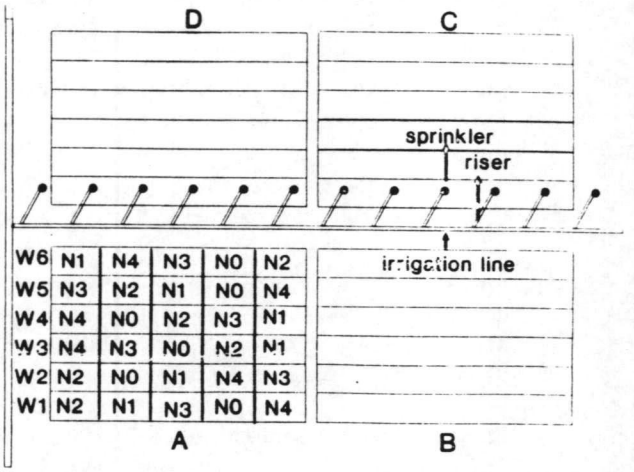


Figure 1 Experimental layout of the line source experiment at Roodeplaat. W & N refer to the water-nitrogen combination treatments respectively and B, C & D are randomized replications of A.

Line source specifications

Model 30H Rain Bird sprinklers, attached by 1.5 m high risers (20 mm in diameter) to the main aluminium supply line (50 mm in diameter), were spaced at 6 m intervals on the line. The water distribution pattern, parallel as well as perpendicular to the line, was thoroughly quantified during the previous season by measuring the amount of water applied with rain gauges placed at specific distances from the line source. The water distribution patterns at an operating pressure of 350 kPa for north and south sides of the line were described by the linear equations $Y = 113.496 - 7.1295X$ ($r^2 = 0.96$) and $Y = 109.235 - 6.42482X$ ($r^2 = 0.96$) respectively, where Y represents the water application rate expressed as a percentage of the maximum and X is the perpendicular distance (m) from the line source. The small differences between the slopes and intercepts are due to light winds (less than 3 m s^{-1}). Irrigations were interrupted when the wind exceeded the 3 m s^{-1} threshold value. These results indicate that the line source technique is suitable for differential water application provided that disturbances by high winds are avoided. In this study irrigations were applied at

night when the wind velocity was below 3 m s^{-1}.

Experimental layout

Based on the results of water distribution pattern assessment, six water treatments (numbered from W6 to W1) were selected, at distances from the line of 1.5; 4.5; 7.5; 10.5; 13.5 and 16.5m on both sides of the line, with the intention of measuring plant water use at the same locations. The N2 plots (Figure 1) were selected to verify the predicted crop water demand. Our selection was based on the conclusion of Howell (1990), who proved that nutrition does not greatly affect crop water use unless the applied fertilizer is over or under supplied. Under and over supplying nitrogen could induce significant effects on leaf area development. The nitrogen application rates of the N2 plots, selected so as to be near-optimal with respect to achieving target yields for the different water treatments, were 40, 60, 80, 100, 120 and 140 kg N ha^{-1} for the W1 to W6 treatments, respectively. The nitrogen rates so selected can be justified if the BEWAB target yields are multiplied by the reported N-concentration in irrigated wheat grain of 18 kg N Mg^{-1} grain (Du Preez & Bennie, 1992). Dimensions of the plots were 3 m x 6 m.

Plant water use measurements

The volumetric water content of the soil, divided into 300 mm layers to a depth of 1 800 mm, was measured weekly, from day 37 after planting until harvesting, with a neutron probe. The average daily crop water use or actual evapotranspiration (ET, mm day^{-1}) was calculated using Equation 1.

$$ET=(\sum_{i=1}^{n} \Theta i.Zi+R)/t \qquad (1)$$

where Θi (v v^{-1}) is the change in the volumetric water content of the soil layer (i), with a thickness (Zi, mm) over a time period (t, days). R represents the amount of rain or irrigation (mm) received during the same time period. Precautions were taken to prevent water runoff by making small basins between the 250mm plant rows.

Model in- and outputs

The production function of the BEWAB model Y=11.38X - 340, where Y represents grain yield in kg ha^{-1} and X the total seasonal water use value expressed in mm, was statistically compared against the Streutker (1983) function for Roodeplaat (Y=12.24X-612). This was done before the experiment was launched to decide whether the function had to be adjusted for the Roodeplaat situation. According to the statistical analysis (r^2=0.99 and D index=0.99; Willmott, 1982) there was no significant difference between the two production functions and hence it was left unchanged.

The only laboratory measured input parameter that the model requires (Bennie *et al.*, 1988), is the silt plus clay content of the individual soil layers (200 mm thick) of the profile. The silt plus clay content gradually increased from 42% from the top 200 mm layer to 62% at the 1 600 - 1 800 mm soil layer. The remaining model-inputs can be described as management inputs such as crop type, growing season length, target yield, reserved rain water storage in the soil profile and irrigation frequency. In the case of the 100% irrigation reference plot (W5), a target wheat grain yield of 6 300 kg ha^{-1} for a 150 day growing season and seven day irrigation frequency were selected as the management options. These choices were further combined with the irrigation option, starting and ending with a profile near field water capacity and a reserved rain storage of 30 mm. The resulting irrigation scheduling program for the W5 treatment was used to irrigate the experiment. The other water treatments received water according to the deficit water distribution pattern as described earlier. The lower limit of plant available water for the W5, calculated with the BEWAB model using the procedures of Bennie, *et al.* (1988), was 351 mm 1 800 mm^{-1}. The upper limit of plant available water determined in situ is 475 mm 1 800 mm^{-1}. This gives a plant available water capacity of 124 mm to a soil depth of 1 800 mm.

Agronomic practices

Prior to planting, the soil water content of the experimental site was raised to field capacity with a commercially designed sprinkler irrigation system. All the plots received a basic fertilizer dressing of 50 kg P ha^{-1} as monosuperphosphate (10.5% P) before planting. Nitrogen was applied in the form of limestone ammonium nitrate (27% N) according to the mentioned rates on day 38 after planting. The surface applied nitrogen was washed into the soil immediately after application using a 20 mm irrigation. From planting to day 38 the crop received a total of 43 mm of irrigation water and 2 mm of rain. Differentiated water treatments were initiated on day 50 after planting. Grain yields were determined by harvesting the plants in an area of 2 m^2.

Statistical evaluation of the model

The statistical comparisons of measured and model predicted data were based on the procedure described by Willmott (1982), who suggested that the index of agreement (D index) is a better measure of model performance than the well known coefficient of determination (r^2). The D index was calculated with the aid of a computer program supplied by J. Booysen (Dept. of Plant Science, Potchefstroom University for CHE, pers. comm., 1991).

Results and discussion

For the purpose of the discussion the growing season

was divided into four periods (Table 1). From planting to day 37 represented the plant establishment period during which all treatments were the same.

The nitrogen applications were given on day 38 after planting and differential water applications started on day 50. During the plant establishment period, the volumetric soil water content was measured on an *ad hoc* basis because no treatments were being applied.

Thereafter, the volumetric water content was measured weekly until harvesting. The mean total profile soil water content, rainfall, irrigation and calculated mean daily water use values for all the irrigation treatments are given in Table 2.

Grain yield - water use relationship

The reference treatment (W5) received a mean total

Table 1 Summary of the cumulative rain, irrigation and total evapotranspiration values for different experimental periods (each value representing the mean of 4 replicates) and the grain yield and water use efficiency (WUE).

Parameters		Experimental periods (days after planting)				Grain yield	WUE
		Period 1 (0 - 37)	Period 2 (38 - 49)	Period 3 (50 - 140)	Period 4 (0 - 140)	kg ha^{-1}	kg ha^{-1} mm^{-1}
Rain (mm)		2	-	**121,5	123,5		
Irrigation:	W6	42,3	-	470,6	512,9		
(mm)	W5	42,3	-	407,7	450,0		
	W4	42,3	-	311,6	353,9		
	W3	42,3	-	238,8	281,1		
	W2	42,3	-	102,5	144,8		
	W1	42,3	-	7,7	50,0		
Cumulative							
Evapotranspiration	W6	29*	14(±6)	576(±13)	620(±16)	7089(±733)	11,43
(mm)	W5	29*	14(±5)	530(±27)	572(±27)	7013(±788)	12,26
	W4	29*	12(±3)	451(±29)	491(±29)	5838(±1236)	11,86
	W3	29*	18(±4)	394(±37)	442(±40)	4804(±822)	10,85
	W2	29*	18(±9)	244(±34)	291(±41)	3636(±1084)	12,49
	W1	29*	18(±7)	158(±37)	204(±44)	2056(±664)	10,08

* The mean of 60 observations
** 75 mm rain that fell after maturing was excluded in the calculation of water use for the W2 and W1 treatment.

Table 2 Water balance data for all water application treatments representing the average and standard deviation of four replicates.

	Days after planting															
	37	42	49	56	63	70	77	84	91	98	105	112	119	126	133	140
Rain (mm)	0	0	0	0	5.0	0	0	0	0	0	0	0	16.5	18.0	7.0	**75.0
W6: Total average soil water content*	472	467	458	468	451	453	449	455	451	455	456	461	451	444	438	473
S.D	23	22	21	20	18	18	17	17	14	21	18	20	18	17	24	25
Irrigation (mm)	20.3	0	0	44.0	11.9	40.7	35.9	45.3	41.8	50.3	41.1	61.7	39.7	25.0	33.2	0
Average daily water use (mm day^{-1})		1.0	1.3	4.9	4.9	5.5	5.7	5.6	6.6	6.6	5.7	8.2	9.4	7.2	6.5	4.3
S.D.		0.6	0.6	0.4	0.4	0.6	0.2	0.4	0.6	1.1	0.5	0.5	0.6	0.5	2.0	1.3
W5: Total average soil water content*	462	460	449	456	439	438	431	433	427	426	425	433	418	412	402	439
S.D	23	26	27	27	30	29	30	29	31	30	31	26	29	29	38	36
Irrigation (mm)	20.3	0	0	39	10.4	34.3	29.9	43.3	39.4	41.6	39	51.4	32.5	19.5	27.4	0
Average daily water use (mm day^{-1})		0.3	1.7	4.6	4.6	5.0	5.3	6	6.5	6	5.8	6.2	9.2	6.1	6.3	4.3
S.D.		0.6	0.5	0.2	0.6	0.8	0.5	0.4	0.5	0.5	0.8	0.9	5.0	0.4	1.6	3.0
W4: Total average soil water content*	475	473	462	462	443	434	425	421	411	411	408	410	401	403	400	445
S.D	37	36	35	36	37	37	40	40	44	46	53	54	57	59	67	65
Irrigation (mm)		20.3	0	31	8.3	30.3	24.2	27.7	32.2	31.9	32.4	36.4	24.7	14	18.5	0
Average daily water use (mm day^{-1})		0.5	1.5	4.4	4.6	5.7	4.7	4.6	6.0	4.6	5.2	4.8	7.3	4.3	4.0	4.3
S.D.		0.4	0.7	0.4	0.3	0.3	0.6	0.7	0.8	0.3	1.1	0.2	0.5	0.5	1.1	0.7
W3: Total average soil water content*	461	455	443	437	416	405	390	376	362	355	356	359	346	350	348	408
S.D	50	50	53	56	57	62	64	65	68	73	81	83	83	84	87	89
Irrigation (mm)	20.3	0	0	22.0	6.6	23.0	20.3	17.0	23.8	24.5	25.5	28.8	20.8	12.0	14.5	0
Average daily water use (mm day^{-1})		1.1	1.8	3.9	4.8	4.8	5.0	4.4	5.4	4.5	3.6	3.7	7.1	3.7	3.4	2.1
S.D.		0.4	0.6	0.6	0.6	0.7	0.4	0.3	0.6	0.8	1.3	0.5	0.3	0.6	0.7	0.5
W2: Total average soil water content*	466	458	445	435	414	402	387	373	357	353	353	353	346	349	350	-
S.D	31	39	39	40	40	44	48	52	55	61	65	68	68	70	72	-
Irrigation (mm)	20.3	0	0	11.0	4.9	12.5	10.8	5.1	7.8	12.3	6.0	11.0	9.8	5.9	5.4	-
Average daily water use (mm day^{-1})		1.7	1.9	2.9	4.5	3.4	3.7	2.7	3.4	2.4	.9	1.5	4.8	2.9	1.7	-
S.D.		1.6	0.3	0.4	0.6	0.6	0.6	0.6	0.6	1.0	0.6	0.7	0.3	0.7	0.3	-
W1: Total average soil water content*	470	464	449	434	413	398	382	370	358	353	353	348	342	347	346	-
S.D	35	39	43	43	45	50	54	58	62	66	73	72	72	71	75	-
Irrigation (mm)	20.3	0	0	1.0	0.7	0	0.4	0.7	0.4	1.4	0	1.3	0.8	1.0	0	-
Average daily water use (mm day^{-1})		1.2	2.1	2.3	3.9	2.1	2.4	1.7	1.8	1.0	0	0.8	3.4	1.9	1.3	-
S.D.		0.7	0.9	0.6	0.6	1.2	0.6	0.5	0.7	0.6	1.0	0.3	0.6	0.4	1.5	-

* The total soil water content was calulated to a maximum depth of 1800 mm
S.D. = standard deviation

amount of rainfall plus irrigation water of 574 mm (period 4 in Table 1), which is 9.8% lower than the W6 plot. The other plots (W4 to W1) received respectively 17, 30, 53 and 70% less water than the reference treatment W5. The mean total seasonal ET and the corresponding grain yield for the different irrigation treatments are listed in Table 1.

The BEWAB water production function was compared with the experimentally obtained water use - grain yield values on a statistical basis (Figure 2). These results (r^2 = 0.98 and D index = 0.99) indicated that all the water treatments gave yields which corresponded well with the expected yields, with the W2 and W5 treatments slightly above the BEWAB +10% variation line. According to Howell (1990) a water production function is not unique for a given situation and could be influenced by several production factors other than water supply, such as soil and water salinity, physical and chemical properties of the soil, and agronomic practices including soil tillage, plant nutrition, planting date etc. Seen in the light of this background, the mentioned factors are not likely to have been limiting, since most of the actual yields were higher than the expected yields. The experimentally obtained water use efficiency of 12.4 kg ha^{-1} grain yield per mm evapotranspiration for the reference plot compared fairly well with reported values varying between 10 and 12 kg ha^{-1} mm^{-1} obtained with spring wheat trials in other parts of the world (Shimshi & Kafkafi, 1978; Cooper, 1980; Aggerwal, Singh, Chaturvedi & Sinha, 1986).

The grain yield-water use production function being used in the BEWAB model therefore seemed to be valid for this experiment.

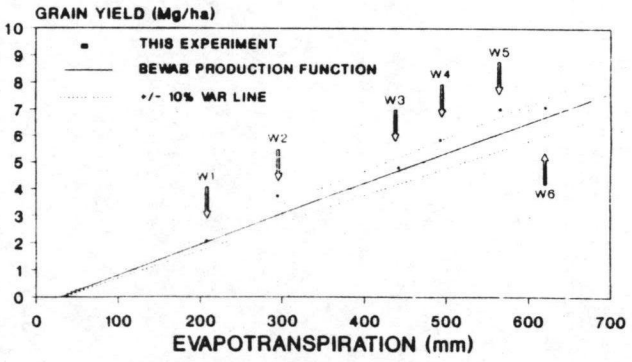


Figure 2 Grain yield (Mg ha^{-1}) as a function of evapotranspiration for the present data as well as the BEWAB water production function.

Comparison of the seasonal water use distribution with the model predicted consumptive use

The cumulative seasonal rainfall, irrigation and ET values for the different experimental periods and treatments are summarized in Table 1. During the plant establishment period all the treatments received a total of 44.3 mm water consisting of 2 mm rain and 42.3 mm irrigation. The average ET for all the treatments and replications (n = 60) over the first 37 days was 0.78 mm day^{-1} with a standard deviation of 0.3 mm day^{-1}. Some unexpected crop water use measurements were obtained during the second period, lasting from day 38 to 49. Although the nitrogen application rates of the W6, W5 and W4 plots, prior to application of differential water treatments, were higher than the W3, W2 and W1 plots, the average ET value of the W6 to W4 plots was 0.4 mm day^{-1} lower than the average of the W3 to W1 plots. No explanation can be given for this phenomenon because it would be expected that higher nitrogen application rates would result in more rapid growth and hence higher water use. The total water use during the third period that lasted from day 50 until harvesting showed a sharp decline from treatments W6 to W1. This reflected the effect of the differential irrigation treatments on the evapotranspiration.

Since treatment W5 was used as an irrigation reference plot, the weekly measured ET values of this treatment could be used to verify the predicted weekly crop water demand of the model. The corresponding cumulative measured and predicted weekly ET values were plotted in Figure 3 (W5) and the statistical comparison of the data based on the procedure describe by Willmott (1982), are presented in Table 3. It is clear from Figure 3 that all the predicted values, except those between days 42 and 49 after planting which were just above the +10% variation line, match the 1:1 line very well. This general good agreement between the observed and predicted crop water use values was confirmed with the high index of agreement (D index of 0.94) obtained from a statistical analysis of the weekly crop water use values. Additionally, the effectiveness of choosing the BEWAB irrigation option of starting and ending the season with a profile at field capacity, is confirmed by the seasonal soil water depletion curve of the W5 profile (Figure 4). The W5 curve shows that the soil water content was close to field capacity at the beginning of the season, whereafter it gradually declined below the predetermined 30 mm storage capacity level for rain. By the end of the season rain had effectively refilled the profile to the 30 mm storage capacity value, thus demonstrating the effectiveness of the irrigation scheduling mode of beginning and ending the season with a wet profile while avoiding plant water stress and permitting efficient use of rainfall.

The good agreement obtained between predicted and observed water use for treatment W5 encourage similar comparisons for the other treatments (W6 and W4 to W1) to verify the predicted crop water demand of the model over a wide range of water application levels. The intention with the experimental layout was that the W6 water treatment would represent an experimental maximum, W4 a sub-optimum and W3 to W1 deficit irrigation regimes. Whereas the target

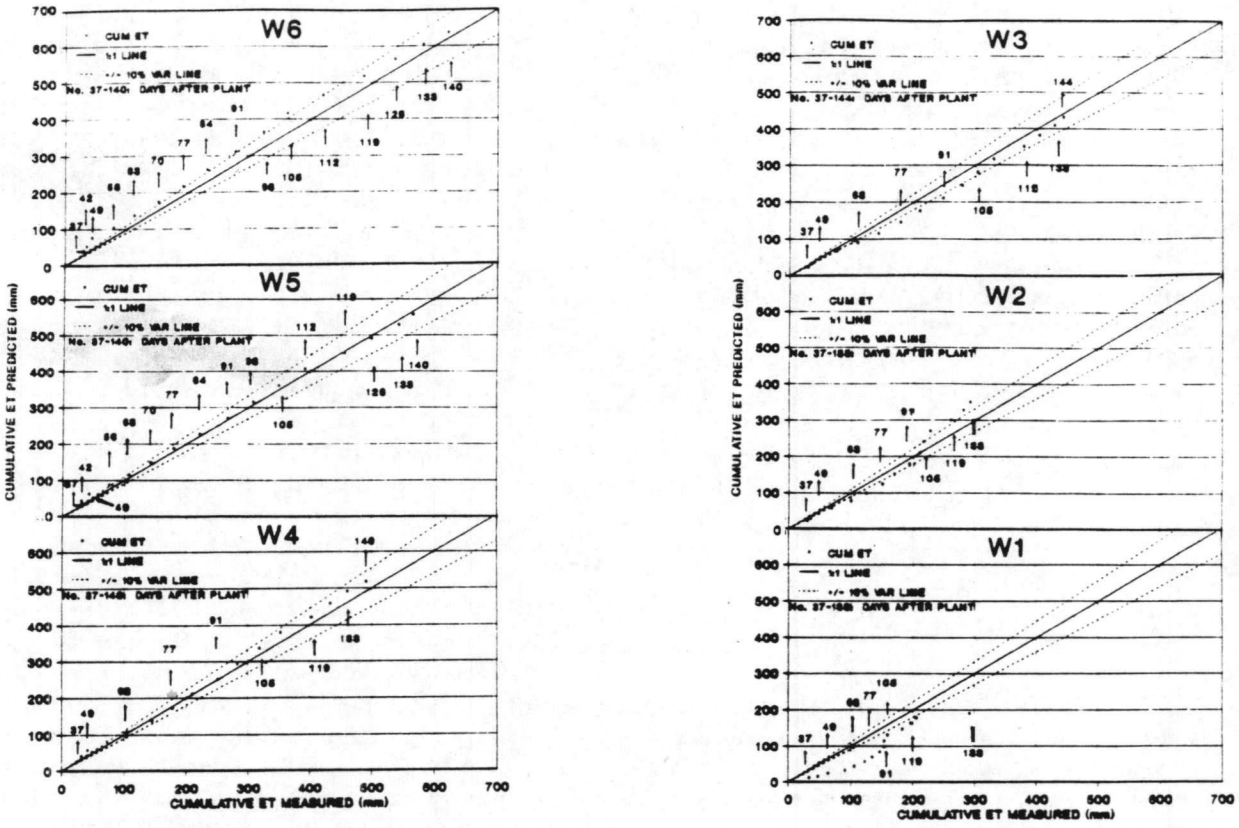


Figure 3 Comparison between the actual cumulative seasonal evapotranspiration (ET) values and those predicted with the model for the deficit irrigation regimes W6 to W1 for different days of planting.

yield of the W5 treatment had been predetermined, the actual recorded mean grain yields for the other treatments were taken as target yields for use as inputs into the BEWAB model in order to predict the weekly crop water demand (Table 4). The results for the maximum yield treatment (W6, in Figure 3) indicated that the model slightly over-predicted the water use over the period 40 to 80 days after planting. However, the high D index value (0.91) proved that the over prediction was not very serious.

The relationship between the predicted and measured cumulative crop water use for the sub-optimum water treatment (W4) is shown in Figure 3. The statistical analysis indicated a good relationship between the measured and predicted cumulative ET. Approximately 40% of the predicted plant available water of 124 mm 1 800 mm^{-1} was never exploited (curve W4, Figure 4). This illustrates the principle of partial deficit irrigation and that, given an initially full soil profile and irrigation application rate through the season which allows a mid-season soil water deficit to develop but nevertheless returns the profile to near the upper limit by the end of the season, water use will take place freely and no drastic yield reduction can be expected.

Because of the unrestricted water use from an initially full profile, it is also logical that BEWAB, by

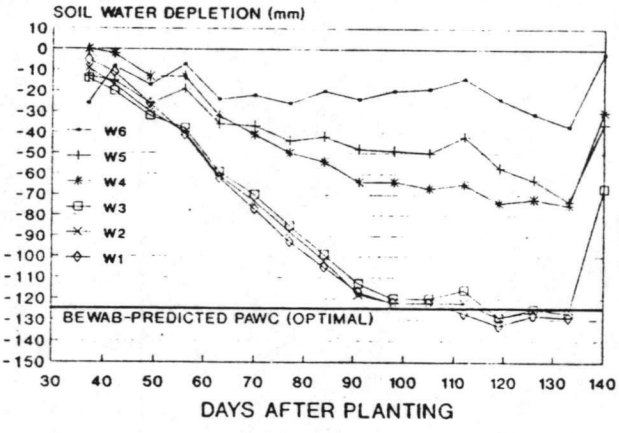


Figure 4 Profile soil water depletion for the different irrigation treatments.

virtue of its assumptions that reduced water use is proportionally distributed through the season, will severely under-predict initial ET rates for treatments which have largely reduced target yields. This can by seen for treatment W3 in Figure 3. From Figure 3 it is evident that the under-prediction was more prominent between days 63 to 91, but the high D index

value supports the conclusion that the model could still be useful as an irrigation tool under these conditions. The amount of water that was applied after day 100, when the profile available water was depleted (Figure 4), was probably sufficient to prevent harmful plant water stress. The plants managed to extract approximately 103% of the model predicted profile available water capacity. This is a good example of deficit irrigation.

Considerably lower D index values (Table 3) for comparisons between the measured and predicted crop water use values for the W2 and W1 treatments were obtained. In fact according to the D-index values of these treatments, there was no relationship between the measured and predicted weekly crop water use values. The reason for the weak performance of the model, could mainly be attributed to the fact that the soil water depletion of the profile approached the lower limit of plant available water on day 100 (Figure 4) and the applied irrigation water was insufficient to prevent plant water stress. According to the W3 to W1 depletion curves in Figure 4, the experimental lower limit of plant available water was 130 mm per 1 800 mm for these treatments, which is only slightly higher than the model predicted PAWC of 124 mm for the optimum W5 plot. When comparing the weekly ET rates of the deficit treatments W2 and W1 with those of W5 in Table 1 it is clear from the lower ET of the W2 and W1 treatments that plant water stress had occurred from day 70 and that it increased gradually towards day 112. The ET rates for the period between 112 to 119 days after planting indicates that the rain temporarily relieved the plant water stress to some extent.

Table 3 Statistical comparison of the weekly measured and predicted evapotranspiration values.

Water treatment	Statistical parameters					
	n	r^2	a	b	RMSE	D-index
W6: All data	15	0,71	15,06	0,629	6,1	0,91
W5: All data	15	0,86	8,98	0,751	3,9	0,96
W4: All data	15	0,66	12,36	0,632	5,5	0,89
W3: All data	15	0,47	12,88	0,521	5,8	0,79
W2 All data	14	0,02	21,50	0,109	6,8	0,19
W1 All data	14	0,04	14,26	-0,110	3,8	0,27

a = intercept; b = slope; RMSE = root mean square error

The second factor which added to the weak performance of the model under conditions of under irrigation, resulting in severe plant water stress is the fact that it does not consider enhanced maturity and thus the shorter length of the crop growing season, induced by plant water stress. At day 130 the wheat of the W1 treatment was already in the early ripening stage, stage 90 according to the Tottman & Broad (1987) scale, while the W6 treatment was still in the soft dough stage (stage 85). This phenomenon showed that the deficit irrigation decreased the length of the crop growing season from 150 days for the optimal W5 treatment to 135 days for these W2 and W1 treatments. Irrespective of these factors the water use efficiency for both treatments were still high and comparable with the other treatments (Table 2).

It is clear from these results that the BEWAB model

Table 4 Weekly crop water demand values as predicted with the BEWAB-model for W1 to W6 and the corresponding mean measured evapotranspiration values (mm).

Days after planting	Water treatment											
	W1		W2		W3		W4		W5		W6	
	P	M	P	M	P	M	P	M	P	M	P	M
42	4	6	8	8,5	9	5,5	11	2,5	11	1,4	13	5,2
49	7	14,5	13	13,3	15	12,3	18	10,5	19	11,7	23	9,1
56	9	16,0	16	20,3	19	27,5	22	30,8	24	37,1	28	39,1
63	10	27,2	19	31,4	22	33,4	27	32,2	29	32,2	33	34,1
70	12	15,0	22	24,0	26	33,5	31	39,9	33	34,8	38	38,3
77	13	16,7	25	26,1	29	35,3	35	32,9	37	36,9	42	39,9
84	15	12,0	27	18,9	31	31,1	38	32,2	41	42,0	46	39,2
91	16	12,4	29	24,1	34	37,8	40	42,0	43	45,5	49	46,1
98	16	6,9	30	16,6	35	31,3	42	32,2	45	42,0	52	46,2
105	17	0,3	31	6,3	36	25,3	43	36,4	46	40,3	52	39,6
112	17	5,6	30	10,5	36	25,8	43	33,6	46	59,0	52	74,0
119	16	23,8	29	33,8	34	49,8	41	51,1	44	64,1	50	65,0
126	15	13,5	27	20,4	32	25,8	38	30,1	41	42,9	46	50,1
133	13	8,8	24	11,7	28	23,8	33	28,0	36	43,9	41	55,5
140	10	-	19	-	22	14,8	26	30,1	29	30,0	33	30,0

P = predicted

M = measured

is a useful approach to irrigation scheduling of wheat under conditions where the target yield exceeds 4 000 kg ha^{-1}.

Conclusions

From the data available it can be concluded that the model responded reasonably well under maximum, optimum and sub-optimum irrigation regimes. At water application rates lower than 65% of those required to obtain optimum yields the BEWAB model requires a subroutine that reduces the length of the expected growing season accordingly. The BEWAB model can thus be recommended when aiming at yields higher than 4 000 kg ha^{-1}. Relative high water use efficiency values, varying between 10.08 and 12.49 kg ha^{-1} mm^{-1} were obtained over a range of grain yields varying between 2 000 and 7 000 kg ha^{-1}.

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CROP WATER STRESS ASSESSMENT FOR IRRIGATION MANAGEMENT

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Irrigations are given to optimize crop production and maximize net income. There are two concerns facing every grower regarding irrigation: when and how much to apply. When water is plentiful there is a low level of anxiety in determining when is the best time to irrigate and how much to apply. Under these conditions, the main concerns are the possibility of leaching fertilizers from waterlogging of the root zone. Where water is scarce, the concerns are quite different. One must apply only enough water (because it is usually costly) at the appropriate time to maintain adequate crop growth and productivity. This report will address the "when" question.

Of all the methods used for scheduling irrigations, the one gaining much attention utilizes the crop as an indicator of plant health. This is because it is the plant we are most interested in and it integrates its total environment, soil and atmosphere. Two such techniques have been developed for scheduling irrigations on farms and will be discussed in this report. Hsaio (1990) reviewed direct and indirect plant stress measurement techniques for irrigation scheduling purposes. In addition to describing the practical aspects of using a variety of instruments for assessing plant water status, he examined the principles involved in the measurements. His report should be required reading for all who wish to use plant measurements for scheduling irrigations.

The pressure chamber technique (Scholander *et al.*, 1965) has been used successfully for scheduling irrigations. Comprehensive studies on cotton (Grimes *et al.*, 1978, 1987), grapes (Grimes & Williams, 1990) and alfalfa (Grimes & Roberts, 1991) have demonstrated that midday plant pressure potential measurements can be used with confidence to determine when to irrigate to maintain high productivity. Their work with grapes also demonstrated that infrared thermometry gave comparable results to those of the pressure chamber.

There is a continuing dialogue in the literature as to what time of day is best for monitoring water potential in plants using the pressure chamber technique. Laker *et al.* (1987), using pre-dawn measurements, found that under conditions of low to moderate plant stress the procedure worked well. But under high evaporative demand conditions, the pressure chamber worked less than satisfactorily because of widely fluctuating values of leaf water potential. Under these conditions, even though there was adequate water in the root zone, plants could not keep up with the evaporative demand, and the stomates closed. These results are not unique to the pressure chamber technique. Any method which depends on a measurement of the water status of plants will suffer in a similar fashion. The concept of utilizing plant surface temperature as an indicator of plant stress was proposed by Tanner (1963) who said "...plant temperature may be a valuable qualitative index to differences in plant water regimes. "However, the technology for measuring plant temperature quickly, easily and non-destructively was not available for another decade. With the development of lightweight, handheld infrared thermometers accurate to 0.5°C, Tanner's prediction was able to be tested under field conditions.

Plant temperatures however, depend not only on available soil water, but on atmospheric conditions as well (Ehrler, 1973). Ehrler found a linear relationship between the leaf-air temperature differential and the vapour pressure deficit of the air. This finding was not explored further until the work of Idso *et al.* (1981) and Jackson *et al.* (1981). Idso *et al.* (1981), through a series of experiments on different crops grown at several locations in the United States, confirmed Ehrler's work (1973) that non-stressed plants had a unique inverse relationship between the plant-air temperature differential and the vapor pressure deficit (VPD) of the surrounding air. From these observations the concept of the crop water stress index (CWSI) was developed. The study by Idso *et al.*, (1981) is generally referred to as an empirical procedure. Using an energy balance approach, Jackson *et al.*, (1981) derived a relationship between the canopy-air temperature differential, the VPD and net radiation. They presented a theoretical basis for the CWSI, and showed that it was equal to one minus the ratio of instantaneous actual to potential evapotranspiration. For a comprehensive review of plant temperature and water stress relations, the reader is referred to Jackson (1982, 1987).

During the decade following the work of Jackson, Idso and colleagues, there have been a plethora of articles and talks on the use of the CWSI for assessing plant stress. Two of the early works using the CWSI for irrigation scheduling were by Reginato (1982) and Reginato & Howe (1985). They demonstrated that optimum yield was obtained in lint cotton w irrigations were initiated when the CWSI reached a value of 0.2.

Nielsen & Gardner (1987) scheduled irrigations for corn using the CWSI, and found that the lower the threshold value of the index, the greater was the water use and the yield. This study confirms similar results with other crops. In addition, they compared the CWSI with another method of plant stress assessment, the crop temperature variability, CTV, as proposed by Clawson & Blad (1982). CTV is defined as the

maximum temperature minus the minimum temperature from replicated measurements of canopy temperature. The CTV did not perform as well as the CWSI in this test. As in other studies, there was an observation that there could be nonstressed baseline shifts in slope and intercept throughout the growing season due to differences in growth stages or plant cover. This issue requires further study.

To schedule cotton irrigations using canopy temperature, Wanjura *et al.* (1990b), demonstrated that the Thermal Stress Index (TSI) was a good indicator of plant stress. TSI is defined as the difference between the measured foliage temperatures and a baseline temperature, this quantity divided by the baseline temperature (27.5C for cotton). Their results showed that the higher the canopy temperature was at irrigation, the lower the lint yield and the lower the fibre strength. Plant height, total biomass and leaf area index were generally proportional to the amount of water applied, which was also correlated to the canopy temperature at irrigation. The threshold canopy temperature may provide an early warning of plant stress which could offer the means to trigger automatic watering systems.

There are many cautions which need to be heeded when using infrared thermometers for scheduling irrigations. First, it must be remembered that anything that interferes with the potential transpiration of a plant will be manifested in an increase in plant temperature. Extremely high evaporative conditions, plant disease, insects, salinity and other such situations may all cause a decrease in transpiration, and have nothing at all to do with the plant needing water.

The effect of clouds on plant temperature was demonstrated by Cselotei & Helyes (1987). They showed that snap bean leaf temperatures would change 5-10°C within 2 minutes after a cloud passed the field of observation. In addition, they found that well watered beans were equal to or slightly less than air temperature, but that stressed beans were warmer than air. These data are difficult to interpret without knowing the meteorological conditions at the times of measurement.

Recent studies, such as one by Hutmacher *et al.* (1991), have shown that nonstressed baselines appear to be dependent on plant morphological stages. Their results with seed alfalfa were related to these stages: fully vegetated (few or no flowers), flowering and pod development. However, two baselines were found adequate for scheduling irrigations on seed alfalfa. They also found that plant temperature provides an earlier assessment of plant stress than leaf conductance.

The idea of using space-based systems to provide information for scheduling irrigations has a great deal of appeal because of the area covered by the observations. Hope & Jackson (1989) investigated several crop water indices, and concluded that the most desirable index would compare canopy temperatures of a field of concern to that which was known to be well watered. Indices utilizing canopy temperature and ground-based meteorological parameters were not easily adapted to a space-based system. However, other studies (Idso *et al.* 1990) demonstrated that this argument needs further investigation. They showed that the development of nonstressed baselines could accommodate ground-based meteorological data which were not in close proximity to the fields of interest, if general air mass conditions were similar for both sites.

In addition to utilizing the CWSI for scheduling irrigations, Wanjura *et al.* (1990a) reported on the relationships between this index and yields of cotton and grain sorghum: that crop productivity decreased with increasing CWSI. They demonstrated that if a cotton crop experiences a completely stressed condition during part of each day between the period from first bloom through first boll maturity, the yield would only be 40% of that from a completely non-stressed cotton crop. Also, they showed that the absolute slopes of nonstressed baselines of cotton generally increased until canopy cover reached 70%. They suggested that the slope increases were due to uncertainties in the estimation of r_a and r_{cp}, which are the aerodynamic and canopy resistances, respectively.

Linking enzyme kinetics to plant temperature provides a novel technique to describe plant stress, and possibly to schedule irrigations. Burke *et al.* (1990), reported that a thermal stress index (TSI) could be described by the thermal kinetic window (the temperature range over which the value of the apparent Michaelis constant of enzymes remains within 200% of the minimum observed value). The results of their study demonstrated that the TSI was well correlated with the CWSI ($r^2=0.92$), the advantage being that only measurements of crop temperature are required for the TSI.

There is still much to do using canopy temperature for scheduling irrigations. The empirical approach by Idso *et al.* (1981), although simple to evaluate and use, is not adequate except where the VPD exceeds 2 kPa. This means that under more humid conditions their technique is not sensitive enough to plant stress. The theoretical approach by Jackson *et al.* (1981) provides the tools necessary to use the technique under essentially all meteorological conditions. However, it requires values of canopy and aerodynamic resistances and net radiation for the calculation of CWSI, the former being difficult to assess and the latter rather easy to obtain. This problem was addressed by Jackson (1987) and paves the way for utilizing infrared thermometry in a routine fashion for scheduling irrigations. The advantage of infrared thermometry is that it can be used on experimental plots or grower's fields using hand-held instruments. The technique is rapid, and results can now be obtained in real-time with the incorporation of microprocessors into small, light-weight infrared thermometers.

Additionally, infrared scanners can be mounted in aircraft to evaluate canopy temperatures, accounting for over large areas in relatively short times. Coupling these measurements with ground-based meteorological data, entire farms can be evaluated for irrigation needs quickly. Spatial variability of plant stress can be determined, and scheduling irrigations based on actual plant need can be done on a field by field basis. The time is coming when much of this information will be obtained from "agricultural" satellites, and will be available to all growers. Regardless of these advancements, it will still be necessary to have the grower look at crops growing in the field. There are subtle differences that only an experienced eye can discern, and which, with present technology, cannot be detected.

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SOUND WATER MANAGEMENT CONCEPTS AND THEIR APPLICATION AT FARM LEVEL

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Abstract

The different approaches and options for irrigation water management at farm level are discussed. These include quantifying and managing the allowable depletion of the plant available water in the root zone of deep and shallow soils both for annual and perennial crops. Different modes of replenishing the soil water deficit in the root zone are discussed for annual crops. The aim of these modes is to increase the quantity of captured rain following directly after an irrigation and to decrease the water application rate during the period of peak evapotranspiration.

Introduction

Most of the on-farm water management and irrigation scheduling decisions that are being taken by Southern African irrigators are based on their past experience and are easy to apply with a reasonable degree of efficiency. These traditional systems were developed through trial and error and visual observation of the crop. Farmers will only adopt a more scientifically based system if it is affordable, comparatively easy to use and will result in considerable yield increases and/or water or energy savings.

Many factors influence the decision-making process of determining when to irrigate and the amount to apply with each irrigation. Stegman (1983) listed the following factors:

* The long term climatic conditions, e.g. arid, semi-arid etc. and the short term variablility in the daily or weekly evaporative demand.
* Water supply and constraints on its availability.
* Crop variables like the water requirements of crops and sensitivity to water stress at different growth stages.
* Irrigation system in terms of the degree of mechanization and control over the application rate and amount.
* Soil type, spatial variability in texture, structure, surface properties and associated hydraulic and water retention characteristics.
* Additional considerations which include electricity load management, salinity control, crop quality at harvesting, labour and cultural aspects.

Keeping all the above mentioned factors in mind, on-farm water management should be based on sound management of the soil water balance. The gains and losses of soil water should be managed in order to keep the soil water content of the rooted zone in an optimum range for plant growth. The upper limit of this optimum range is the drained upper limit (DUL) which is the *in situ* water content of the rooting depth at a constant slow draining rate following thorough wetting (Ratliff, Ritchie & Cassel, 1983). The lower limit is the water content of a well rooted profile determined *in situ*, when the plants become water stressed to a specified degree.

The amount of water between the upper and lower limits represents the profile available water capacity (PAWC) (Hensley & De Jager, 1982; Boedt & Laker, 1985, Vanassche & Laker, 1989).

Wetting of the maximum rooting zone beyond the DUL will result in unproductive water percolation losses. Drying of the rooting zone below the lower limit will result in plant water stress and, depending on the severity of stress, inefficient water use and biomass production. Irrigation scheduling therefore is the art of balancing the gains (rainfall plus irrigation) and losses (evapotranspiration) through irrigation in order to keep the water content of the rooting zone at an optimum level and percolation losses low. Percolation losses from rainfall can be reduced by not wetting the entire rooting zone to the DUL with irrigation, thus allowing storage capacity for rainfall. Runoff losses should be prevented by the design of the irrigation system and correct field preparation. Evaporation losses can be reduced with agronomic practices which induce rapid or maximum ground cover by the crop.

The aim of this paper is to discuss the means by which efficient on-farm irrigation water management can be achieved with the existing knowledge of managing the components of the soil water balance (Equation 1). The water balance equation for the purpose of irrigation scheduling can be written in the form:

$$D_x = D_{x-1} - ET_x + P_x + IR_x \pm DR_x \qquad (1)$$

where D_x is the root zone soil water depletion on day x ($D_x = 0$ when the rainfall and/or irrigation amounts exceed the prevailing depletion), D_{x-1} is the soil water depletion on day x-1, ET is the estimate of evapotranspiration, P is the effective (corrected for runoff) precipitation and IR the nett irrigation depth and DR is the drainage loss from (+) or upward flow to (-) the active root zone (Stegman, 1983).

Discussion of management approaches

Quantifying the allowable depletion (D):

The difference between the upper limit of plant available water and the lowest level to which the root

zone soil water content can be allowed to decrease before the plants become unacceptably water stressed represents the most suitable definition of the allowable depletion (D). The allowable depletion is therefore the maximum value of soil water depletion that can be allowed, for a specific soil-plant-atmosphere combination, before the next irrigation has to be applied.

The most acceptable upper limit of plant available water or drained upper limit (DUL) (Ratliff, Ritchie & Cassel, 1983) is obtained from the *in situ* drainage curves of thoroughly wetted soil profiles. Boedt & Laker (1985) and Bennie, Coetzee, Van Antwerpen, Van Rensburg & Burger (1988) carried out several DUL determinations and obtained remarkably similar regression equations with which the DUL can be estimated from the silt (0.05 - 0.002 mm) plus clay content of the different depth intervals of a soil profile (Figure 1).

The most acceptable lower limit of the plant available water is also obtained from *in situ* field measurements. The upper limit of allowable plant water stress and its recognition have not yet been agreed upon. Hensley & De Jager (1982) used visual signs of stress; Boedt & Laker (1985) and Vanassche & Laker (1989) used plant physiological and morphological parameters; Bennie *et al.* (1988) used the ratio between the evapotranspiration rate of well watered and stressed parts of a field. Stress indicated by these measures was relatively "mild" stress. However, Ratliff *et al.* (1983) used the point where the plants became dormant and started to wilt permanently to indicate "severe" stress. Hensley & De Jager (1982) used the term profile available water capacity (PAWC) to define the difference between the upper and lower limits of plant available water in the root zone before the onset of mild stress (visual signs of wilting) and to provide an indication of the allowable root zone water depletion.

The depth of the root zone remains constant for fully developed perennial plants but increases from planting and reaches a maximum at the beginning of seed filling for annual plants. The PAWC will therefore be constant for perennials but will increase over the growing season for annual crops, with increasing rooting depth, as having been confirmed by Vanassche & Laker (1991) for durum wheat. Bennie *et al.* (1988) developed a computer simulation model which can be used to estimate the PAWC of certain crops from soil and rooting parameters at different days after planting as illustrated in Figure 2. The maximum PAWC for maize and wheat at the beginning of seed fill can be estimated with an empirical model developed by Boedt & Laker (1985).

Quantifying evapotranspiration (ET):

The level of soil water depletion or cumulative ET since the previous irrigation, thus how much to irrigate, can by quantified by: i) direct measurement of the water content or depletion of the rooted profile with e.g., a neutron probe; ii) estimation from the potential evapotranspiration or the Class A pan evaporation using the relevant conversion factor for a crop (Doorenbos & Kassam, 1979; Department of Agriculture and Water Supply, 1985); or iii) estimation from seasonal water production functions and curves of day-to-day variation in crop water demand (Bennie *et al.*, 1988).

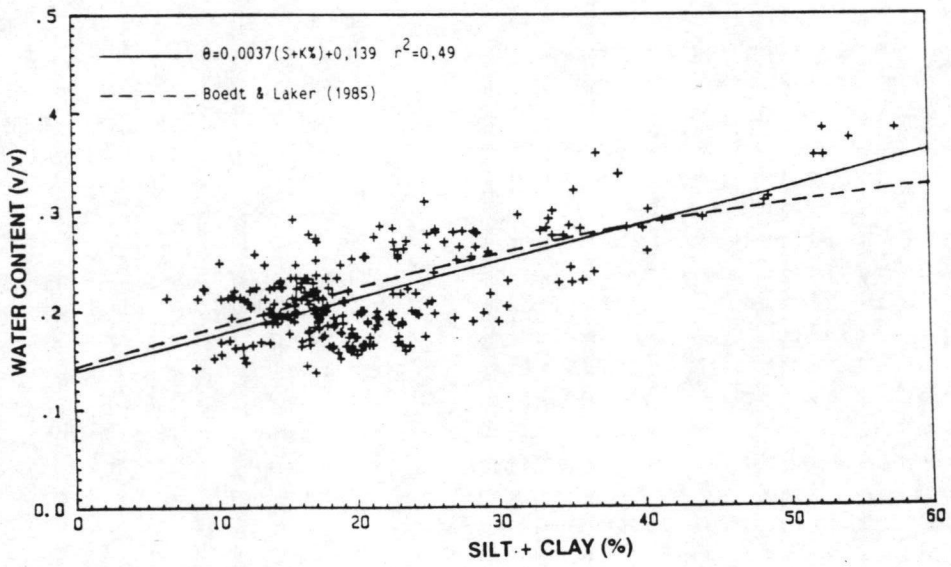


Figure 1 DUL values of soil layers as related to the silt 0.05-0.002 mm diameter plus clay percentage (Bennie *et al.*, 1988.

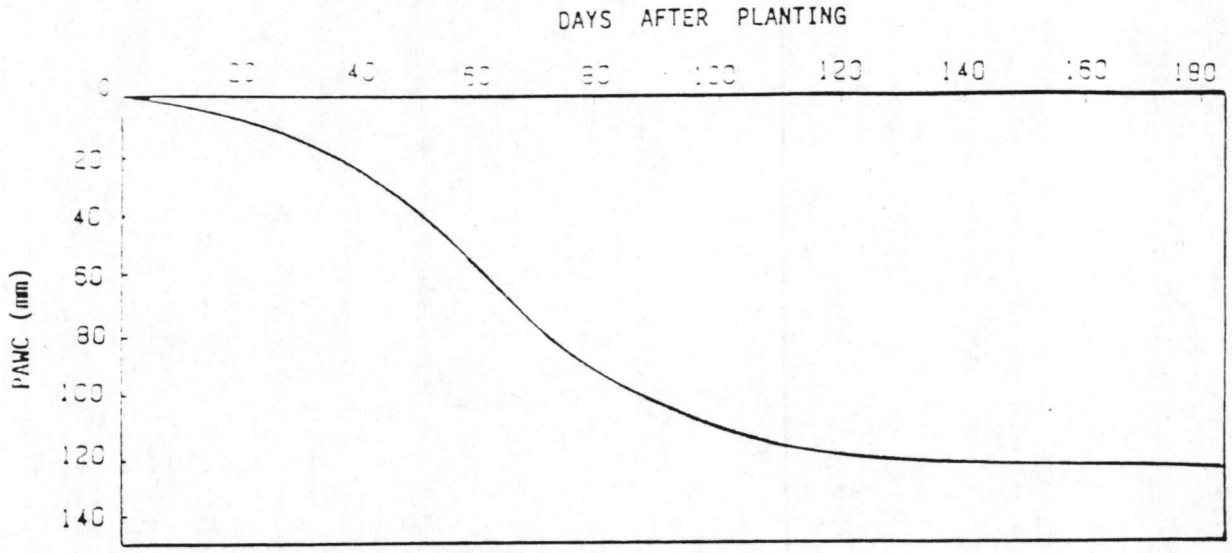


Figure 2 Change in PAWC of wheat over a 170 day growing season.

Direct measurement of the soil water content of the rooted profile to determine the water depletion through the sum of ET and deep percolation is the most accurate but also an expensive procedure. The estimation of ET from Class A pan evaporation without *in situ* calibration of the recommended crop factors against direct ET measurements can result in considerable over-irrigation (Bennie *et al.*, 1988). The calculation of the potential evapotranspiration requires the intensive measurement of atmospheric input variables. The atmospheric data can be centrally collected, processed and distributed to a number of farms for on-farm use to make the meteorogical approach a more acceptable option. Bennie *et al.* (1988) used curves showing daily consumptive use over a season, constructed from historic direct ET measurements, to estimate ET requirements for specific target yields. In applying these procedure, the total consumptive use (W) over the growing season for the predetermined target yield was first calculated from the upper boundary water production function, which is the relationship between the total ET over the growing season and maximum yield, assuming all production inputs other than water to be non-limiting. Using the curves of daily ET from historic data, successive mean 10-daily ET-values over the growing season for different crops and planting dates were then divided by ET_{max}, which is the maximum 10-daily ET measured over the peak period, to obtain time-related relative ET values. As an example, Figure 3 shows the variation in relative ET with days after planting for wheat with a 170 day growing season. This variation is described by a third order polynomial curve fitted through the data points, allowing the area under the curve (in days) to be calculated. The daily consumptive use for a selected target yield can then be calculated using Equation 2.

$$Y_x = Y_{relx} (W/A) \quad (2)$$

where: Y_x = consumptive demand for day x (mm day^{-1}).

Y_{relx} = relative consumptive demand for day x calculated with the relevant polynomial equation.

W = total consumptive use at a selected target yield calculated from the relevant water production function (mm).

A = Area underneath the relative consumptive use curve (days).

Managing rainfall (P) storage and deep drainage (DR):

There are mainly two reasons for water losses through deep drainage (DR) below the rooting zone. The first is over-irrigation, when the amount of applied irrigation water exceeds the root zone depletion because of an over-estimation of the ET. The second is rainfall in excess of the soil profile storage capacity occurring soon after an irrigation. Deep drainage due to both these causes can be avoided on deep soils with a PAWC larger than approximately 80 mm by not filling the root zone to the upper limit of PAWC but by limiting irrigation to a soil depth less than the root zone to allow a predetermined storage capacity to accommodate rain which may occur. The criterion for selecting rainstorage capacity value can be the quantity of an average rain storm or series of rainstorms during the growing season.

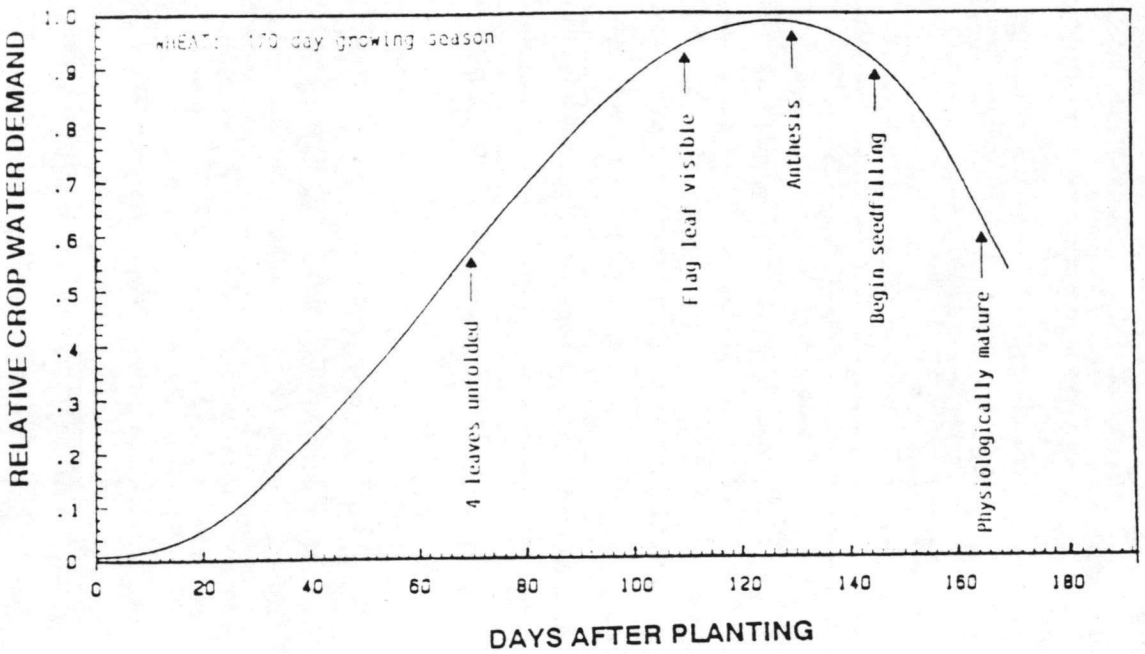


Figure 3 Change in realtive consumptive demand over the 170 day growing season of wheat.

Managing the allowable depletion on deep soils:
The distinction between deep and shallow soils is arbritrary, but a PAWC of 80 mm seems a realistic threshold value. This would, e.g., provide for a rain storage capacity of 30 mm and a residual allowable depletion of 50 mm. Allowing for a peak demand of, say, 8 mm d^{-1} and a small reserve of plant available water (PAW) as a buffer, this would imply a required peak irrigation interval of 5 days or less on shallow soils.

i) Annual crops: For annual crops the interval between irrigations and the amount of irrigation are determined by the ET rate, which is controlled by the crop age, atmospheric evaporative demand, and the chosen mode of allowable depletion or recharge. With well developed root systems the PAWC of greater than 80 mm for crops on deep soils can be managed to provide a buffer against excessive, short-term, peak demand.

When the potential root zone water content at planting is wetted to near the DUL three management modes of the PAWC can be used as illustrated in Figure 4.

Mode A requires that irrigation be applied according to the actual measured or estimated cumulative ET over the chosen irrigation cycle in order to keep the root zone water content near a level equivalent to the DUL minus the reserved rain storage capacity. *Mode A* ensures the largest reserve of PAW throughout the season but also carries the highest risk of over-irrigation or drainage losses.

In *Mode B* the PAWC is gradually depleted during the period of peak water demand by applying irrigation equivalent to the cumulative crop water demand (ET) minus a calculated depletion rate for each irrigation cycle (Figure 4).

The area under the water demand curve equalling the PAWC (e.g. 180 mm) minus the rain storage is determined by integration to obtain the first and last day of this peak demand period (eg. days 55 and 141 in Figure 5). The depletion rate for this example is therefore 150/(141 - 55) = 1.74 mm d^{-1}, starting on day 55 and ending on day 141 after planting. With this mode, the root profile will become gradually drier towards the end of the growing season, thus increasing the retention capacity for rainfall later in the season when ET decreases. This is an example of controlled deficit irrigation that ensures the maximum rain storage capacity and rain utilization during the peak growing season by reducing the possibility of drainage losses. This mode also decreases the peak water application rate.

Mode C is based on a gradual depletion of the PAWC beginning just after planting, thus gradually increasing the retention capacity for rain (Figure 4). For the example in Figure 5, a value of 150/160 = 0.94 mm d^{-1} will be subtracted from the measured or calculated ET or from the calculated crop water demand.

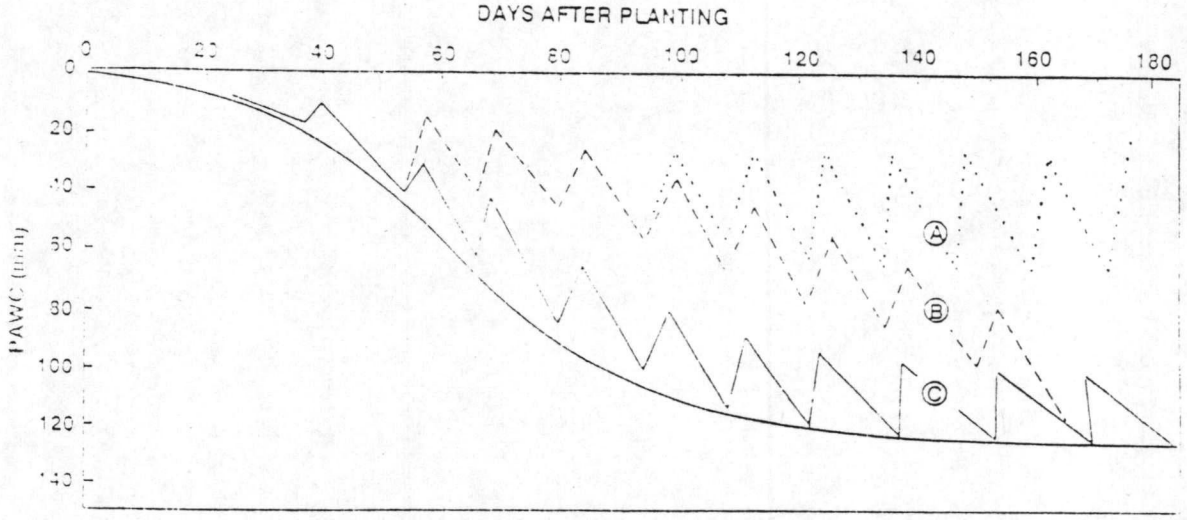


Figure 4 A hypothetical illustration of the different PAWC-based water management modes during the growing season of an annual crop.

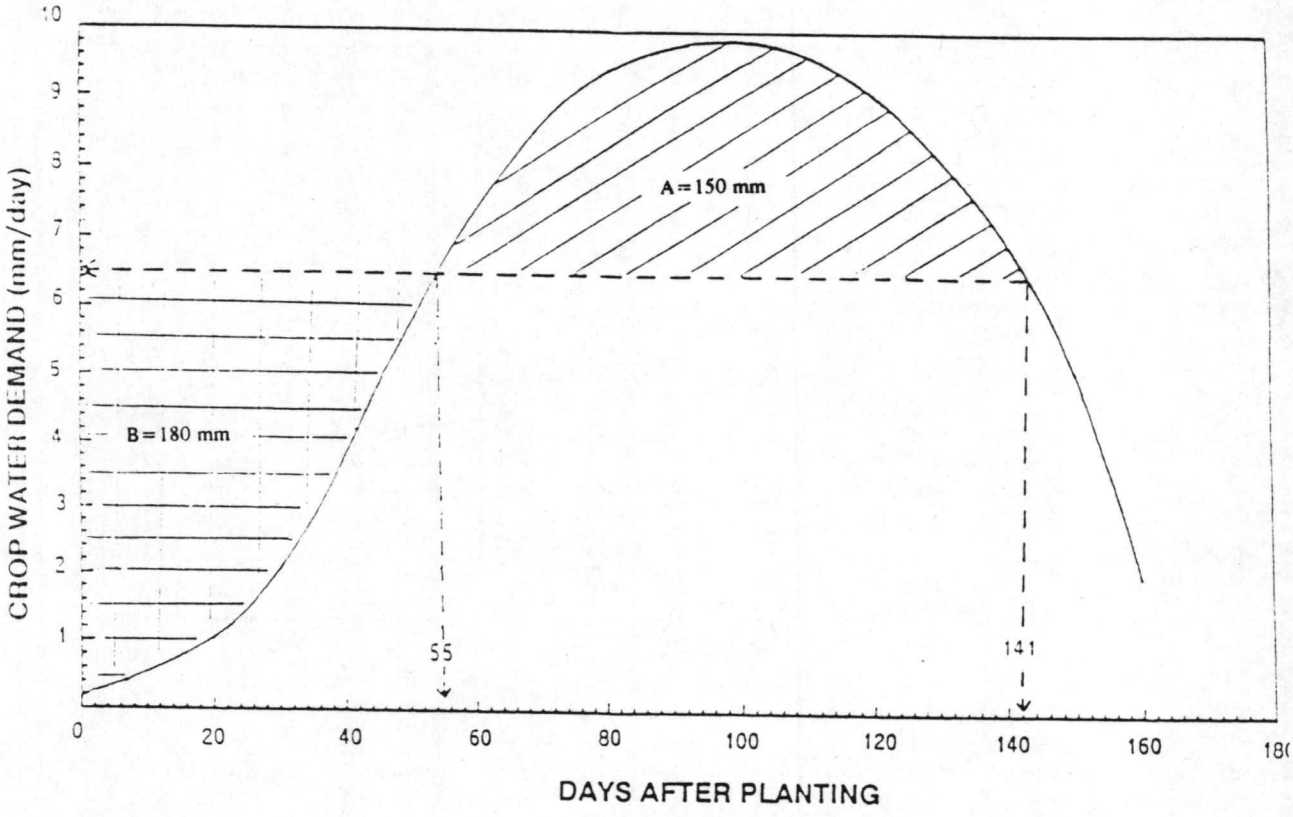


Figure 5 An example of how the crop water demand curve can be used to identify the beginning and end of the peak water demand period for a soil with a PAWC of 180 mm and a crop with a 10 mm d^{-1} peak consumptive use

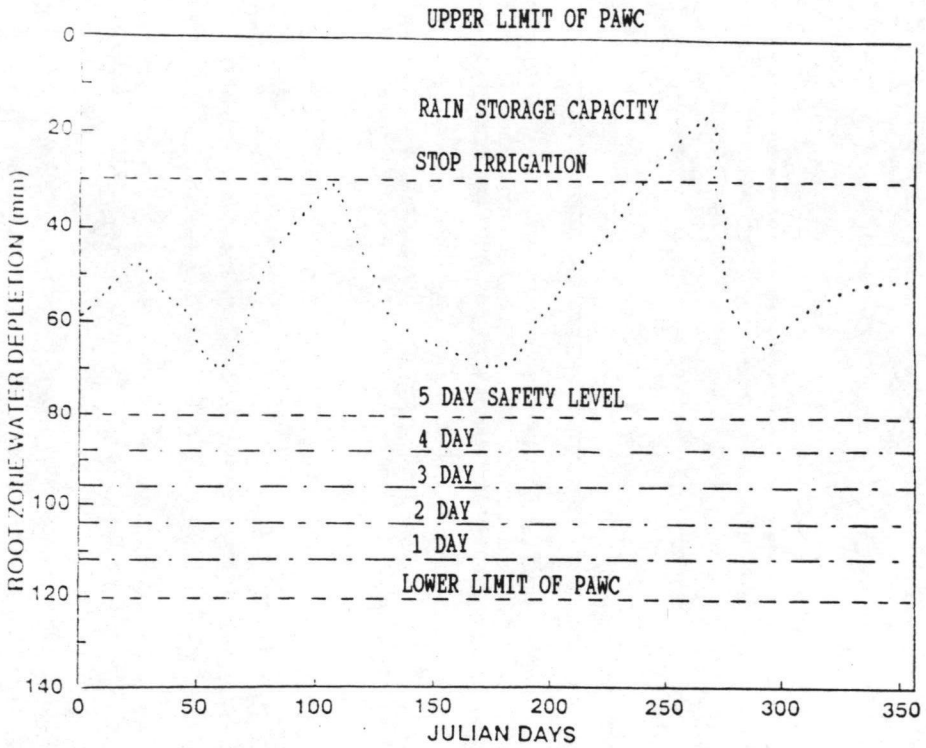


Figure 6 An example of a profile water management graph for a perennial crop with a constant rooting depth and PAWC.

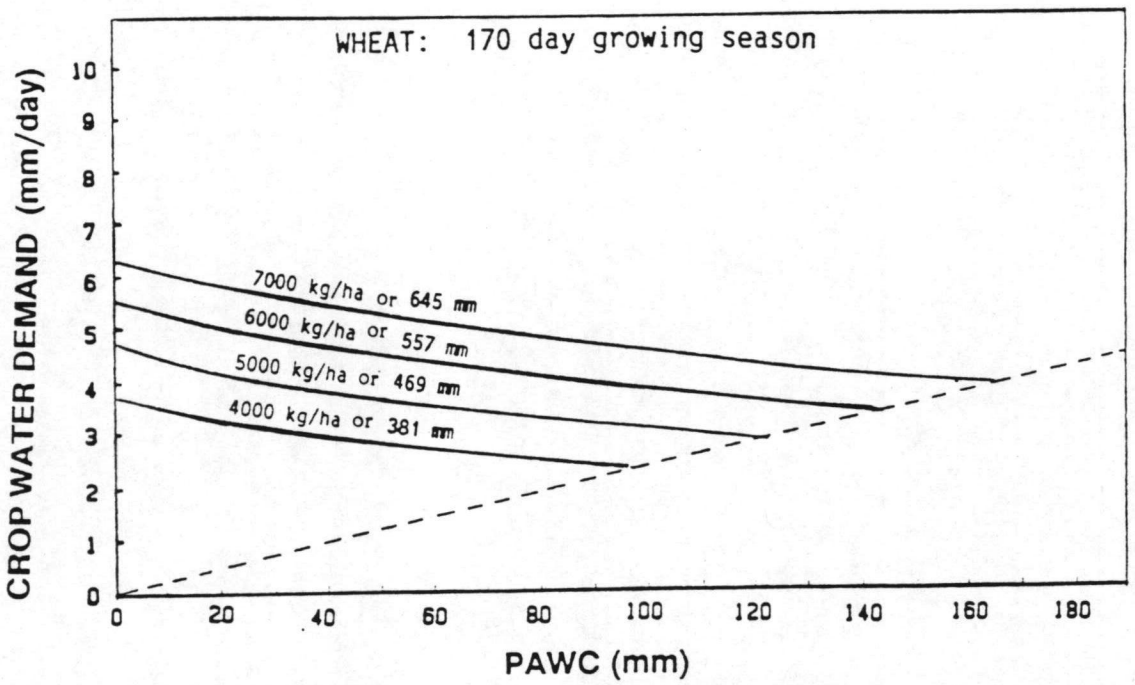


Figure 7 The peak water application rate needed to obtain different wheat yields at different PAWC values.

Modes A to C apply only to cases where the water content of the potential root profile is near the DUL at planting. In cases where it is totally or partially dry to near the lower limit of PAW, another mode (D) should be followed.

With *Mode D* the reserve water application capacity of the irrigation system early in the growing season when ET is low, is used to recharge the deficit in the

PAWC by controlled over-irrigation. The quantity of irrigation for each cycle is determined by the ET or crop water demand plus the recharge rate for the period between planting and the first day of the period of peak water demand. The recharge rate is calculated by dividing the water deficit by the number of days between planting and the pre-determined day representing the beginning of peak water demand, for example day 55 in Figure 5, thus 150/55 = 2.73 mm d^{-1}. From day 55 onwards *Mode B* is followed. This mode allows for beginning and ending the growing season with a dry soil, depending on the amount of rain, and optimum utilization of the irrigation system.

ii) Perennial crops: For perennial crops the PAWC and rooting depth stay constant once the canopy of the crop is fully developed. Under these conditions sound irrigation scheduling should be aimed at keeping the root zone water content between two optimum levels. Irrigation should be stopped when the root zone water content reaches the DUL minus the storage capacity reserved to capture rain following soon after an irrigation (Figure 6). Irrigation should begin or the quantity per irrigation cycle increased before the lower limit of PAW is reached. A 1 to 5 day consumptive use safety margin, based on the mean daily ET and the reliability of the water supply and irrigation system, should be maintained (Figure 6). *In situ* determination of the upper and lower limits of PAW using the same procedure as has been previously described is recommended. Regular (one to two weekly) water content measurements with a neutron probe are recommended after which the irrigation cycle or quantity per cycle can be adapted to stay within the preset limits on the water management graph for each monitoring site.

Managing allowable depletion on shallow soils:
The PAWC of less than 80 mm on shallow soils leaves little room for error or management options in terms of irrigation scheduling. At a peak water demand of approximately 8 mm d^{-1}, for most crops only a few days' consumptive use are held in reserve. Under these conditions only *Mode A*, as described for deep soils, is recommended in conjunction with a short (less than a week) irrigation cycle and a small rain storage capacity. Direct measurement of the soil water content, an accurate estimation of ET, or knowledge of the historic crop water demand is necessary to prevent over- or under-irrigation. Water management on shallow soils for these reasons remains a sophisticated exercise and irrigation development on these soils should therefore be discouraged.

Managing the peak water application rate:
Previous discussion on the irrigation scheduling *Modes B to D* illustrated the advantage deep soils with large PAWC values have in moderating the peak irrigation demand of crops. The higher the PAWC, the lower the peak water application rate that is needed under good management. Relationships between the peak water application rates needed to obtain different wheat yields and the PAWC values of the soil are illustrated in Figure 7.

When *Mode D* is followed it is important to make sure that, when the first and last days of the depletion period are determined by integration, the areas A and B indicated in Figure 5, should be properly matched. Area B should preferably be equal to the PAWC and area A equal to the PAWC minus the rain storage capacity. This way it will be possible to meet the crop water demand without any supplementary rain. Bennie *et al.* (1988) produced equations and a computer program for calculating the peak water application rate for several crops at different target yields for all the irrigation scheduling modes. It must be emphasized that the peak water application rates in Figure 7 and those recommended by Bennie *et al.* (1988) represent the quantities of water to be applied at the top of the crop canopy (measurable with rain gauges) assuming that there will be no runoff or irrigation system inefficiency. In practice certain adjustments will therefore have to be made.

The BEWAB approach:
BEWAB is an irrigation water management computer program (Bennie *et al.*, 1988) based on the water balance irrigation scheduling principles that have been discussed in this paper. The inputs needed are the type of crop, length of the growing season, target yield, depth of the soil, silt plus clay content for 200 mm depth intervals and the selected rain storage capacity. The DUL is estimated from the silt plus clay content and the lower limit for calculating the PAWC is estimated with the root water uptake simulation model described by Bennie *et al.* (1988). The total consumptive water use over the season is estimated for a selected target yield from the upper boundary water production functions based on historic water use-yield relationships. The daily crop water demand is estimated from relative crop water demand curves, also based on historic data. The output consists of a printout of a recommended water application schedule for *Modes A to D.*

Conclusions

After many years of research on irrigation water management and irrigation scheduling, results should be integrated and presented in an acceptable form for on-farm use. Sound on-farm water management should be based on the principle of managing the soil water balance with or without the aid of direct measurement of the soil water content. Direct measurement of the soil water content at fixed intervals, to support management decisions especially

for perennial crops, is preferred if financially viable.

Upper boundary water-yield functions are essential for the calculation of the seasonal crop water demand associated with a realistic target yield. This calculation is needed to determine the area to be planted and for water budgeting. Three options exist for determining the daily crop water use (ET). These are direct monitoring of the root zone water content with, for example, a neutron probe; estimation from the atmospheric evaporative demand with calibrated crop factors and estimation from historically based crop water demand curves.

The adoption of the profile available water capacity concept makes it possible to prevent the harmful effects of plant water stress in practice, provided that the lower limit is defined accordingly. On deep soils, available water reserves can also be managed to provide a buffer for carefully controlled deficit irrigation in order to make better use of rainfall in the irrigation scheduling programme. Careful management of such reserves allows for lower peak water application design requirements for irrigation systems.

Sound on-farm water management on shallow soils with a PAWC smaller than 80 mm requires a high level of precision.

The reasons why so many farmers abstain from applying sound on-farm water management principles are still not clear and need clarification.

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CURRENT RESEARCH ON IMPROVING WATER MANAGEMENT AND WATER USE EFFICIENCY ON MULTI-FARM IRRIGATION PROJECTS

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Abstract

Concepts and individual efficiencies important for improving overall irrigation project water use efficiency have been defined. The aspects which can be managed in order to attain this goal have been identified. The use of crop growth model and automatic weather station is proving to be a convenient, accurate method of providing irrigation scheduling advice to a group of farms. The Penman-Monteith evaporation equation and PUTU crop growth models are being used. Lands irrigated according to this system have outyielded surrounding areas by 35 to 72%. The distribution of water between farms is best managed using crop water production functions which account for climatic influences. Climatic fluctuation adds a stochastic element to irrigation scheduling. Basing decisions upon the long term mean water production function minus one standard deviation of crop yield accommodates risk-averse decision makers. A linear programming technique optimizes water allocation and the area planted in times of water shortage. Systems for both pre-season planning and within-season water management have been developed. Guidelines for effective, efficient management of multi-farm irrigation projects have been developed from on-farm surveys.

Introduction

Competition for limited water supplies between agricultural, municipal and industrial sectors is increasing. Approximately 50% of surface water resources are allocated to irrigation. Of this, up to 40% can be lost due to leakage and/or mismanagement before reaching the cropped surface. It is these latter losses which this paper addresses. Management loss may be divided into application, distribution and conveyance losses.

Much can certainly be done to reduce physical leakages during the conveying of water from source to farm. This, however, is the domain of the engineer and will not be considered here. Of primary importance here will be study of the means of increasing efficiencies with which water is distributed and applied. The focus of attention is multi-farm situations and particularly overall irrigation project efficiency, ϵ_p. Overall project efficiency may be analysed by studying its various components. Most of the results here described have been drawn from research reports to the Water Research Commission.

The objectives of this paper are to:

(i) Identify aspects of irrigation management which might be manipulated to improve overall irrigation project efficiency,

(ii) Describe the methodology for accurately determining irrigation requirements for a group of farms.

(iii) Establish a methodology for managing the application, as well as distribution, of irrigation water on individual farms and multi-farm schemes.

Definitions

It is necessary to define clearly the concepts applied in this paper.

Water use and supply

Weather is the ultimate determinant of water consumption by crops. Consumption is dictated by atmospheric evaporative demand. Atmospheric evaporative demand is defined (De Jager & Van Zyl, 1989) as the water vapour transfer to the atmosphere required to sustain the energy balance of a given vegetated surface (crop), in its present growth stage, when the water status of its root zone permits unimpeded plant evaporation and the water status of the top 150 mm of soil equals its current value. The total water actually consumed by an unstressed crop in a given season is equal to cumulative daily atmospheric evaporative demand.

In this study, two cases of management were considered, these being either water limited and cultivated land area unlimited, or water supply unlimited for the given available irrigable land area. In addition, for both situations, water supply could be either controllable (in dams), or uncontrollable (as when drawn from streams). Certain of the irrigation management procedures here considered could be applied to both water limited and water unlimited scenarios.

Water limited situations usually arise when flow in a river, or the supply from a dam, ceases. With respect to dammed water sources the annual yield, AY, from a dam was defined by Alexander (1978) as the maximum yield which the dam would be capable of supplying without interruption should the historical flow sequence be repeated in future. This value is obtained from nomograms of annual dam yield. The latter is expressed as a percentage of river mean annual run-off, MAR, and is plotted versus capacity of the dam (also expressed as a percentage of MAR). The size of dam providing uninterrupted flow can be obtained from such yield-storage graphs. In most cases dams with a capacity of 160% of MAR provide an

annual yield equal in magnitude to approximately 50% of MAR (Alexander, 1978). In practice, however, managers frequently irrigate areas requiring more water than MAR (in the case of streams) or AY (in the case of dams). This practice results in irrigation scheduling under conditions of limited water supply. When irrigation is provided directly from either a stream or, in the case of a state scheme, a canal, the water supply is uncontrollable. For the latter, minimum stream flow rate, SF_{min}, will determine the area which could possibly be cultivated to a given crop. Particularly in such cases, optimization of water use is imperative.

Efficiencies

The concepts used in the investigation of water use and irrigation efficiency are defined as follows:

Water use efficiency, ϵ_w, is the water evaporated in the crop production process, i.e. plant evaporation E_v, per unit of water applied over the cropped area, V_a, viz.

$$\epsilon_w = \frac{E_v}{V_a} \tag{1}$$

Application efficiency is the ratio of the net quantity of irrigation water used to produce the crop to the total quantity applied to the fields. Thus, the application efficiency, ϵ_a, is given by

$$\epsilon_a = \frac{AED - R_e}{V_a} = \frac{V_n}{V_a} \tag{2}$$

where AED = atmospheric evaporative demand,
R_e = effective rainfall (rainfall stored in the root zone and used in plant evaporation),
V_n = nett irrigation requirement.

In practice, some application losses always occur so that AED < V_a and hence $V_n < V_a$. For zero rainfall, ϵ_a is a characteristic of the irrigation system itself. Typical data concerning application efficiencies, for zero rainfall, are given in Table 1.

The other relevant efficiencies as defined by ICID (Shvelik, 1987a) are as follows:

Farm canal and system efficiency:

$$\epsilon_b = \frac{V_a}{V_f} \tag{3}$$

Farm efficiency:

$$\epsilon_f = \frac{V_n}{V_f} = \epsilon_a \epsilon_b \tag{4}$$

Water conveyance efficiency:

$$\epsilon_c = \frac{V_f}{V_t} \tag{5}$$

Table 1 Approximate application efficiencies for different irrigation systems (after Jensen, 1980).

System	Application efficiency ϵ_a	
	Potential ϵ_a (%)	Observed ϵ_a (%)
Surface	70 - 80	25 - 100
Sprinkler	80	63 - 65
Drip	95	92

Distribution efficiency:

$$\epsilon_d = \frac{V_a}{V_t} = \epsilon_b \epsilon_c \tag{6}$$

Overall project efficiency:

$$\epsilon_p = \frac{V_n}{V_t} = \epsilon_a \epsilon_b \epsilon_c = \epsilon_a \epsilon_d = \epsilon_f \epsilon_c \tag{7}$$

where, V_f = water supply to a farm, or to the group of farms, and
V_t = total water supply to the irrigation area.

Irrigation requirements

Net irrigation requirement, V_n, is defined (see also Equation 2) as the difference between atmospheric evaporative demand and effective rainfall. Thus,

$$V_n = AED - R_e \tag{8}$$

Effective rainfall, R_e, is the rain water which passes through the plant and produces carbohydrate biomass. It is a function of rainfall amount, soil depth, crop type and cultivation practice.

It is evident from Figure 1 that net irrigation requirement varies markedly between and within seasons because of climatic variation. For this reason it is necessary to define:
the maximum peak net irrigation requirement, V_{nx}, as the highest historic irrigation requirement,
the seasonal peak net irrigation requirement, V_{nxs}, as the peak requirement in a given season,
the seasonal mean net irrigation requirement, V_{ns}, as the mean requirement in a given season,
the mean peak net irrigation requirement, V_{nxs}, as the average of the peak seasonal requirements,
the mean net irrigation requirement, V_n as the average net irrigation requirement over a given period of time, viz., weekly, V_{nw}; monthly, V_{nm}; and seasonally, V_{ns}.

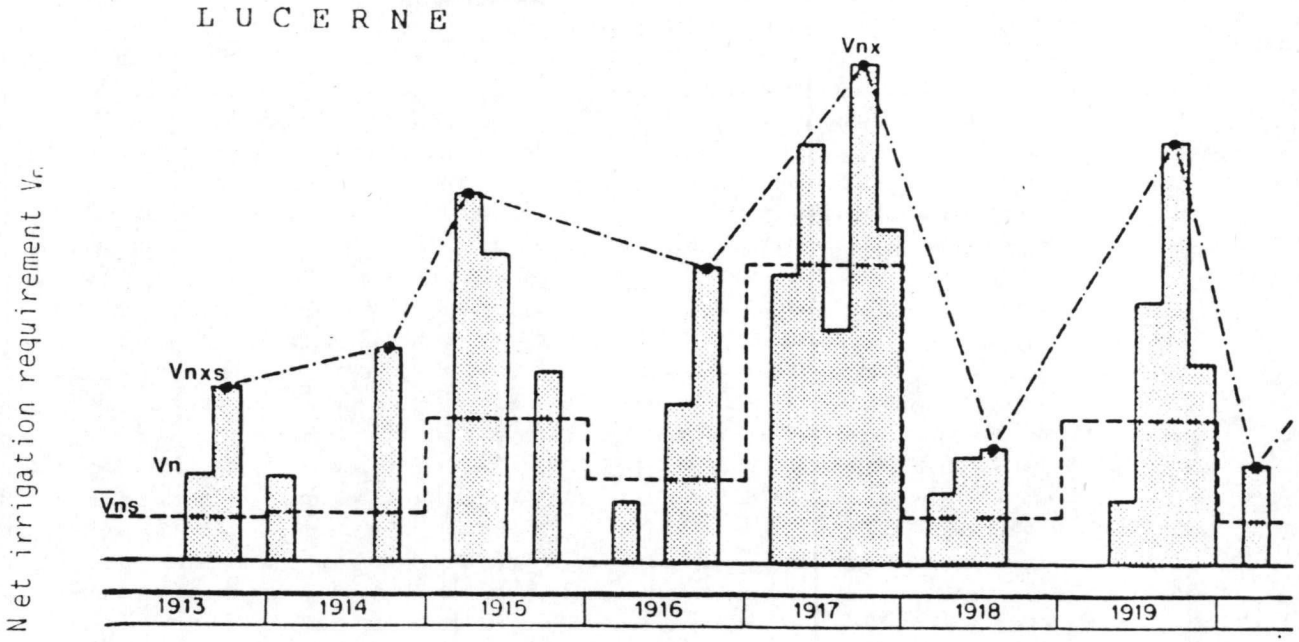


Figure 1 Monthly variation in net irrigation requirement for lucerne (After Shvelik 1987b). V_n = net irrigation requirement; V_{nx} = maximum peak; V_{nxs} = seasonal peak; V_n = monthly requirement; V_{ns} = seasonal mean.

The large seasonal fluctuation in all those entities caused by climate is well illustrated in Figure 1. It is abundantly clear from this that irrigation, (particularly under water limiting conditions) is a highly stochastic phenomenon and any decision must take this into account. This paper introduces some simple procedures for doing this.

Not only does the variability of the irrigation requirement have a stochastic component, but so does stream flow variability. Thus, acceptance of calculated risks is unavoidable in irrigation planning and decision-making.

Identification of aspects which can be managed for improving efficiency

From the definitions contained in Equations 1 to 8 it is possible to identify critical aspects worthy of consideration when endeavouring to improve overall project efficiency. These will briefly be addressed.

Net irrigation requirement (rainfall efficiency)

It is evident, from Equation 8, that with AED and presumably also crop yield remaining constant, V_n can be decreased by increasing rainfall efficiency R_e. Increasing R_e must therefore potentially make a major contribution to increasing the economic efficiency of irrigation water use on an irrigation project. This is best attempted either by paying careful attention to current weather forecasts, or by practising deficit irrigation. The latter dictates that each irrigation must leave sufficient water holding capability in the root zone to ensure that most of any subsequent rainfall will be held in the soil for utilization by plants. The implication is that run-off and deep percolation should be minimized.

Acting upon weather forecasts will diminish the chances of irrigating immediately prior to a rainfall event. This too will eliminate run-off and deep percolation.

It is evident that R_e is not constant for a given situation, but varies each season with rainfall amount and frequency, soil depth and crop type. Because of this, accurate estimation of the daily soil water balance becomes imperative for maximising R_e. Such estimates are computed using a crop growth model.

Overall efficiency

Once V_n has been minimised, the next step towards maximization of overall project efficiency (see Equation 7, viz. $\epsilon_p = \epsilon_s \epsilon_d$) is to maximise individual application and distribution efficiencies.

Water use efficiency

Water use efficiency (Equation 1) is given by E_v/V_s. Thus, since E_v is determined by weather and crop, the best manner in which management could maximise water use efficiency is by minimising V_s. This can only be achieved for a given irrigation system by accurate irrigation scheduling.

Application efficiency

From Equation 2 it is apparent that application

efficiency is increased by decreasing V_a, the volume of water applied for a given irrigation requirement. Once again, the way in which to reduce V_a for a given irrigation system is to utilize accurate estimates of daily AED and calculations of the daily soil water balance to facilitate accurate irrigation scheduling and elimination of deep percolation and run-off.

How to determine AED and schedule irrigations accurately will be discussed in following sections.

Distribution efficiency

Distribution efficiencies (see Equation 6) are maximised by minimising the amount of water supplied to the irrigation area, V_t. This generally involves economic optimization of irrigation amounts and the area irrigated for a given quantity of water. Such optimization is ideally carried out using linear programming techniques.

Computation of efficiencies

The manager may assess his irrigation prowess by attempting to maintain V_n as low as possible and overall project efficiency, ϵ_p, as high as possible. This requires evaluation of Equation 7 ($\epsilon_a.\epsilon_d$). Application and distribution efficiencies are calculated using Equations 1, 2 and 6.

Overall project efficiency, ϵ_p, is the product of ϵ_a and ϵ_d (Equation 7). From Table 1 it can be seen that the former varies between 30% and 100% with 65% a likely value for sprinkler and 92% for drip systems. Assuming a distribution efficiency to a group of farms of 70% suggests that ϵ_p could be of the order of 44% for sprinkler and 64% for drip.

Determination of irrigation requirements

In order to provide optimum V_a on a farm in a group of farms, it is important to have an accurate estimate of mean and peak irrigation requirements. This will facilitate (a) accurate control of the water supply, and (b) planning of the size of the area to be irrigated and selection of the crop. Peak and mean irrigation requirements have been defined. It is evident that, in order to plan such an operation effectively, knowledge regarding past irrigation practices is required. A series of irrigation scenarios needs to be constructed for each crop situation. The best method of obtaining such information is by utilizing a crop growth model in conjunction with an extended climatic time series. From graphs similar to Figure 1, estimates of peak (V_{mx}), mean peak (V_{mxa}), and mean (V_m) irrigation requirements may be made.

Accurate determination of AED

The need for accurate determination of AED has been explained and emphasized. The technique and computational method for determining AED will now be described.

Technique

When confronted with a large group of farms, the most convenient and accurate method of estimating AED for a variety of crops and planting dates is to use suitable crop growth models with input data provided by an automatic weather station (AWS).

Recent research has shown that a weather station can provide data for AED computations which are representative of an area of radius approximately 50km around the weather station. In this way an area, covering a large number of farms, may be served from one central point. This proves to be extremely cost effective and convenient. The installation and maintenance of an AWS for this purpose is described in detail by De Jager, Van Zyl, Kelbe & Singels (1987). When several groups of farms which are geographically separated need to be served, it is necessary to transfer data from each of several weather stations to a computational centre. Rapid data transfer is a prerequisite. There are numerous such applications in the RSA. The technical details of a suitable telecommunications network providing links to Campbell Scientific weather stations have been described by Mottram, De Jager & Savage (1991b).

Computation

The computation of AED requires an accurate estimate of reference evaporation, E_o. It has been shown convincingly (Van Zyl & De Jager, 1987; Jensen, Burman & Allen, 1990) that the Penman-Monteith equation is the best available method of achieving this. For the purpose of estimating reference evaporation from AWS data, however, the original Penman-Monteith equation requires several modifications. These modifications, described by Allen, Jensen, Wright & Burman (1989) have been computerised in the PUTU irrigation model. They include the adjustment of:

(i) crop canopy resistance to gaseous diffusion according to leaf area index of the reference crop,
(ii) surface roughness parameters for crop height,
(iii) windspeed for height of measuring apparatus, and
(iv) wind observations according to whether anemometers were exposed within, or above the equilibrium boundary layer.

Where possible the Penman-Monteith equation should be used in preference to alternative equations. A useful alternative when wind and humidity observations are not available is a modified form of the Priestley-Taylor formula (Meiring, 1989).

The Value of E_o thus obtained is then used to estimate AED and schedule irrigation on the numerous plots of land comprising the irrigation schemes of interest.

A description of how AED is obtained from E_o is given by Mottram & De Jager (1991a). In brief, a

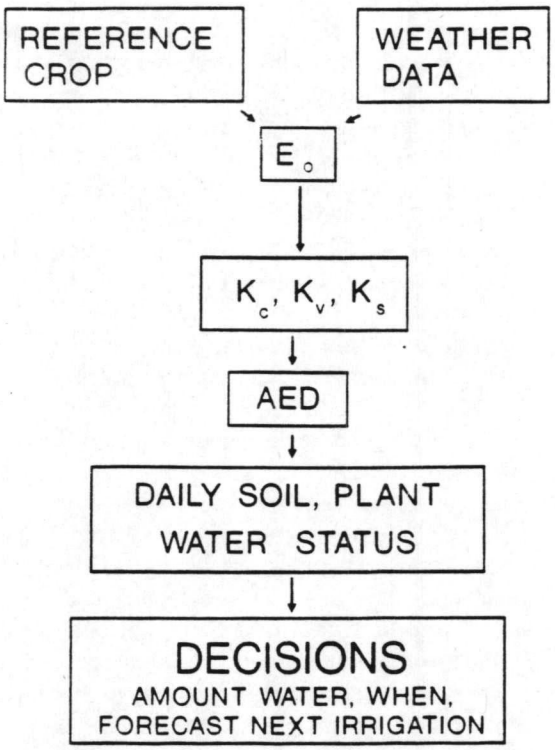


Figure 2 Flow chart describing computation of daily soil and plant water status in PUTU which makes possible deciding when how much water should be applied, or how long before the next irrigation. The symbols E_o, K_c, K_v,K_s and AED are explained in the text.

computerised decision support system (PUTU) has been developed whereby atmospheric evaporative demand AED and daily crop water status may be computed from weather data collected by an AWS. The flow chart describing this operation is given in Figure 2. Importantly, certain precautions are necessary. These include:

(a) Selection of a suitable reference crop. The choice here lies between a short grass surface 0.15 m or lucerne 0.5 m tall, and
(b) Initialization of the height of all instruments.

Initially AED is computed from reference evaporation, E_o, using a vegetative evaporation coefficient k_v, defined as the ratio of vegetative to reference evaporation, and a soil evaporation coefficient k_s, which is the ratio of soil to reference evaporation. The relevant equations are

$$AED = k_c E_o \tag{9}$$

and

$$k_c = k_v + k_s \tag{10}$$

Research has shown (Hanks & Hill, 1980; Jones & Kiniry, 1986) that both k_v and k_s need to be known independently to arrive at a satisfactory value of the overall crop coefficient, k_c. It is not sufficient to compute a composite k_c on the basis of previously measured values of AED and E_o, as has been a widespread practice. A composite K_c does not permit adequate simulation of the effect of the drying soil surface on AED. It is therefore necessary to compute k_c daily using Equation 10.

The vegetative evaporation coefficient, k_v, is computed from leaf area index, which, itself, may either be measured, estimated or computed. The soil evaporation coefficient, k_s, is computed from the soil water deficit below field capacity in the top 100 mm of the soil.

Distribution strategy

The efficient distribution of the available water, V_t, amongst a group of farms is beset with problems. How to attain maximum water use efficiency on a single farm will be considered first. Thereafter, adjustments necessary for the multi-farm situation will be examined. No strategy decisions are possible without crop water production functions. These are derived using crop growth models and weather data.

Use of crop water production functions

On single plots, the water distribution strategy is decided upon with the assistance of a crop water production function. An example thereof for wheat is given in Figure 3.

To ensure economic rationality, the farmer is constrained to operate in the region of diminishing returns (indicated by X_o and X_d on Figure 3). Maximum water use efficiency is obtained at a water application of X_m. Similarly, in the multi-farm situation, it must be ensured that all plots receive between X_o and X_d. Where a number of plots of land on a number of farms in a group are concerned the equimarginal product principle must be applied (see Doll & Orazem, 1984). This prescribes that the marginal product of additional water must be identical on all plots of land within the project (group of farms). Should this policy be followed, maximum water use efficiency will be ensured for the entire project.

Influence of climate

Seasonal variations in climate drastically affect the shape of crop water production functions and must be accounted for. Such variability due to climate is illustrated for maize in an arid climate in Figure 4, which reflects the mean production function plus or minus one standard deviation. Thus, stochastic effects will necessarily affect the choice of an irrigation strategy.

This variability makes it difficult to determine the boundaries of the region of diminishing returns (Phase II) in Figure 4. As a first step it is suggested that the

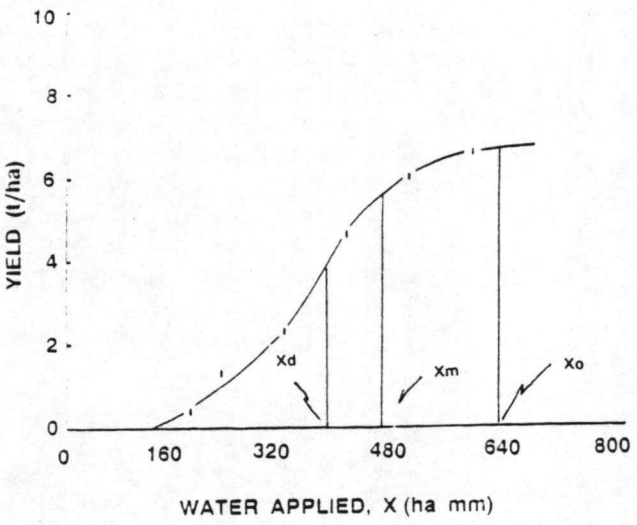


Figure 3 The crop water production curve using several hypothetical irrigation strategies together with weather for the central OFS in the wheat crop growth model PUTU 9. The water application producing the onset of diminishing returns, maximum water use efficiency and the maximum yield are denoted by X_d, X_m and X_o, respectively.

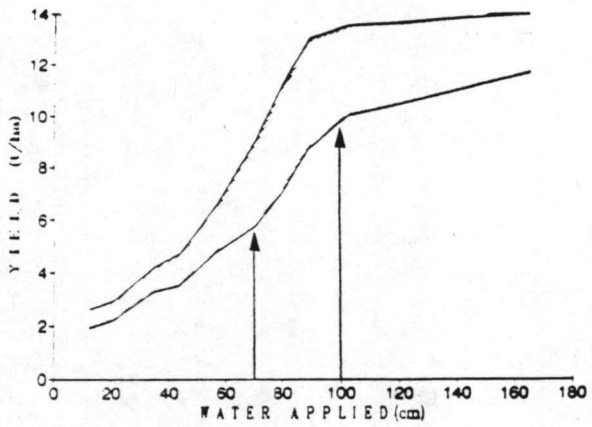


Figure 4 Variation in crop water production functions for maize due to timing of rainfall and influence of air temperature on phenology and growth processes when a fixed irrigation strategy is applied in an arid climate.

curve through the long term mean minus one standard deviation be adopted. This represents a risk averse decision because it means that, on 84% of occasions (years) yields will exceed those predicted by such a production function. Phase II for maize is therefore found between the two arrows in Figure 4.

It needs to be stressed that, due to climatic variability, the SE of estimate of yield of crop water production functions can be as high as 27% of the mean yield. Furthermore, we have found (unpublished data) curvilinear crop water production functions fit data better than do straight line functions.

Maximum economic efficiency and maximum water use efficiency seldom correspond. The production termin the crop water production functions shown in Figure 3 and 4 is crop yield. Improved decisions would probably result from use of water production functions drawn in terms of gross margin.

Use of linear programming

As a first approximation, striving for maximum efficiency on each farm in a group with the help of crop water production functions would lead to a high overall efficiency for the group. The sophisticated approach however, would be to apply the equimarginal product principle recommended by Groenewald (1991). He states that equalizing the degree of yield reduction due to water stress permitted within each crop growth stage will minimize seasonal yield losses. Linear programming procedures can be used for this. The objective of these will be to optimize areas planted to given crops and the amount of water applied. An outline of the procedure for such linear programming is given in Figure 5.

In order to undertake optimization using a linear programme, a suitable objective function in terms of yield, applied irrigation and area needs to be established. The yield equation from the PUTU model (De Jager *et al.*, 1987) is:

$$Y_c = \sum_i Y_{ci} \tag{11}$$

where Y_c denotes final yield for crop c, and i represents crop growth stage.

The linear programme requires yield to be expressed in terms of water applied. In order to do this, Equation 11 needs to be transformed and expressed in terms of relative yield deficit so that the relationship between this latter concept and relative evaporation deficit of Doorenbos & Kassam (1979) may be invoked. This relationship reads

$$\frac{Y_{c\infty} - Y_c}{Y_{c\infty}} = k_{yc} \frac{AED_c - E_c}{AED_c} \tag{12}$$

where subscript $_\infty$ denotes maximum value corresponding to no water stress, E_c denotes the modified value of AED_c due to water stress and k_{yc} is called the yield response factor.

When Δ is taken to denote decrement below the maximum value, Equation 12 may be written

$$\frac{\Delta Y_c}{Y_{c\infty}} = k_{yc} \frac{\Delta E_c}{AED_c} \tag{13}$$

Now following Equation 12, crop yield may be

estimated from

$$Y_c = Y_{oc} (1 - k_{yc} \frac{\Delta E_c}{AED_c}) \quad (14)$$

Furthermore, Equation 14 can be expressed in terms of applied irrigation reduction below AED_c by making the simplifying, yet justifiable, assumption that reduction in V_{ac}, the water applied to the cropped area, is equivalent to the reduction in E_c below AED_c. Thus, $\Delta E_c = \Delta V_{ac}$ and, since economic optimisation would involve consideration of actual (gross field) irrigation requirement, this may be transformed using Equation 2 to read:

$$\Delta E_c = 1/\epsilon_a * \Delta V_{ac} \quad (15)$$

Substitution of this relationship into Equation 14 and extending it to accommodate individual growth stages, yields.

$$Y_c = \sum_i Y_{oc} (1 - k_{yci} \frac{\frac{1}{\epsilon_a} \Delta V_{aci}}{AED_{ci}}) \quad (16)$$

Alternatively, the multiplicative exponential law of Jensen (1968) for combining the effects of water stress occurring in different growth stages could have been applied which yields

$$Y_c = \prod_i (1 - \frac{1}{\epsilon_a} \frac{\Delta V_{aci}}{AED_{ci}})^{\lambda_i} \quad (17)$$

where λ_i = water stress exponent for the i^{th} growth stage.

This equation however, is difficult to include in the linear programme because it is not additive. Since the objective is to optimize profit, Equation 16 must be transformed so as to enable calculation of gross margin.

First, the maximum gross margin per unit area for the crop when no yield reductionter stress was experienced, GM_{oc}, may be expressed by

$$GM_{oc} = Y_{oc} * SP_c - DAV_{oc} \quad (18)$$

where SP_c is the selling price of crop type c and DAV_{oc} represents the directly allocatable crop production costs without plant water stress. DAV_{oc} includes production, harvest and the variable irrigation costs, $CW_c * V_{aoc}$, where CW_c denotes the cost per unit of irrigation water applied to the given crop. Currently CW_c is rated at R0.5/mm of water applied. In the event of less than maximum water requirement (ΔV_{ac}) being applied, the corresponding gross margin is expressed from Equation 18 and 16 as

$$GM_c = GM_{oc} - \sum_i (Y_{oc} * k_{yci} \frac{\frac{1}{\epsilon_a} \Delta V_{aci}}{AED_{ci}} SP_c - CW_{ci} * \Delta V_{aci}) \quad (19)$$

Apart from the normal variable production costs, it is thus apparent that calculation of GM_c requires the following input values:

(a) Water non-stressed final crop yield (Y_{oc}).
(b) Selling price of the crop (SP_c)
(c) Irrigation decrements below maximum requirement in each crop growth stage (ΔV_{ac}).
(d) Atmospheric demand in each crop growth stage (AED_{aci}).

For a variety of different crop types, gross margin can be maximised at given applied irrigation in each growth stage using linear programming. The objective function for this is:

$$MAX \sum_C GM_C * A_c \quad (20)$$

where A_c is the area planted to crop c. Equation 20 is used in conjunction with Equation 19.

Integrating yield reductions due to insufficient water applied in growth stage i (see Equation 19), presents a problem for the linear programme model. How to overcome this is explained by Mottram, De Jager,

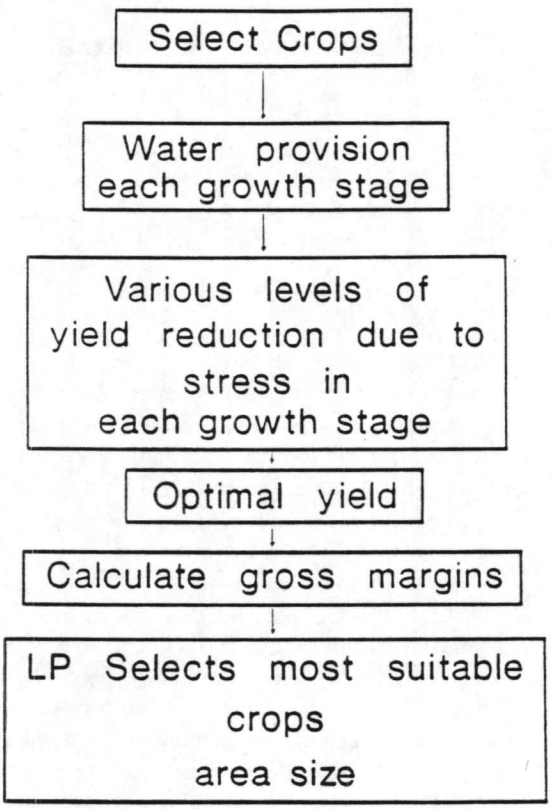


Figure 5 Procedure and steps undertaken in linear programme which determines final gross margin, crop rotation and size of area under each crop.

Munton-Jackson & Gordijn (1991c). An example of the results obtained applying this method to different rotations in Winterton and Rietriver are given in Table 2.

The supposition in cases a, b and e (Table 2), is that the farmer has knowledge of the water available (70 m ha) in the pre-season and must optimize given rotations on 50 ha. In cases c, d and f, the farmer has already decided to plant 50 ha and subsequently learns that he will have only 60 m ha of water available for the season.

These results (Table 2) indicate the value of the LP techniques in pre-season planning (a,b,e) and in-season scheduling (c,d,f) of irrigation. It is obvious that the method may easily be extended to numerous irrigation plots on a group of farms. As such it constitutes a powerful decision support procedure for managing irrigation.

Use of Equation 17 instead of Equation 16 for estimating yield decrements given growth stages complicates the linear programming procedures. A dynamic linear programming optimisation should however be possible and is being investigated.

Irrigation scheduling for maximum application efficiency

Water supply non-limiting

The benefits accruing from use of PUTU 9 are evident from Table 3, which compares yields obtained on lands scheduled by farmers following their normal practice with those obtained from fields scheduled according to PUTU 9. As explained, it is imperative to have an accurate estimate of AED for both irrigation scheduling and the estimation of peak and mean net irrigation requirements.

PUTU 9 contains a simplifying procedure making it possible very easily and quickly to establish a workable crop growth model for any crop. The only expertise required for this is to estimate the maximum ratio of plant evaporation to reference evaporation ($k_{vo}=E_{vo}/E_o$) for each crop growth stage. Such relationships are readily available in the literature (Doorenbos & Kassam, 1979; or Hinkle, Gilley and Watts, 1984; or Jensen *et al.*, 1990). For certain crops these ratios can actually be computed in the PUTU 9 programme itself.

Careful scheduling aims at minimizing water applied, V_a, which for a given net irrigation requirement V_n will increase water application efficiency (Equation 1), and hence overall project efficiency (Equation 7).

The limited water supply situation

As explained, when water supply is limited, two situations are possible, viz. those pertaining when supply is controllable or uncontrollable. The latter will be discussed here as all the principles relevant to it may be applied to the former as well.

As a first approximation, the area to be cultivated to given crops can be calculated using the following equations. Where net irrigation requirement is

Table 2 Results of LP optimization of cropped area and irrigation strategy (a,b and e) and irrigation strategy for a fixed cropped area (c,d and f) at two localities. Strategy max indicates irrigation for maximum yield. The numbers in the "Strategy" column denote growth stage in which irrigation less than maximum should be applied (after Mottram, De Jager, Munton-Jackson & Gordijn, 1991c).

		Water Allocation (m ha)	Crop Area	Strategy	Gross Margin (R)
Winterton	(a)	70	50 ha maize	max	67 157
			43 ha wheat	max	
	(b)	60	50 ha maize	max	65 071
			29 ha wheat	max	
	(c)	70	50 ha maize	max	35 100
			50 ha wheat	2.3	
	(d)	60	50 ha maize	5.6	-42 710
			50 ha wheat	1-5	
Rietrivier	(e)	70	50 ha peas	max	60 700
			47 ha soya	max	
	(f)	70	50 ha peas	max	50 900
			50 ha soya	2	

denoted V_n, the size of irrigated area, A, is given by:

Controllable situation:

$$A = \epsilon_a \epsilon_b \frac{AY}{V_n} = 0.5 \frac{MAR}{V_n} \qquad (21)$$

Uncontrollable situation:

$$A = \epsilon_a \epsilon_b \frac{SF_{min}}{V_n} \qquad (22)$$

Such calculations are simplistic however, as they do not take into account the vagaries of weather.

Strategy decisions are, however, more appropriately carried out by matching crop water use to minium water supply rate. The risk of high crop water use at a given site is obtained from curves similar to the illustrated in Figure 6. Here, risk is defined as the probability of non-exceedance of a given seasonal peak weekly water requirement. Such information is obtained by computing the highest weekly AED each year using a crop growth model. The longest period possible for which there are data available must be used. The risk adverse manager using Figure 4 would plan to irrigate fully an area size for which rainless weekly crop water use would not exceed 84 mm/week, a safe practice in 84% of all seasons. For an irrigated area of 100 ha the minimum stream flow (assuming $\epsilon_a = 1$) would thus have to be 84 x 10^3 m^3/week.

Further, to facilitate decisions of this nature, the

entrepreneur requires an indication of yield losses expected for various reduced stream flow rates. For such conditions peak irrigation equals stream flow rate. Once again, crop growth simulations using weekly weather data may be used to compute expected yield for different minimum stream flow rates. The results may be graphically presented as in Figure 7. The large variability to be expected in yield (here expressed as percentage of maximum yield obtainable under ideal water conditions), due to climatic variability, is evident from the figure.

Practical organisational problems

Certain practical issues which have profound influence on the achievement of optimal efficiency upon multi-farm projects have been identified in a situation survey carried out for Little Tugela and Sterkspruit Water Boards near Winterton. Listed below are the salient findings:

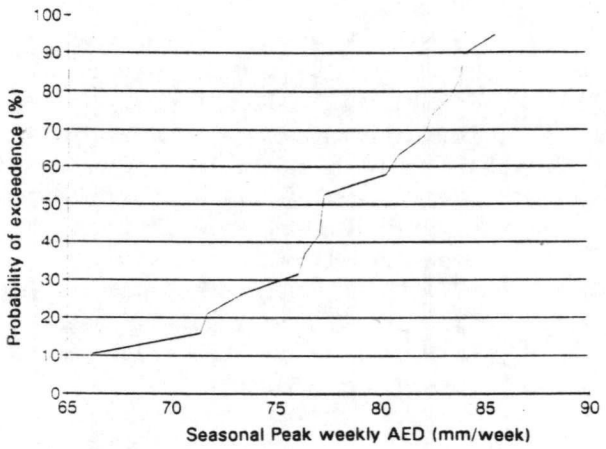


Figure 6 Probability of non-exceedance of given peak water use AED (mm/week) for cotton at Kakamas.

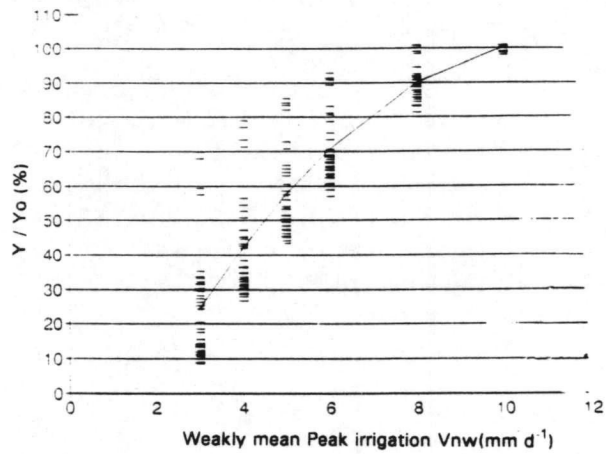


Figure 7 The relationship between weekly average daily possible irrigation water supply rate and relative yield of cotton at Kakamas.

- * Management decisions made at irrigation board level are not always acceptable to all irrigators. This is especially the case with regard to the allocation and distribution of water.
- * When two or more irrigation boards share the same water resource, disputes concerning the allocation and distribution of water can arise between boards.
- * Pre-season planning of allocation of water, either on-farm or at irrigation board level, is rare.
- * Neither accurate nor consistent monitoring of river flow, which is absolutely vital for irrigation scheduling, is undertaken,
- * No monitoring of distribution of water on-farm and between farms is carried out. Normally distribution is on an apportionment schedule and for this to be successful the pump capacity, river flow and scheduled area must be known.
- * No accurate record of irrigation amounts is kept.
- * There is a tendency to over-irrigate.
- * Preplant saturation of soil profiles especially during winter, is common though inadvisable.
- * A tendency exists to cut short irrigation before the crops have reached physiological maturity, with concomitant reduction in yield.
- * Pump systems are not calibrated.
- * Irrigation systems are not always suitable for the soil type, land slope, soil depth and crop type.
- * Little or no irrigation scheduling is practised.
- * There are insufficient storage dams especially where water is provided by stream flow.
- * Basic agronomic practices are not being carried out effectively. For example, as a result of double cropping, seed beds are hastily prepared giving rise to poor plant stands. Maize plant populations tend to be low (40 000 - 50 000 pl ha^{-1}) for production under irrigation. Poor weed control prevails in large areas, probably as a result of spiralling costs.

Many of these shortfalls can be avoided by taking appropriate action where possible, and by careful and continual proactive decision making. Adoption of computer-based management models as described in this article would encourage actions resulting in the elimination of many current shortfalls.

Conclusions and recommendations

The main conclusions which can be drawn from the above discussion could also serve as recommendations for the managing of irrigation on a group of farms. The important aspects are as follows:

- * Accurate estimates of daily AED for the area are required.
- * The use of automatic weather station data together with appropriate software is the most suitable technique for obtaining daily AED for individual farms on a multi-farm project.
- * Available crop growth models should be used to determine:

net irrigation requirements
crop water production functions
irrigation scheduling
climatic influences upon irrigation management.

* Climate variability must be accounted for in management.
* Crop water production functions are needed for maximising irrigation efficiency.
* Crop water production functions are highly sensitive to climate variation and are non-linear. All planning decisions are stochastic by nature.
* Irrigation undertakings must operate in the region of diminishing returns (Phase II).
* Within season water shortage and multi-farm irrigation efficiencies can be optimized using the equimarginal product principle.
* A linear programming model can assist in optimal distribution of water over areas and crops both in pre-season planning and within-season scheduling.

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IRRIGATION MANAGEMENT ON LARGE FARMS, WITH SPECIAL REFERENCE TO THE USE OF A NEUTRON HYDROPROBE

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Introduction

Stillwater Estates is situated on the banks of the Vaal River approximately 30 kilometres northwest of Kimberley. Irrigation water is obtained from the Lower Vaal River Government Water Control Area. Approximately 600 hectares are irrigated, the main crops being table grapes, vegetables and grain crops. There are basically two soil types: a red sandy soil (Hutton form, Mangano series) and a heavier loamy soil (Hutton form, Shorrocks series).

During the development of the farm over the past ten years, it became apparent that a more scientific approach should be used to determine irrigation demand in the vineyards. The method used up to that time was a combination of managerial judgement supported by soil sampling with hand augers and adjustments to fixed irrigation schedules according to rainfall and climate.

Water restrictions imposed on the farm from April 1983 through to 1986 made the optimum use of limited irrigation water necessary. During this period, management had only two options to consider: firstly, to find an additional source of water to supplement available irrigation water; and secondly, to utilise the existing water quota as efficiently as possible.

The first option proved to be very costly and unable to yield water of sufficient quantity in the short time-span available. Two boreholes sunk at the most logical positions were both found to be dry.

It was then decided to exploit the second option by implementing a series of measures designed to make the most effective use possible of available water. All open irrigation furrows were replaced with pipelines and flood irrigation in vineyards was replaced with drip irrigation. A manual irrigation control system was replaced by a Motorola MIR 3000 irrigation computer. Finally the existing scheduling system was replaced with a more sophisticated system using a neutron hydroprobe. The large number of vineyards to be monitored was the main reason for the decision to use a neutron probe with the capability of storing data. At the time, the cost of a sound, second-hand probe was approximately equivalent to that of equipping 54 vineyards with tensiometers. Moreover, had tensiometers been selected, at least 162 would have had to be maintained and monitored. Acquiring and processing this quantity of tensiometer data for timeous use by the irrigation computer would have proved impractical.

In this paper we describe the development of the irrigation management system using the neutron probe, its application, and its advantages and disadvantages.

Development of the Irrigation Management System

After purchasing the neutron hydroprobe (Model CPN 503 DR) for use in irrigation management of table grapes at Stillwater Estates, the main concern was to immediately implement an irrigation scheduling methodology which could be adjusted and refined with experience, rather than to initiate a research programme to establish an optimal methodology prior to implementation. Professor ATP Bennie (Department of Soil Science, University of the Orange Free State, Bloemfontein) was requested to assist in the development and refinement of such an irrigation management system based on neutron probe readings.

For each soil type, the lower limit (permanent wilting point) and upper limit (field capacity) of plant available water capacity were determined. Three steps were involved in arriving at the most appropriate values. The first step was to use historical data to identify vineyards with a history of good growth, high yields and fruit of acceptable quality. It was assumed that observations in these vineyards would provide a good starting point for establishing the range over which management could permit soil water content to fluctuate. The second step was to withhold irrigation on a section of this vineyard for a period long enough to allow *in situ* determinations of the lower limit of available water to be made. Thereafter, in the same vineyard, ponds were constructed and filled with water to ensure that thorough wetting of the entire soil profile would take place. Regular readings were then taken as the profile drained so that the upper limit of plant available water could be determined. The final step was to take soil samples for textural analysis by the University of the Orange Free State. This was to confirm that previously published relationships between soil texture and limits of plant available water are valid for Stillwater Estates and to enable the use of textural analysis to refine initial estimates of the upper and lower limits of plant available water for various vineyards.

Once having established the upper and lower limits of available water in that part of the soil profile from which water is extracted by plant roots, it was possible to set realistic soil water content levels for the control of irrigation. A "start irrigation" level was set to coincide with a soil water content halfway between the upper and lower limits. A "stop irrigation" level was made to coincide with a deficit of 30 mm below the upper limit. In this way, a reserve capacity of at least 30 mm is left to allow for interception and effective storage of rainfall, a most important consideration when the effective use of available irrigation water

needs to be maximised. Ideally, soil water content should be managed so that fluctuations are contained between the "stop" and "start" levels. However, at times when it is not possible to prevent the water content from declining below the "start" level, it is useful to be aware of the "critical" level, set at 33% of the range from the lower limit to the upper limit.

Having determined these irrigation control parameters (expressed in terms of mm of water in a 2 m depth of soil), neutron probe measurements allow the water content of the root zone to be calculated and expressed as an irrigation shortfall, i.e. the difference, in mm, between the "stop" level and the actual soil water content. The demand of a block can then be calculated in m^3 of water, by multiplying the shortfall with the area of that particular block. The data are processed on a Lotus 1-2-3 spreadsheet and presented in a format which permits them to be manually fed into the Motorola MIR 3000 irrigation controller. This is the only point in the management system where data is actually handled by the staff.

In the field, two 40 mm galvanised steel pipes per block were installed as neutron probe access tubes. Readings are taken at each of three depths, these being 250 mm, 750 mm and 1 500 mm. The readings are used to calculate the average water availability per 2 meter soil profile for each access tube position. The data for these two positions per vineyard are then further averaged and used to deduce the average irrigation shortfall for the vineyard block.

Application and Use

In practice, soil water content readings are taken once a week, each measurement cycle comprising a total of 381 readings. These readings are stored in the memory of the hydroprobe along with the ID number of each access tube. The shortest possible counting time on the hydroprobe, viz. one second, is used. The data are dumped onto a PC which does the calculations, prints graphs showing the fluctuating soil water status of each block and transforms the data to a form acceptable to the irrigation computer. It takes approximately six hours from the start of the neutron probe measurement cycle to the point where processed data is entered into the Motorola irrigation computer. Once the Motorola has received the new readings, it is ready to proceed with irrigation aimed at replenishing the particular shortfall in each of the vineyards.

Advantages

The accuracy of the neutron hydroprobe in irrigation scheduling applications, compared to other methods of scheduling, is well known. Once the necessary parameter values for each soil type have been determined, the management of the estate can rest assured that the maintenance of a sound soil water regime is easily attainable.

Secondly, the advantages of speed and ease of application of the system make it very attractive to management. It is important to have irrigation shortfall data almost immediately available once readings have been taken. Very large volumes of data can be handled by the system with ease.

Thirdly, once the system has been set up and is operating, it has proved fairly simple to train farm labour to perform the tasks required by the system.

Disadvantages

The cost of all the components necessary to make a system of the kind described operational can only be justified on larger farms or for a group of farmers who agree to co-operate. The high capital outlay is due to the cost of the hydroprobe, galvanised steel pipes and a personal computer and printer.

Farmers will usually require professional help and knowledge to initiate and maintain the system. In our case most of the expertise needed was provided by the Soil Science Department of the University of the Orange Free State. The exception was the software development, done jointly by the farm management and a computer company in Kimberley.

The hydroprobe, because it is a radioactive instrument, needs to be stored, transported handled in a way prescribed by the Atomic Energy Board. Owners are also subjected to inspections and annual reports as prescribed by the Atomic Energy Act of 1967. Because of the radiation risk, special care has to be taken to adequately protect and train the staff in the handling of the instrument.

Knowledge of the physical properties of each land, e.g. depth, drainage and soil type, is necessary. Investigations, needed to determine and refine parameter values for each soil type, need to be ongoing. One should ideally also have a good knowledge of the irrigation requirements of each specific cultivar.

Our experience has shown that the hydroprobe cannot be used as successfully for managing irrigation of shallow-rooted crops as it can for deep-rooted crops. Finally, the system is not as suited to cash crops as it is to permanent crops. With cash crops, the access tubes have to be removed prior to each cultivation and replaced after the crop has been planted. Also, the computer programs presently in use have difficulty in accommodating the changes to the positions and ID numbers of access tubes which are frequently necessary in the case of cash crops.

Conclusions

Over the past five years, the system of irrigation scheduling described above has proved to be well suited to the needs of Sillwater Estates, and is living up to expectations. It must be stressed, however, that parameter values for each soil type and irrigation block should be reviewed on an annual basis. Furthermore, as with any irrigation scheduling method, it is

advisable to carry out performance checks from time to time.

IRRIGATION WATER DISTRIBUTION MANAGEMENT USING LINEAR PROGRAMMING

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Abstract
The aim of the research was to develop a linear programming model which provides guidelines for planning crop rotations and planting areas. The first case considered was for pre-season planning when there is a known volume of water available for that season. The second scenario examined was where no pre-season planning has taken place and various crops were planted and water restrictions have to be imposed during the season. A description of how this approach may be applied to both these situations is presented. The irrigation areas chosen for this study were the Rietrivier area where dried peas or wheat are grown in rotation with soyabeans, and the Winterton irrigation schemes where maize, soyabeans and wheat are the main crops grown. The necessary inputs and linear programming matrix were determined and the results calculated for the irrigation areas studied. For the first scenario it appears to be most profitable to reduce area planted in order to maximise gross margin. For the second scenario the system determines the extent of irrigation reduction in each crop growth stage which will maximise gross margin. Because of simplifying assumptions requiring revision, this must be considered a preliminary study.

Introduction

Regional and local irrigation boards are formed in order that irrigators in a particular catchment, or along a demarcated stretch of river, may control water allocations within their system. Water management decisions are generally based upon the experience of one or more of the board members. This subjectivity is perhaps the major cause of variation in system performance. Normally the distribution of water within these boards is on an apportionment schedule, where irrigators register scheduled areas of land to be irrigated during a minimum period of three years. When water is limited, the principle of sharing water *pro rata* per hectare of scheduled land breaks down if, for reasons other than water availability, a substantial land area was not planted, and surplus water must then be re-shared *pro rata* per hectare of scheduled land planted. Such re-allocation does not benefit irrigators who, in their forward planning, voluntarily reduced land areas planted in a particular season.

This paper is aimed at developing and illustrating procedures for deciding on the distribution of water within an irrigation system. Because of the preliminary nature of the study and the use of simplifying assumptions, some unanswered questions are likely to remain.

Linear programming frameworks, with design and cost estimating procedures to evaluate the economics of irrigating with less than optimum water supply, have been developed. Irrigation costs were reduced with less water applied, but in practice other input costs remain the same.

Pre-season planning involves determination of water supply, from water storage and/or seasonal river flow, and thereafter a selection and costing of climatically suitable crops. By utilising linear programming (LP), areas under production and suitable crops are selected to maximise profits with imposed water restraints. The inputs required are variable crop production costs, crop water requirements, water stress induced yield deficit factors, and product prices. The LP output, having economically selected the areas to be placed under production, allocates the water available for distribution to specific crop growth periods during the season, using water stress induced yield deficit factors.

Two scenarios are examined in this paper, namely the Rietrivier soyabean-pea/wheat crop rotation, and the Winterton maize-wheat-soyabean crop rotation. In each case, results indicated that in order to maximise profit with imposed water restrictions, the area planted to certain of the rotation crops must be reduced rather than water stress being imposed during the growing season. The LP model is used to determine which crop in the rotation should have a reduced planted area and the extent of this area.

In most instances the situation arises where no pre-season planning has been implemented and the full scheduled area has been planted. The irrigation board is now faced with having to satisfy its members. The LP model (Eastern Software Products, 1987) can be used to determine during which crop growth stage water restrictions should be imposed in order to maximise gross margin. The output also indicates what returns can be expected from each crop enterprise.

Methodology

In the Rietrivier area, rainfall is ignored as it is relatively insignificant for crop production and total irrigation is practised with all irrigation water being supplied from storage dams i.e. water supply is controlled but limited.

In the Winterton area, rainfall plays a significant role in summer and supplementary irrigation is practised. The irrigation water is supplied either by (a) dam and river, i.e. controlled and limited or (b) river

alone i.e. uncontrolled and limited. In applying the LP model, winter rainfall was ignored and it was assumed that summer rainfall was 50% effective in the Winterton area. Long term mean monthly rainfall totals for the summer months were incorporated in the model.

Table 1 presents the crop production costs, which, with the exception of those for peas (K. Hogg, NLK, Winterton. Personal communication, 1991), were extrapolated from COMBUD figures (COMBUD, 1990) and exclude irrigation costs.

Initially, the simplifying assumption was made that irrigation and application efficiencies are unity. This will eventually have to be revised. For the present, however, such assumptions greatly simplify computation, because crop evaporation may be assumed equivalent to irrigation when irrigation applied is deficient.

Table 1 Crop production costs and selling prices of various crops produced under irrigation in 1991.

Crop	Production Cost (R ha^{-1})	Selling Price (R kg^{-1})
Maize (9 t ha^{-1})	2 010	0.260
Wheat (5-7 t ha^{-1})	1 764	0.373
Soyabeans (3 t ha^{-1})	1 236	0.588
Peas	942	1.000

For the purposes of the linear programme, irrigation costs were allocated in Rands per millimetre of water applied, to allow for the variable costs when irrigating at different levels. The figure of R1.00 per millimetre was used, taking into account equipment and irrigation system repairs, power utilised in irrigation, and irrigation motor and pump repairs.

Six crop growth stages were recognised, these being establishment, development, mid-season, flowering, grain formation and ripening.

The total water requirement for optimum yield production of each crop was estimated to be:

Maize	1 000 mm
Wheat	700 mm
Soyabeans	900 mm
Peas	550 mm

The water requirements during each stage are dependent upon climate and length of the growth stage. The water required to produce an unstressed yield is equivalent to AED, the atmospheric evaporative demand (De Jager & Van Zyl, 1989). For each growth stage, i, long term

(a) climatic norms of stage reference evaporation, Eo_i, and

(b) irrigation system type average crop evaporation coefficient, kc_i

as required to estimate AED_i from

$$AED_i = kc_iEo_i$$
$$AED = \Sigma AED_i$$
$$= kc_1Eo_1 + kc_2Eo_2 \ldots . kc_iEo_i \quad (1)$$

where,

AED_i = Atmospheric evaporative demand in the ith crop growth stage (mm)

AED = Total atmospheric evaporative demand (mm)

kc_i = Crop evaporation coefficient for the ith growth stage

Eo_i = Reference crop evaporation for ith growth stage (mm)

For the purpose of illustrating the linear programming techniques, AED_i was estimated for each growth stage and crop. These values are given in Table 2.

Table 2 Estimated water requirements AED_i during the six stages of each crop (mm).

Growth stage	Crop			
	M Maize	W Wheat	S Soya-	P Peas
1 Establishment	73	58	78	46
2 Development	73	67	91	63
3 Mid-season	146	105	130	114
4 Flowering	244	211	287	167
5 Grain formation	268	173	196	114
6 Ripening	196	86	118	46
TOTAL	1000	700	900	550

The model uses irrigation reductions below optimal in 10 mm steps from 0 mm (no water limitation) to 50 mm (i.e. 50 mm less irrigation than is required for a given growth stage). Two assumptions explained in De Jager & Mottram (1991) were made:

i) irrigation requirements were assumed equivalent to AED;

ii) irrigation efficiency was assumed to be unity so that reduction in irrigation amount was deemed equivalent to reduction in AED.

Six irrigation levels were applied to each growth stage and the subsequent yield reductions calculated. Here the approach of Doorenbos & Kassam (1979) was used to calculate the yield reduction for different growth stages and irrigation levels. This approach utilises the concept of relative yield deficit, RYD, being directly proportional to relative evaporation deficit, RED. Unfortunately Doorenbos & Kassem (1979) do not

indicate how yield deficits in the different growth stages should be combined. Hence the theory of additive limitation (De Jager, Van Zyl, Kelbe & Singels, 1987) constrained to 100% total yield reduction was adopted, i.e. seasonal yield reduction was assumed to be the aggregate of yield reduction due to water stress in each growth stage.

$$RYD = 1 - Y/Yo \text{ and} \quad (2)$$
$$RED = 1 - E/AED \quad (3)$$

where,

- Y = yield produced under less than ideal water conditions (kg ha^{-1})
- Y_o = potential yield (kg ha^{-1})
- E = actual crop evaporation (mm)
- AED = total maximum crop evaporation required to produce potential yield (assumed equal to atmospheric evaporative demand)(mm)

The fundamental yield equation is,

$$RYD = ky.RED \quad (4)$$

where,

- ky = yield reduction factor

and hence,

$$Y = Yo(1 - ky.RED) \quad (5)$$

For the ith growth stage

$$RED_i = 1 - E_i/AED_i \quad (6)$$

De Jager *et al.* (1987) applied the additive law of limitation. Thus for a season of n growth stages each having its own ky_i

$$Y = Yo\ (1 - \sum_{i}^{n} ky_i.RED_i) \quad (7)$$

The potential yields selected for each crop (ideal nutrient and soil water conditions) are:

Maize	11 000 kg ha^{-1}
Wheat	7 000 kg ha^{-1}
Soyabeans	4 000 kg ha^{-1}
Peas	2 500 kg ha^{-1}

The yield reduction factors, ky (Doorenbos & Pruitt, 1977), used to calculate reduction in yield due to water stress are shown in Table 3.

Equation 7 was used to calculate the yield reductions in Table 4.

For the purposes of the linear programme, an economic return (gross margin) was calculated for each growth stage at each irrigation level as follows:

$$Ri = [(Yo/n)-YD)].SP - (PC/n) - ICi \quad (8)$$

where,

- Ri = Gross margin for growth stage i
- Yo = Potential yield
- n = Number of crop growth stages i
- YD = Yield deficit
- SP = Selling price
- PC = Production costs
- ICi = Irrigation costs for growth stage i

Table 3 Yield reduction factors used in calculating yield reduction in each of the six growth stages.

	Maize	Wheat	Soya-Beans	Peas
ky_1	0.40	0.20	0.20	0.20
ky_2	0.70	0.20	0.20	0.30
ky_3	0.50	0.30	0.60	0.90
ky_4	2.20	0.65	0.80	0.70
ky_5	0.60	0.55	1.00	0.25
ky_6	0.40	0.40	0.40	0.20

Division of Yo and PC by n has no physical meaning, but is a theoretical ploy to enable the LP programme to function properly.

The method of calculation YD for given irrigation reductions and necessary assumptions is provided in De Jager *et al.* (1991).

The objective of the LP model is to maximise gross margin at any specified water availability. The form of the objective function is:

$$MAX \sum_{\substack{c=1 \\ 1=1}}^{d,i} A_c * R_c,i \quad (9)$$

where the objective function is expressed in Rands.

- c = crop type
- d = number of crops
- i = 1-6 growth stages
- A_c = Area planted to crop c
- $R_{c,i}$ = gross margin for crop c in the ith growth stage

The variables are the different irrigation levels of each crop growth stage. The returns due to each of these are computed and used in the objective function.

The constraints are land (ha) and water availability (mm ha). The unit mm ha represents the number of millimetres of water available to the crops over the two seasons multiplied by the number of hectares. For example, 70 000 mm ha represents 1 400 mm available over two seasons multiplied by 50 ha.

Results

Example 1

A wheat, maize, soyabean rotation was selected in the

Table 4 Yield reductions for different growth stages and irrigation levels for the crops under study.

Water Reduction (mm)	Maize yield deficits for growth stages 1 to 6 (kg ha^{-1})					
	M1	M2	M3	M4	M5	M6
0	0	0	0	0	0	0
10	603	1055	377	992	246	224
20	1205	2110	753	1984	493	449
30	1808	3164	1130	2975	739	673
40	2411	4219	1507	3967	985	898
50	3014	5274	1884	4959	1231	1122

Water Reduction (mm)	Wheat yield deficits for growth stages 1 to 6 (kg ha^{-1})					
	W1	W2	W3	W4	W5	W6
0	0	0	0	0	0	0
10	241	209	200	216	223	326
20	483	418	400	431	445	651
30	724	627	600	647	668	977
40	966	836	800	863	890	1302
50	1207	1045	1000	1078	1113	1628

Water Reduction (mm)	Soyabean yield deficits for growth stages 1 to 6 kg ha^{-1})					
	S1	S2	S3	S4	S5	S6
0	0	0	0	0	0	0
10	103	88	185	111	204	136
20	205	176	369	223	408	271
30	308	264	554	334	612	407
40	410	352	738	446	816	542
50	513	440	923	557	1020	678

Water Reduction (mm)	Pea yield deficits for growth stages 1 to 6 (kg ha^{-1})					
	P1	P2	P3	P4	P5	P6
0	0	0	0	0	0	0
10	109	119	197	105	55	109
20	209	238	395	210	110	217
30	217	357	592	314	164	326
40	435	476	789	419	219	435
50	543	595	987	524	274	543

Winterton area. The restraint on available irrigated area was 50 ha and the restraint on the amount of irrigation water available for the two seasons was 70 000 mm ha, which is insufficient to satisfy the full requirements of any two of these crops.

The solution obtained from the LP model indicated that, in order to maximise profits from these enterprises, there should be no reduction in irrigation but rather a reduction in land area planted.

The rotation selected in this example was 50 ha maize in the summer season and 28.57 ha wheat in the winter season.

Unused land was therefore 21.43 ha in the winter season. The overall total gross margin (profit) from both enterprises was R35 171.43.

It should be noted that the selling price of maize used in this model (R330 per tonne) was that offered by Rainbow Chicken Farms (Pty) Ltd in their maize production scheme. The reason for using this price was that, using the selling price of maize indicated in the COMBUD report (R260 per tonne), maize was never selected in preference to soyabeans.

Example 2

The wheat, maize, soyabean rotation in the Winterton area was again studied, with the amount of irrigation water available being 70 000 mm ha, as in Example 1. However the area planted was fixed at the full 50 ha, making irrigation deficits during the growing periods unavoidable. This scenario reflects no pre-season planning.

The rotation selected by the LP model in this example, and in particular the timing of irrigation deficits, is indicated below:

Summer: 50ha soyabeans, irrigated as follows:
- 1st gr. stage - 50 mm reduced (28 mm applied)
- 2nd " " - 50 mm reduced (41 mm applied)
- 3rd " " - full irrigation (130 mm applied)
- 4th " " - 50 mm reduced (237 mm applied)
- 5th " " - full irrigation (196 mm applied)
- 6th " " - full irrigation (118 mm applied)

Winter: 50 ha wheat, irrigated as follows:
- 1st gr. stage - full irrigation (58 mm applied)
- 2nd " " - 40mm reduced (27 mm applied)
- 3rd " " - 50mm reduced (55 mm applied)
- 4th " " - full irrigation (211 mm applied)
- 5th " " - full irrigation (173 mm applied)
- 6th " " - full irrigation (86 mm applied)

The gross margin (net loss) of these two enterprises is -R34 900.00. This is assuming that input costs are not reduced despite the fact that optimum yield is no longer possible. In order to minimise loss in the case where no pre-season planning has taken place, the farmer could attempt to reduce input costs during the remainder of the growing season.

As the objective was to maximise return (gross margin), it can be inferred that had 50 ha maize been planted instead of soyabeans in the summer season, an even greater economic loss would have been suffered.

Example 3

A wheat, pea, soyabean rotation was selected in the Rietrivier area. The maximum irrigated area was

50 ha and the amount of irrigation water available was 50 000 mm ha, which is insufficient to satisfy the full requirements of any two of these crops.

As in Example 1, results indicate that, in order to maximise profits, there should be no reduction in irrigation but rather a reduction in land area planted.

The rotation selected was 50 ha peas in the winter season and 25 ha soyabeans in the summer season. Unused land is therefore 25 ha in the summer season. The gross margin (net profit) from these two enterprises is R55 900.00.

Example 4

The wheat, pea, soyabean rotation, prices and costs in Example 3 were again used, but land area planted was fixed at the full 50 ha for both summer and winter crops. The selection by the LP model is indicated below.

Summer: 50 ha soyabeans, irrigated as follows:
1st gr. stage - 50 mm reduced (28 mm applied)
2nd " " - 50 mm reduced (41 mm applied)
3rd " " - 50 mm reduced (80 mm applied)
4th " " - 50 mm reduced (237 mm applied)
5th " " - full irrigation (196 mm applied)
6th " " - full irrigation (68 mm applied)

Winter: 50 ha peas, irrigated as follows:
1st gr. stage - 40 mm reduced (6 mm applied)
2nd " " - 30 mm reduced (33 mm applied)
3rd " " - full irrigation (114 mm applied)
4th " " - 50 mm reduced (117 mm applied)
5th " " - 50 mm reduced (64 mm applied)
6th " " - 40 mm reduced (6 mm applied)

The gross margin (net loss) from these two enterprises is -R102 900.00. The large difference between Examples 3 and 4 is due mainly to yield reductions in Example 4 resulting from severe water deficits being incurred.

Discussion

The value and effectiveness of the method has been demonstrated. The results must, at this stage, be considered preliminary for various reasons (mostly due to the simplifying assumptions). Aspects which may benefit from reconsideration are the following:

a) The economic inputs, particularly the cost of applied irrigation water.
b) The theory of additive yield reduction could possibly be replaced by a multiplicative theory or the law of the minimum.
c) Rainfall has to be accounted for. This could be done quite easily using long term averages.
d) Adjustments to irrigation and water use efficiencies are required.

The optimization method applied here is an application of the procedure suggested by De Jager *et al.* (1991) for maximizing profit on a multi-farm or multi-plot project. This is so, since linear programming applies the equimarginal principle. The method here presented differs only in that the linear programme matrix is constructed using RYD based upon the simplifying assumptions listed above, instead of being a crop growth model. The latter should be more accurate because it takes climatic variation (particularly rainfall) into account. Both methods have the advantage of determining optimal water application in each growth stage.

The overall solution for pre-season planning, that maximum yield should be striven for on reduced areas, is most important but must be considered a preliminary result because of the assumptions made. It could change as the limitations listed in the previous paragraph are addressed.

Conclusion

The use of the LP model indicates that, in order to maximise gross margin under conditions of limited water availability, the planted area should be reduced and the crop irrigated to achieve maximum yield, rather than reducing the amount of irrigation water applied.

Furthermore, the LP model can be utili effectively to help schedule irrigation in a situation where no pre-season planning has taken place. The method determines the extent to which irrigation should be reduced in each crop growth stage in order to maximise gross margins.

This has been a preliminary study. Many simplifying assumptions were introduced. Particularly, some of the water use and economic inputs require revision.

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IRRIGATION SCHEDULING OF CROPS USING NEAR REAL TIME WEATHER DATA

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Abstract
Automatic weather stations continuously record weather data which are retrieved either manually or via telecommunication networks. Simulation models use these data to schedule irrigation in specific areas. Appropriate software is employed to transform the data and calculate reference crop evaporation using the Penman-Monteith equation. The crop growth simulation model, PUTIRRI, computes the atmospheric evaporative demand by multiplying the reference crop evaporation by a crop coefficient which varies throughout the crop's growth. This crop coefficient is derived from two other coefficients, which in turn reflect soil surface drying and account for the degree of vegetative cover and the ratio of maximum plant evaporation from the crop to reference evaporation. The water budget technique of irrigation scheduling is used. Using near real time weather data enables irrigators, consultants and irrigation boards to keep abreast of crop water requirements and irrigation water allocation on a day to day basis. These models have been successfully used in the Winterton and Karkloof irrigation areas.

Introduction

Competition for our limited water supplies is increasing. This competition does not only exist between the agricultural, municipal and industrial sectors but within the agricultural sector itself. K.O. Bang (Dept. of Agric. Development, Pietermaritzburg. Pers. Comm., 1989) reports that of the surface water resources allocated to irrigation in Southern Africa, up to 30% may be lost before reaching the edge of the cropped surface. Mottram & de Jager (1991), in their review on computerised water management for irrigation projects, emphasised the need for responsible and thrifty management of all aspects of water distribution on irrigation projects. Water can be saved, *inter alia* by scheduling irrigation.

In the recent survey (unpublished IPE project progress report, R. Mottram & J.M. de Jager, 1991) in the Winterton irrigation area, the following problems relating to irrigation scheduling were identified:

- no accurate record of irrigation amounts
- tendency to over-irrigate
- tendency to cut short irrigation before the crops have reached maturity which reduces yields
- little or no irrigation scheduling

These problems are not unique in Southern Africa. In California, CIMIS was initiated in 1982 (Hawkins & Cradock, 1985) to achieve greater efficiencies in water use and thus reduce the projected deficit between water supply and use. CIMIS' strategy was to develop a weather station network and computerised data dissemination system, develop irrigation scheduling programmes, verify the accuracy and utility of water budget scheduling on-farm, and conduct adaptive research to improve water budget scheduling technologies. Slabber (1989) attributes the disappointing levels of performance encountered in many recently constructed irrigation schemes in developing countries to the large differences between irrigation theory and practice.

In Southern Africa, the Water Research Commission is promoting research on maximising irrigation project efficiencies (the IPE project).

The objectives of this paper are to:

a) Describe the simulation models used to calculate the atmospheric evaporative demand used in the water budget technique employed.
b) Examine the results of this irrigation scheduling technique.
c) Propose solutions to scheduling irrigation within irrigation areas.

Materials and Methods

Automatic weather stations

Automatic weather stations (AWS) comprising dataloggers and associated sensors, which do not require mains power at the site, were set up in the Winterton and Karkloof irrigation areas. Solar panels are used to supply power to these AWS and the data are either stored on magnetic tape and thereafter downloaded onto computer or, data re-accessed via modems and telecommunication networks (Mottram, De Jager & Savage, 1991).

Hourly values of incoming solar radiation, temperature, relative humidity, wind speed and direction, and rainfall are monitored by these AWS. Where there are no relative humidity sensors, a wet bulb thermometer is installed.

After retrieval, these data are checked, sorted for the most recent 24 h period and then merged into data archives.

Simulation models

DATCON: DATCON is a computer programme in Quickbasic which converts, lists and saves hourly weather data from the AWS in a standard format for use in the PUTEREF programme.

PUTEREF: PUTEREF is a computer programme in Quickbasic which transforms hourly weather data

converted by DATCON, to daily data and calculates reference crop evaporation (Eo). Eo is defined by Doorenbos & Pruitt (1977) as the rate of total evaporation of an extended surface of an 80 to 150 mm tall grass cover of uniform height actively growing, completely shading the ground and not deficient in water or nutrients.

Before PUTEREF can be run a parameter file which contains monthly mean values of the weather variables concerned must be established in order to be able to substitute these for any missing data from the AWS.

De Jager (1984) and De Jager & Van Zyl (1989) suggest that the Penman-Monteith equation provides the best method of determining Eo. De Jager *et al.* (1987) demonstrated the accuracy of using this equation with hourly mean values of relevant weather variables. Equation 1 represents the Penman-Monteith equation to estimate Eo.

$$Eo = \frac{[\Delta(RN-G)+C\rho(e_s(T)-e)\phi_a]}{[\Delta+\gamma(1+\phi_a/\phi_v)]} \quad (1)$$

where

Δ = slope of the saturated vapour pressure vs. temperature curve (at temperature T) (mbar $°C^{-1}$)
Rn = net radiation (mm d^{-1})
G = soil heat flux density (mm d^{-1})
ρ = density of air
C = specific heat of air
$e_s(T)$ = saturated atmospheric vapour pressure (mbar) at T
e = actual atmospheric vapour pressure (mbar)
ϕ_a = atmospheric conductance of gaseous exchange (function of wind speed and crop height)
ϕ_v = conductance of vegetative surface to gaseous water diffusion
γ = psychometric constant (mbar $°C^{-1}$)

PUTIRRI: In order to schedule irrigation it is necessary to determine the atmospheric evaporative demand, AED, which is the water vapour transfer to the atmosphere required to sustain the energy balance of a given vegetative surface, in its present growth stage, when the water status of the root zone permits unhindered plant evaporation and the water status of the top 150mm equals its current value (De Jager & Van Zyl, 1989). It is important to note that this definition of AED acknowledges the dominant influence of the atmospheric conditions, but also basically accounts for crop type, crop growth and surface soil water content.

PUTIRRI determines the daily AED which can vary from 0 to 15 mm d^{-1}.

AED is the upper limit of atmospheric demand from a natural surface on that day.

$$AED = kc.Eo \quad (2)$$

where

kc = appropriate crop coefficient, and
Eo = reference crop evaporation.

This crop coefficient, kc, may be defined as

$$kc = kv + ks \quad (3)$$

where

kv = fraction of reference evaporation contributed by plant evaporation to AED
ks = fraction of reference evaporation contributed by soil evaporation to AED

Maximum values of kv and ks exist, namely kvm and ksm respectively. These depend upon crop architecture and soil character and are determined empirically.

The major problems encountered with the use of crop coefficients to determine AED usually stem from failure to account for the variation in kc due to variation in ks as the soil surface dries. Relationships, however, exist which can account for this variation (De Jager & Van Zyl, 1989). These are of the form:

kc = f (crop growth stage)
kv = f (leaf area index, plant water status)
ks = f (time since last wetting event)
= f (water deficit below the upper limit of soil water content in the top layer of soil)

PUTIRRI computes kv, ks and kc and determines the AED each day in the manner illustrated in Figure. 1. The influence of plant water status upon kv is evaluated with the help of an iterative procedure (see de Jager & Singels, 1985; De Jager, Van Zyl, Kelbe & Singels, 1987).

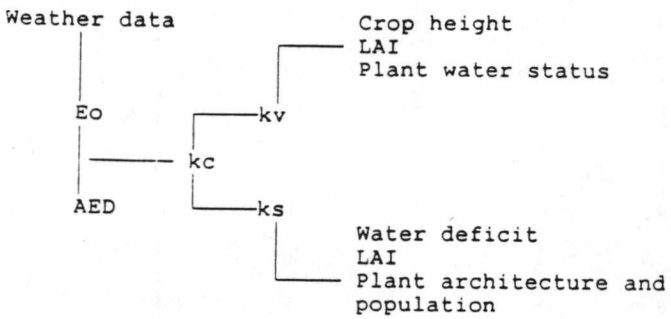


Figure 1 Schematic diagram illustrating the computational procedure for determining AED.

The soil water balance equation employed in PUTIRRI is

$$W = Wo + I + R - D + \Delta W - AED \quad (4)$$

where

W = soil water content (mm)
Wo = soil water content at 24h00 (mm, i.e. ontent

at end of previous day

I = irrigation amount (mm)

R = rainfall (mm)

D = drainage out of the root zone (mm)

ΔW = change in soil water content due to root extension and capillary flow

AED = atmospheric evaporative demand (mm)

The inputs for PUTIRRI are daily weather data and specific plant and soil characteristics. The programme determines the soil water balance for nine soil layers, after requesting the depth of each of these layers. The source code of PUTU9-86, the original scheduling programme upon which PUTIRRI is based, may be found in De Jager *et al.* (1987).

Results and discussion

Table 1 illustrates an output of PUTEREF for AWS 11 in the Winterton area.

Table 1 Daily weather data computer from hourly weather variables collected from Station 11, Winterton, using the reference crop evaporation model, PUTEREF.

DOY	Tmax	Tmin	RAIN	RADD	Eo	SVDD
168	19.8	1.4	0	11.7	2.2	16.2
169	15.4	1.3	0	10.0	2.3	14.1
170	14.9	-1.7	0	12.5	2.2	12.1
171	19.2	-1.2	0	11.3	1.8	15.0
172	21.8	4.7	0	12.6	4.5	19.5

where,

DOY = day of year

Tmax = maximum temperature (°C)

Tmin = minimum temperature (°C)

RAIN = rainfall (mm)

RADD = mean incoming solar radiation (MJ $d^{-1}m^{-2}$)

Eo = reference crop evaporation (mm)

SVDD = calculated saturated vapour pressure deficit (mbar)

Accumulated values of evaporation from a Class A pan, reference crop evaporation estimated using the Penman-Monteith equation and actual crop evaporation from a short grass sward growing in a weighing lysimeter (W.H. van Zyl, Univ. of the O.F.S., Bloemfontein. Pers. Comm., 1991) are compared in Figure 2.

Figure 2 illustrates the overestimation of crop evaporation by Class A pan evaporation and to a much lesser extent by Eo. The overestimation of Eo can be attributed to the fact that the grass sward growing in the lysimeter was not of uniform height and not 150 mm tall. The overestimation using the Class A pan is substantiated by van Zyl, de Jager & Maree (1989) in their comparisons using wheat growing in a lysimeter. Hundal & Sandhu (1989) found that pan

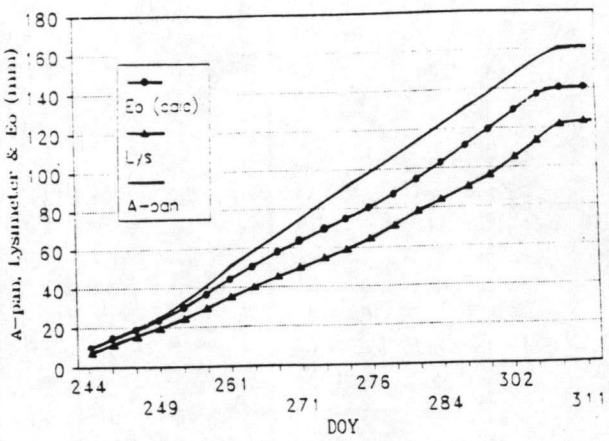


Figure 2 Comparison between cumulative reference evaporation, E_o, calculated using the Penman-Monteith equation and cumulative short grass evaporation measured in a lysimeter and cumulative A-pan evaporation during spring on the West Campus of the UOFS.

evaporation overestimated both actual and potential crop evaporation from maize over two seasons by between 15 and 90% and 6 and 50% respectively.

Table 2 illustrates an output of PUTIRRI for AWS 11 in the Winteron area.

The water stress factor, Fw, in Table 2 is determined by an iteration process for each day, climate and soil condition. It is expressed as the fraction of physiological water stress existing in the crop. The method of computation is described in De Jager *et al.* (1987) and executed using the following relationships. The equations pertaining to soil evaporation, Es, are included for completeness.

$$Ev = kv\ Eo \quad (5)$$

$$Es = ks\ Eo \quad (6)$$

$$kv = kvm\ Fv\ (1 - Fw) \quad (7)$$

$$ks = ksm\ Fg\ (1 - Fv) \quad (8)$$

where

FW = water stress factor (0-100)

LAI = leaf area index (%)

IR = irrigation amount (mm)

PERC = drainage out of root zone (mm)

PPAW = relative (profile) plant available water (%)

AED = atmospheric evaporative demand (mm)

DEF = water deficit below the upper limit (mm)
= maximum amount of water required (mm)

Thus actual crop evaporation, E, is given by

$$E = Ev + Es \quad (9)$$

Table 2 Daily output of crop growth, water use and requirement using the simulation model, PUTIRRI, with data from Station 11, Winterton.

Farmer's name: FREESE — Land no: GROOTDRAAI TOP

Plant population: 300 pl m^{-2} — Crop: Wheat (Gamtoos) — Planting date: 1-6-1990

Soil description: Hutton — Effective rooting depth: 0.8 m

Soil water content: ($mm\ m^{-1}$) Upper limit - 263; Lower limit - 144; Initial - 248

DOY	FW (%)	LAI (%)	IR (mm)	RAIN (mm)	PERC (mm)	PPAW (%)	AED (mm)	DEF (mm)
168	0	12	0	0	0	52	0.9	26
169	0	12	6	0	0	50	1.0	27
170	0	12	5	0	0	59	1.0	22
171	0	12	0	0	0	66	1.1	18
172	0	14	0	0	0	61	2.6	21

where FW = water stress factor (0-100)
LAI = leaf area index (%)
IR = irrigation amount (mm)
PERC = drainage out of root zone (mm)
PPAW = relative (profile) plant available water (%)
AED = atmospheric evaporative demand (mm)
DEF = water deficit below the upper limit (mm)
= maximum amount of water required (mm)

Fv is a normalized factor reflecting the degree of vegetative ground cover. For kvm = 1 and Fw = 0 it expresses plant evaporation as a fraction of Eo. The value of Fv is read as input from the parameter file, or calculated from simulated leaf area index. Thereafter, since a non-linear equation defying solution by conventional methods, is involved, Fw can only be determined by an iteration process in PUTIRRI. Essentially a single equation is solved for two unknowns, daily transpiration rate and leaf water potential (see De Jager *et al.*, 1987).

The water deficit below the upper limit, DEF, is the amount of water required to replenish the soil profile (root zone). Should the irrigator not irrigate on the planned day, the soil water deficit will continue to be incremented in accordance with real time data until such time as he is able to do so. The Fw value must be examined each day during this irrigation delay to avoid imposing excessive stress on the crop. Monitoring Fw is vital when deficit irrigation is being practised.

Water management trials using PUTIRRI were conducted on selected farms in the Winterton area. These involved running the models for each irrigation system and in each case comparing the crop yields with those of the surrounding farms/lands. The latter were obtained from the farmers and the local farmers' cooperatives.

With respect to crop yield increments, Table 3 illustrates the benefit of irrigation scheduling. No comparisons could be made with the water used by the surrounding areas as no irrigation amounts are recorded by the irrigators and many of the water delivery systems need to be calibrated to ensure uniform water application.

The economic yield increases due to this type of irrigation scheduling have motivated the Winterton Irrigation Boards to adopt the techniques outlined in this paper for the purpose of allocating water to their

Table 3 Crop yields obtained using PUTIRRI as compared to the mean yield of surrounding areas/lands in the Winterton area.

Farm	Season	Crop	PUTIRRI		Surrounding area - crop yield ($kgha^{-1}$)
			Crop yield ($kgha^{-1}$)	Water applied (mm)	
A Muirhead	89/90	Soyabeans	2950	680	1800-2300
J Muirhead	89/90	Soyabeans	2700	680	1800-2300
D Sclanders	89/90	Maize	9800	740	7800
J Muirhead	90	Wheat	6100	420	4000-4900
L Freese	90	Wheat	6500	420	4000-4900

members.

Conclusion

Automatic weather stations enable a computerised weather network to be established in order that data may be collected, collated and crop water use values disseminated sufficiently timeously to enable irrigators to react before yield-reducing crop water stress occurs. The simulation models and programmes used in the IPE project have proved successful in the Winterton area during the past two seasons, with profitable results for the irrigator. The operation of these models is relatively simple for an operator with basic hands-on computer knowledge and experience. However, experience suggests that before irrigators can themselves use these models, they would have to understand the basics of water budgeting and gain the ability to develop a typical irrigation schedule to assist them with advance planning.

Efficient use of water is not only dependent upon good irrigation scheduling but also the ability to apply irrigation water uniformly and accurately. For these reasons it is suggested that specialist consultants have a role to play in a number of irrigation districts in the setting up and operating of AWS and irrigation scheduling programmes and in implementing irrigation system evaluation programmes for the benefit of the irrigation community.

Acknowledgements

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A COMPUTER-BASED PRACTICAL MANAGEMENT PROGRAMME FOR AUTOMATED LINEAR AND CENTRE-PIVOT SYSTEMS

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Introduction

In an overview of practical irrigation scheduling methods, Burgers (1982) recognised the serious lack of scientifically based methods among those generally adopted by farmers. He then proceeded with the development of the so-called *Irrograph*, which was proposed as a practical on-farm irrigation scheduling aid. However, since then it has become evident that, while the Irrograph may work well with a single uniform field of limited size, the normal circumstances on most farms are not that simple and implementation of the *Irrograph* becomes too complicated for even the most progressive farmer.

It appears that most farmers would prefer to schedule irrigation applications to fit in with routine farm activities, often implying a more or less fixed time schedule. At the same time, however, they would like to have the assurance that the water requirements of their crops are met. A fixed schedule which is well planned according to the average atmospheric evaporative demand for the time of the year, the soil profile water retention characteristics, and the design features of the irrigation system could work well, provided the correct amounts of water are applied on the scheduled dates.

1 An accurate estimate of soil water extraction since the previous scheduled application, taking into account any effective rain during the same period, would be essential to such a scheduling procedure. Any such estimate would necessarily involve fairly complicated calculations, which may not be acceptable to most farmers. However, computers are fast becoming an essential facility on farms, and a user-friendly programme which computes the amount of water to be applied on each of the scheduled dates, may well be the answer to the farmer's scheduling problems.

This paper describes a computer programme called IRRISCHED, which should, in particular, facilitate the day to day management of automated centre pivot and linear irrigation systems according to a predetermined time schedule which may be adjusted from day to day, depending on the preferences of the farmer. Crop water use estimates are based on daily pan evaporation readings and all calculations are done by the computer. Graphic displays of the day-to-day profile soil water balance, will indicate to the farmer to what limits his schedule may be stretched without jeopardising his crop due to excessive soil water extraction.

Description of the programme IRRISCHED

The main purpose of the programme is to estimate crop evaporation (E) on a continuous basis, provide for effective rain and then display the estimated soil water deficit (SWD) when the irrigation system arrives at the starting point of a section of the field to be irrigated. The farmer may then decide on an application amount (d) equal to, or smaller than the SWD (as in deficit irrigation) or larger than the SWD (in order to meet the leaching requirements of the soil).

The programme also displays the corresponding speed setting for the control panel of the mechanised irrigation system which would allow the chosen d-value to be applied.

Finally, the programme gives a graphic display of the daily march of the profile soil water balance as affected by soil water extraction, application amounts and effective rain. An imaginary horizontal line on the graph, representing the lower limit of available water or Profile Available Water Capacity (PAWC), as described by Vanassche & Laker (1989), would guide the farmer in the application of a system of deficit irrigation.

The different components of the programme which were highlighted above, as well as the underlying principles on which they are based, are described in more detail in the paragraphs that follow.

Master schedule

The farmer compiles his master schedule according to the way in which he wishes to irrigate his crop by considering the field and crop characteristics, design features of the irrigation system, peak crop water requirements during different growth stages and availability of operators on Saturdays, Sundays and public holidays.

The irrigation field should be divided into convenient units or blocks and properly marked. In the case of the linear system on the University of the North experimental farm, the hydrants on the mother pipe line, spaced at intervals of 200 m, divide the field into 11 blocks of exactly 7.0 ha each.

The *Master Schedule* is now compiled through the following steps:

1. Commence by creating a new schedule at the beginning of a new crop season by entering the planting date on the create a new schedule screen (Figure 1).

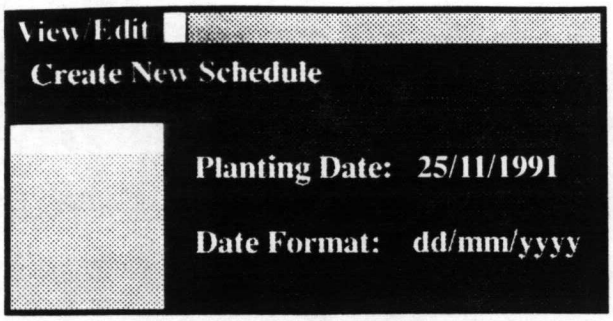


Figure 1 Monitor screen display for the creation of a new irrigation schedule at the start of the cropping season.

2. Enter all relevant information on the *View/Edit* screen regarding: estimated length of crop growing period, number of blocks on the field, minimum application depth (at 100% speed setting), maximum application depth, maximum number of work hours per day, crop planted in each block etc. (Figure 2).

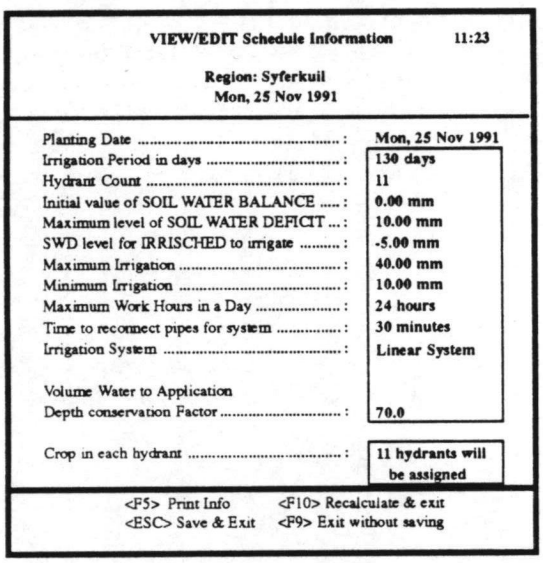


Figure 2 Monitor screen display for setting initial settings regarding schedule and system characteristics.

3. Having entered all the relevant information, the programme would simulate a time schedule for the whole season, indicating dates of arrival at each of the blocks along the field as well as which blocks should be irrigated on particular dates, how much water to apply and what the speed setting should be. The time schedule is displayed on the *Master Schedule* screen as illustrated in Figure 3.
4. The farmer may now adjust the scheduled dates to synchronise with other farming activities by using the appropriate function keys as illustrated in Figure 4.

MASTER SCHEDULE

Date	First Hydrant	Last Hydrant	Schedule for the Day			
			Hydrant	SWB	D(adj)	Speed
Mon, 25 Jan 1992	0	1	1	-47.09	Da=40.00	8.70
Tue, 26 Jan 1992	0	1	2	-18.79	Da=32.00	10.90
Wed, 27 Jan 1992	0	1				
Thu, 28 Jan 1992	0	1				
Fri, 29 Jan 1992	1	2				
Sat, 30 Jan 1992	3	3				
Sun, 31 Jan 1992	0	3				
Sat, 1 Feb 1992	0	3				
Sun, 2 Feb 1992	0	7				
Mon, 3 Feb 1992	4	11				
Tue, 4 Feb 1992	8	9				
Wed, 5 Feb 1992	11	6				

<ESC> Save & Exit <ENTER> Edit Schedule
<F5> Print Schedule <F10> Recalculate "*" Projected Data

Figure 3 Monitor screen display of master schedule for rescheduling or entering actual irrigation amounts.

Date	First Hydrant	Last Hydrant	Schedule for the Day			
			Hydrant	SWB	D(adj)	Speed
EDIT SCHEDULE INFO						
			1	-47.09	Da=40.00	8.70
<ENTER>Edit highligthed hydrant <F2>Add an extra hydrant for this day <F3>Move last hydrant to next day <F5>Print Schedule <ESC>Return to Schedule			2	-18.79	Da=32.00	10.90
			Total Irrigation Time: 22:40 hours			

Figure 4 Monitor screen display when a particular date in the schedule is selected for modification or updating.

Through these function keys it is possible to add or delete blocks to be irrigated on a particular date. The estimated application amounts will then automatically be adjusted by the programme according to daily crop evaporation or the farmer can adjust them manually on the *Master Schedule edit screen* (Figure 5), in order to satisfy his own circumstances.

Day to day operation

Simulation of the *Master Schedule* was done with the aid of an *on board data file* (OBDF #1) which contains long term average E_p-values as illustrated in Table A1 of the Appendix. The *Master Schedule* thus displays only projected dates and projected application depths while no rainfall has been considered. All projected data is indicated by an asterisk (*).

The actual running of the programme with real data comprises the entering of daily pan evaporation readings and daily rainfall data on the *Daily Input Data* screen (Figure 6). The *Master Schedule* for future dates is then adjusted accordingly and the farmer may also effect his own adjustments where

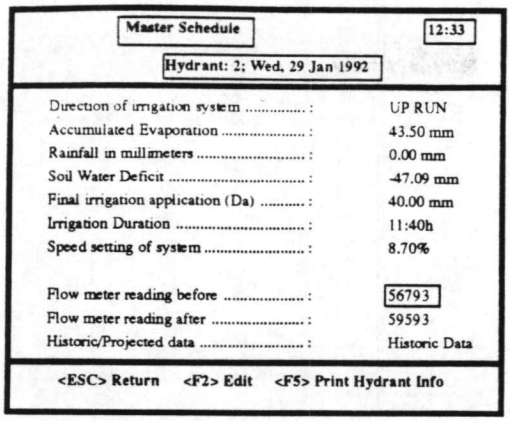


Figure 5 Monitor screen display when a particular hydrant on a particular date is selected for modification or updating.

necessary. The field information regarding the block numbers to be irrigated on that day and the *speed settings* for each block can then be printed or conveyed to the operator by two-way radio.

Programme functions and calculations

Daily crop evaporation (E_i)

Estimation of daily crop evaporation (E_i) is based on pan evaporation (E_p) and daily crop factors (F_{day}):

$$E = F_{day} \cdot E_p \qquad (1)$$

The daily crop factor (F_{day}) is a function of crop growth stage and the moisture condition of the soil surface. As indicated by Burgers (1983), the so called *F-curve* of a particular crop (Figure 7, curve B) actually represents the average values of individual curves for each irrigation cycle throughout the growing season (Figure 7, curves A1 to A14).

The average value (F_{av}) of each individual F_{day}-curve depends on the growth stage of the crop, while each F_{day}-value within the F_{day}-curve depends on the wetness of the soil surface which in turn depends on the time lapse and average atmospheric evaporative demand (AED) conditions since the previous water application. For the purposes of this programme the cumulative pan evaporation (ΣE_p) since the previous irrigation or rain shower was used as an indication of both the time lapse and average AED.

$E_{p(av)}$ is a function of the week of the year. After having selected the week number according to the date, the corresponding $E_{p(av)}$ must then be imported from Table A1 into *Screen Table 1* (Figure 6) for calculated projections of crop evaporation as well as into *Screen Table 4* (Figure 3) for the calculation of projected or estimated application depths (d_{est}).

To carry out the calculation for a particular day (the i^{th} day) in the equation:

$$E_i = F_{dayi} \cdot E_{pi} \qquad (2)$$

the programme would first identify the growth stage according to the number of days after planting and select the corresponding F_{av}-value from the OBDF #2, as in Table A2 of the Appendix, which represents the actual values for the F_{av}-curve of Figure 7, curve B. The selected F_{av}-value would now allow the programme to select the corresponding column in OBDF #3 (Table A3 of the Appendix) which represents the actual values for the simulated F_{day}-curves in Figure 7 (curves A1-A14). The F_{day}-value for the day in question can now be selected by comparing the actual ΣE_{pi} on that day with a similar value in column 1 of OBDF #3 and selecting the corresponding F_{day}-value.

Example:

For January 29 which is day 66 after planting or when 51% of the growth period of the soyabean crop has lapsed, when 10 mm has evaporated during the

Daily Input Data 12:21

DATE: Thu, 2 Apr 1992

Date	A-Pan Readings BEFORE REG	A-Pan Readings AFTER REG	Evaporation $E_{(p)}$	RAIN	HYDRANT NO
Sat, 25 Jan 1992	71	71	10.5	0.00	1
Sun, 26 Jan 1992	81	81	5.00	0.00	1
Mon, 27 Jan 1992	98	50	8.50	0.00	1
Tue, 28 Jan 1992	69	69	9.50	0.00	1
Wed, 29 Jan 1992	**89**	**50**	**10.00**	**0.00**	1
Thu, 30 Jan 1992	69	38	9.50	1.30	3
Fri, 31 Jan 1992	38	38	0.00	38.00	4
Sat, 1 Feb 1992	50	50	6.00	0.00	4
Sun, 2 Feb 1992	66	66	8.00	0.00	4
Mon, 3 Feb 1992	83	50	8.50	0.00	4
Tue, 4 Feb 1992	68	68	9.00	0.00	8
Wed, 5 Feb 1992	87	50	9.50	0.00	11
Thu, 6 Feb 1992	72	72	11.00	0.00	8

<ESC> Recalculate & Exit <F2> "*" ON/OFF <F4> Graph
<F10> Save & Exit "*" Projected Data <F5> Print

Figure 6 Monitor screen display for entering daily evaporation and rainfall data.

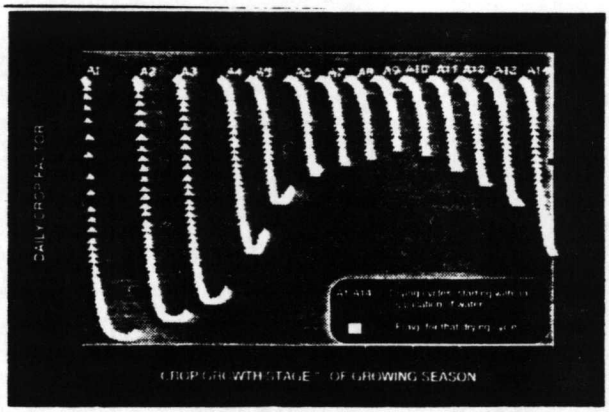


Figure 7 Average (F_{av}) and daily (F_{day}) crop factor curves on which OBDF files 2 & 3 are based.

accumulated since the previous irrigation, the following procedure will be followed:

(i) From OBDF #2 the F_{av}-value of 0.72 is identified as being the current F_{av} when 51% of the crop's growth stage has lapsed;

(ii) From OBDF #3 an F_{day}-value of 0.6632 corresponds with the ΣE_p-value of 44 mm, in the column under F_{av}=0.72;

(iii) Crop evaporation for day 65 is now calculated from:

$$E_{65} = 0.6632 \cdot 10.0$$
$$= 6.63 \text{ mm}$$

Soil water balance (SWB)

When the soil profile is at *field capacity the SWB* is defined as *0.0 mm*. As soon as the soil water content drops to below *field capacity* due to crop evaporation, a soil water deficit (SWD) develops and the SWB becomes negative. When the initial SWB is known through intensive monitoring, it should be entered on the *View/Edit screen*. Otherwise a default value of 0.0 mm is assumed by the programme, because the soil is usually brought to *field capacity* before or soon after planting.

SWB is calculated by subtracting daily crop evaporation from the previous day's total and adding any irrigation applications or effective rain which occurred during the day in question. In the *example* illustrated above, day 65 started with a soil water deficit of 40.46 mm and after subtracting the calculated crop evaporation for the day (6.63 mm), ended the day with a soil water deficit of 47.09 mm. The daily march of the SWB throughout the growing season as calculated for the Block served by Hydrant #1, is depicted in the screen display illustrated in Figure 8.

Since field capacity was taken as zero SWB, a negative value in Figure 8 would indicate a soil water deficit (SWD), while a positive SWB in Figure 8, represents an indication of some excess water (above *field capacity*) occurring in the profile, as is sometimes experienced immediately after an irrigation application or rain shower. For the Syferkuil soils, provision was made for a maximum of 10 mm which could be accommodated in the soil profile in such an event. This amount would vary according to soil texture, depth and sub-soil permeability. Consequently an option is provided in the *View/Edit screen* where this value could be entered when creating or editing the

Master schedule.

It should be noted that Block #1, like Block #11, is at the end of the irrigation field, and may thus be irrigated on the same or consecutive days during the *up*-and *down*-run of the Linear system. The total of these applications is then displayed as one application in Figure 8. In Figure 9 the situation for Block #6 which is situated in the middle of the field, is

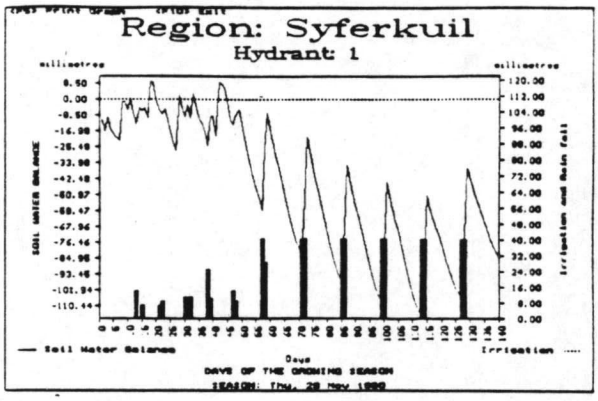


Figure 8 Daily march of computed Soil Water Balance, rainfall and irrigation applications for Block 1 served by Hydrant #1.

illustrated.

Computed SWB values depicted in Figures 8 and 9 ended the season with soil water deficits of 63 mm and 113 mm respectively. These correspond reasonably well with actual measurements of the profile water content which revealed a progressive decline in SWB, ending the growing season with soil water deficits of between 53 mm and 127 mm in different blocks along the field.

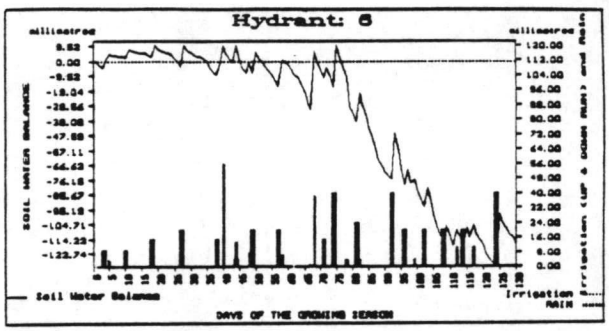


Figure 9 Daily march of computed Soil Water Balance, rainfall and irrigation application for block 6, served by Hydrant #6.

Speed Setting (SS)

OBDF #4 (see Table 4A of the Appendix) contains possible application amounts (d-values) of up to 50 mm with corresponding speed settings and travelling times (TT) to cover the 200 m distance between two hydrants However, both SS and TT can also be calculated from:

$$SS = \frac{d_{100} \cdot 100}{d} \quad (3)$$

and

$$TT = \frac{T_{100} \cdot d}{d_{100}} \quad (4)$$

where d = intended application amount;
d_{100} = application at 100% SS and
T_{100} = travelling time between two hydrants at 100% SS.

In a future version of Irrisched, these equations may be used to calculate SS and TT, instead of the OBDF #4.

Discussion

The Irrisched programme is now in its second season of testing under commercial circumstances on the experimental farm of the University of the North and appears to be working well. The manager of the linear system is a former farmer, Mr J T van As, who has been trying to schedule irrigation applications with a Class A-pan according to the Irrograph of Burgers (1982). for the past five years without a great deal of success. After the introduction of Irrisched, Mr Van As listed several important advantages of the new method. These include user friendliness; ease of learning; minimal input data requirements and elimination of the need for record keeping and performing complex calculations. Furthermore, the programme is adaptable to forced deviations from the schedule, during spraying of pesticides and herbicides or application of fertilizers. It copes efficiently with intermittent rain showers and provides a visual display of changes in soil water status as well as a permanent record of historical data for later comparisons and possible explanations.

There seems to be little doubt that Irrisched may facilitate the practical management of irrigation systems. However, the method must still be tested over a wider range of farmers and irrigation systems.

The problems that beset the validity of using A-pan evaporation for computing crop evaporation, as discussed by Maree (1988) and Van Zyl, Maree & De Jager (1989), are acknowledged but the method used to compute E is not contentious and the programme can easily be modified for the introduction of alternative methods and corresponding crop factors as they become available.

The *average crop factors* for soyabeans used in this version of Irrisched are based on the standard F-curve for annual crops of Metelerkamp (1968), which may or may not be the most accurate information currently available. Furthermore, *the daily crop factors* in Table A3 depicted as curves A1-A13 in Figure 8, were chosen to logically fit the average values and there are no experimental results available against which their validity can be verified. However, the principle is consistent with publicised results of several researchers, particularly concerning the early growth stages (Jensen, 1969; Meyer, Walker & Green, 1979; Van Zyl, De Jager & Van Rooyen, 1981; Wright, 1981; Wright, 1985) and it remains only to be refined for particular crops grown under specified circumstances, like zero tillage.

Wright (1981) suggested that the effects of surface wetness on the crop coefficient (K_s) may be estimated by:

$$K_s = f_w(K_1-K_{cb})[1-(t/t_d)^{0,5}] \quad (5)$$

where K_1 is the maximum crop coefficient usually occurring after rain or irrigation, K_{cb} is a basal crop coefficient, t is the number of days after rain or irrigation, t_d is the usual number of days for the soil surface to dry, and f_w is the relative portion of surface originally wetted.

It is doubtful whether the same pattern as depicted in Figure 7 will prevail during the later growth stages, especially when high frequency irrigation is practised. The model may therefore have to be modified as soon as more results become available. However, under conditions of limited soil water, the daily crop factors may well follow the pattern shown in Figure 7. This view is supported by Wright (1985), citing Jensen, Wright & Pratt (1971) and Jensen (1974) who suggested that K_s (crop coefficient related to available soil water) may be assumed to be proportional to the logarithm of the percentage of remaining available soil water (AM) by:

$$K_s = ln(AM + 1)/ln\ 101 \quad (6)$$

These and other refinements can easily be incorporated into the model, without affecting its simplicity and user-friendliness for the farmer.

It is believed that, should Irrisched prove to find favour with farmers and researchers in the field, it might provide much needed direction to research programmes concerned with water requirements of crops and methods of irrigation scheduling.

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Appendix

Table A1 On-board data file #1: Long-term average pan Evaporation data $\{E_{p(av)}\}$ for Syferkuil.

WEEK nr	E_{pan} mm	WEEK nr	E_{pan} mm	WEEK nr	E_{pan} mm	WEEK nr	E_{pan} mm
1	8,0	14	5,0	27	4,0	40	7,5
2	8,0	15	5,0	28	4,0	41	7,5
3	8,0	16	5,0	29	4,0	42	7,5
4	8,0	17	5,0	30	4,0	43	7,5
5	7,5	18	4,5	31	5,0	44	7,8
6	7,5	19	4,5	32	5,0	45	7,8
7	7,5	20	4,5	33	5,0	46	7,8
8	7,5	21	4,5	34	5,0	47	7,8
9	7,0	22	4,0	35	6,0	48	7,8
10	7,0	23	4,0	36	6,0	49	8,0
11	7,0	24	4,0	37	6,0	50	8,0
12	7,0	25	4,0	38	6,0	51	8,0
13	5,0	26	4,0	39	6,0	52	8,0

Table A2 On-board data file # 2: Average crop factors for different growth stages of Soyabean.

GROWTH STAGE NUMBER	PERCENTAGE OF GROWTH PERIOD	DAYS AFTER PLANTING	F_{mn}
1	0 - 9	0 - 12	0,19
2	10 - 23	13 - 30	0,29
3	24 - 30	31 - 40	0,39
4	31 - 35	41 - 46	0,49
5	36 - 39	47 - 51	0,59
6	40 - 44	52 - 58	0,74
7	45 - 50	59 - 66	0,85
8	51 - 68	67 - 90	0,90
9	69 - 78	91 - 103	0,85
10	79 - 84	104 - 111	0,80
11	85 - 90	112 - 119	0,74
12	91 - 100	120 - 132	0,59

Table A3 On-board data file # 3: Part of the range of F_{day} - values for various stages within an irrigation cycle in terms of ΣE_p since the previous application.

ΣE_p	F_{day} at F_m =0,19	F_{day} at F_m =0,29	F_{day} at F_m =0,39	F_{day} at F_m =0,49	F_{day} at F_m =0,59	F_{day} at F_m =0,74	F_{day} at F_m =0,77	F_{day} at F_m =0,80	F_{day} at F_m =0,83	F_{day} at F_m =0,85	F_{day} at F_m =,90
2	0.9990	0.9992	0.9995	0.9996	0.9997	0.9999	0.9999	1.0000	1.0000	1.0000	1.0000
4	0.9800	0.9888	0.9975	0.9980	0.9985	0.9993	0.9995	0.9997	0.9999	1.0000	1.0000
6	0.9300	0.9610	0.9919	0.9939	0.9958	0.9984	0.9988	0.9991	0.9995	0.9999	1.0000
8	0.8400	0.9084	0.9768	0.9836	0.9905	0.9978	0.9982	0.9985	0.9989	0.9995	0.9999
10	0.7100	0.8287	0.9473	0.9647	0.9820	0.9963	0.9968	0.9973	0.9978	0.9988	0.9993
12	0.5700	0.7384	0.9068	0.9386	0.9705	0.9929	0.9937	0.9945	0.9953	0.9973	0.9987
14	0.4700	0.6613	0.8525	0.9030	0.9535	0.9862	0.9880	0.9895	0.9914	0.9944	0.9973
16	0.3900	0.5834	0.7768	0.8536	0.9305	0.9768	0.9800	0.9827	0.9860	0.9900	0.9942
18	0.3382	0.5213	0.7044	0.8028	0.9017	0.9648	0.9698	0.9741	0.9791	0.9841	0.9893
20	0.2900	0.4581	0.6261	0.7460	0.8658	0.9501	0.9573	0.9636	0.9708	0.9768	0.9827
22	0.2561	0.4131	0.5701	0.6972	0.8243	0.9328	0.9416	0.9491	0.9578	0.9658	0.9742
24	0.2272	0.3710	0.5147	0.6457	0.7766	0.9142	0.9246	0.9335	0.9439	0.9539	0.9640
26	0.2000	0.3339	0.4678	0.5976	0.7274	0.8912	0.9039	0.9147	0.9274	0.9394	0.9520
28	0.1776	0.3018	0.4261	0.5525	0.6789	0.8562	0.8741	0.8894	0.9073	0.9203	0.9381
30	0.1574	0.2728	0.3881	0.5112	0.6343	0.8152	0.8389	0.8591	0.8827	0.9017	0.9216
32	0.1400	0.2478	0.3555	0.4753	0.5951	0.7703	0.7992	0.8240	0.8529	0.8779	0.9014
34	0.1243	0.2252	0.3261	0.4425	0.5589	0.7301	0.7611	0.7876	0.8185	0.8495	0.8769
36	0.1101	0.2049	0.2996	0.4127	0.5258	0.6893	0.7215	0.7491	0.7813	0.8123	0.8471
38	0.0975	0.1866	0.2756	0.3857	0.4958	0.6525	0.6850	0.7129	0.7454	0.7764	0.8127
40	0.0863	0.1702	0.2541	0.3615	0.4689	0.6220	0.6531	0.6798	0.7090	0.7400	0.7754
42	0.0765	0.1560	0.2355	0.3405	0.4451	0.5972	0.6279	0.6542	0.6805	0.7115	0.7427
44	0.0681	0.1441	0.2201	0.3222	0.4243	0.5773	0.6080	0.6343	0.6605	0.6875	0.7177
46	0.0610	0.1343	0.2077	0.3072	0.4066	0.5615	0.5935	0.6209	0.6483	0.6683	0.6993
48	0.0551	0.1268	0.1985	0.2952	0.3920	0.5497	0.5844	0.6142	0.6439	0.6639	0.6877
50	0.0503	0.1204	0.1905	0.2853	0.3801	0.5419	0.5795	0.6117	0.6438	0.6638	0.6821
52	0.0462	0.1145	0.1828	0.2763	0.3697	0.5381	0.5773	0.6108	0.6543	0.6643	
54	0.0427	0.1096	0.1766	0.2687	0.3608	0.5377	0.5774	0.6114	0.6453	0.6653	
56	0.0397	0.1055	0.1713	0.2600	0.3500	0.5383	0.5784	0.6127	0.6471		
58	0.0371	0.1017	0.1664	0.2566	0.3502	0.5398	0.5803	0.6150	0.6496		
60	0.0349	0.0993	0.1637	0.2544	0.3511	0.5325	0.5832	0.6181	0.6530		
62	0.0330	0.0976	0.1624	0.2541	0.3534	0.5463	0.5872	0.6222			
64	0.0315	0.0972	0.1629	0.2569	0.3569	0.5509	0.5919	0.6270			
66	0.0302	0.0967	0.1632	0.2592	0.3616	0.5563	0.5974				
68	0.0291	0.0966	0.1642	0.2622	0.3675	0.5625	0.6038				
70	0.0283	0.0971	0.1658	0.2659	0.3746	0.5695	0.6109				
72	0.0276	0.0976	0.1675	0.2700	0.3829	0.5773					
74	0.0271	0.0983	0.1696	0.2748	0.3924	0.5859					
76	0.0266	0.0994	0.1722	0.2802	0.4031						
78	0.0263	0.1008	0.1753	0.2816	0.4150						
80	0.0260	0.1024	0.1788	0.2929	0.4231						
82	0.0279	0.1043	0.1827	0.3012							
84	0.0319	0.1070	0.1882	0.3094							
86	0.0359	0.1102	0.1946								
88	0.0399	0.1134	0.2009								
90	0.0439	0.1166	0.2072								
92	0.0479	0.1198									
94	0.0519	0.1230									
96	0.0559										
98	0.0599										
100	0.0639										

Table A4 On-board data file # 4: Speed Settings (SS) for the control panel of the Linear System, as well as the Travelling Time between hydrants (TT), which would facilitate the application of the required application depth (d).

d mm	SS %	TT minutes	d mm	SS %	TT minutes
3,5	100.0	61	27	12.9	473
4	87.1	70	28	12.4	490
5	69.7	88	29	12.0	508
6	58.1	105	30	11.6	525
7	49.8	123	31	11.2	243
8	43.6	140	32	10.9	560
9	38.7	158	33	10.6	578
10	34.9	175	34	10.3	595
11	31.7	193	35	10.0	613
12	29.0	210	36	9.7	630
13	26.8	228	37	9.4	648
14	24.9	245	38	9.2	665
15	23.2	263	39	8.9	683
16	21.8	280	40	8.7	700
17	20.5	298	41	8.5	718
18	19.4	315	42	8.3	735
19	18.5	333	43	8.1	753
20	17.4	350	44	7.9	770
21	16.6	368	45	7.7	788
22	15.8	385	46	7.6	805
23	15.2	403	47	7.4	823
24	14.5	420	48	7.3	840
25	13.9	438	48	7.1	858
26	13.4	455	50	7.0	875

The application amount (d) is a function of the speed at which the linear system is travelling because at the appropriate pressure of, say 120 kPa, the pump delivers 240 $m^3.h^{-1}$.

After having calculated and adjusted the d-value, the corresponding speed setting must be selected from OBDF # 4.

After having entered the *starting time*, the *approximate completion time* can then be calculated by taking the *travelling time* from OBDF # 4 into account.

IRRIGATION OF COTTON AT VAALHARTS DURING THE REPRODUCTIVE PHASE

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Abstract

Since cotton yields are enhanced mainly by increased water applications during flowering and boll development, diminished irrigations are generally restricted to the period prior to square formation. Further increase in irrigation efficiency can be obtained by applying water only during the periods sensitive to water stress over the prolonged reproductive growth phase. Daily leaf water potential values below -1.7 MPa at 14:00 were summed for previously determined water sensitive periods. These values were correlated with various yield criteria to estimate the effect of water stress on each yield component separately. Water stress during early and peak flowering resulted in a smaller number of mature bolls without affecting individual boll size, while during peak boll development stress produced smaller bolls but did not increase boll shedding. The most pronounced inhibiting effect on yield was detected during boll development. Ripening of bolls was hastened by water stress occurring after opening of the first bolls and since reproduction is terminated by early frost, this enhanced yields.The following equations for predicting yields, in kg ha^{-1}, were established: seed cotton yield= 2360.35 - 0.56A - 1.58B - 2.87C + 2.72D; lint yield = 924.82 - 0.32A - 0.51B - 1.12C + 1.10D; where A, B, C & D are summed water potentials below -1.7 MPa at 14:00 for early flowering, peak flowering, peak boll development and boll ripening respectively. Optimal water requirements for the corresponding periods, with the exception of boll ripening, were 147 mm, 223 mm and 75 mm.

Introduction

It is generally accepted that cotton yields are enhanced by higher irrigation applications as illustrated by Howell, Davis, McCormick, Yamada, Walhood & Meek, (1984). They found lint yield to be directly though slightly non-linearly related to total evapotranspiration, while the relationship between dry matter production and estimated transpiration was absolutely linear. This concept is confirmed by Plaut & Carmi (1984) who obtained the highest yields (6 820 kg ha^{-1}) from cotton which was drip irrigated twice daily from 14 days after planting onwards. It is, however, important that the cotton plant is not water-logged in this process, because this may induce stress conditions which will inhibit yields (De Bruyn, 1982; Reicosky, Meyer, Schaffer & Sides 1985a; Reicosky, Smith & Meyer, 1985b). Water sensitivity during flowering and boll development is well documented (Constable & Hearn, 1981; Cull, Hearn & Smith, 1981a; Turner, Hearn & Constable, 1986), although the exact duration of growth stages sensitive to water stress has not been clearly defined. This is mainly because research had been done on the reaction of the plant to water stress during pre-selected periods.

Furthermore, the effect of leaf water stress on the growth and production of a crop should be more relevant than measuring the effect of soil water depletion, as done by Constable & Hearn (1981) and Cull *et al.* (1981a).

In irrigation scheduling it is important to identify the critical periods during which plant water stress will have a pronounced effect on the growth and yield of a crop. Hearn & Constable (1984) developed a model for estimating a water stress day in which they defined the threshold value as -1.8 MPa for the first 90 days of development and -2.4 MPa thereafter. Idso, Reginato & Farah (1982) monitored canopy temperatures from which they developed their stress degree day concept, enabling them to identify the duration of water sensitive periods in cotton. De Bruyn & De Jager (1978) illustrated how correlation coefficients between plant water stress and crop yields can be used to identify the duration of these critical periods. By developing a more sophisticated model which estimates leaf water potential instead of merely identifying stress days, it should be possible to estimate the daily magnitude of water stress in cotton plants based on data obtained from irrigation experiments.

De Bruyn & Human (1983) developed a graphic model which calculates the degree of stress in cotton from Class A pan evaporation and soil water potential. This model was refined by De Kock, De Bruyn & Human (1990) to estimate leaf water potential (in kPa) from these inputs. Since this relationship was determined on plants after the appearance of the first squares up to full bloom, the model proved to be reliable during the period 60-120 days after emergence of the seedlings. Correlations between calculated daily leaf water potential values summed over pentads (i.e., 5-day periods) and both seed cotton and lint yields were obtained. This was done for all treatment-year combinations in irrigation experiments on Vaalharts over the growth period from 50 to 160 days after seedling emergence. This period covered the developing stages from the appearance of the first squares up to ripening of the bolls. Coefficients below the significance level of $P=0.05$ were disregarded. Because pentads over which leaf water potentials were summed were advanced one day at a time (giving a 4-

day overlap between successive totals), De Kock *et al.* (1990) were able to detect sensitive periods for water stress during the reproductive phase of cotton to within one day for both yield criteria. They identified the periods as 66-82, 88-117, 129-141 and 145-156 days after seedling emergence, which correspond to phenological growth stages of early flowering, flowering peak, peak boll development and boll ripening.

It now remains to determine the effect of water stress during each identified water sensitive period during the reproductive phase on seed cotton and lint yields as well as on boll size and the number of mature boll produced. With this information at hand, available irrigation water can be applied in such a way as to obtain the largest beneficial effect, thereby maximizing the efficiency of irrigation applications. The total evapotranspiration for the duration of each sensitive period will indicate the total amount of water which is to be applied during the corresponding period.

Materials and methods

In order to estimate the response of the plant to water stress conditions during the reproductive phase, it was necessary to calculate the daily plant water potential.

The graphic model for estimating leaf water potential developed by De Kock *et al.* (1990) and tested for the site on which the data from previous irrigation experiments were collected, was used. The daily leaf water potential was estimated from measurements of Class A pan evaporation as well as soil water potential at 14:00. The experiments were carried out at Vaalharts (27°57S, 24°50E) where six different irrigation levels were applied. The first four irrigation levels were according to constant crop factors, viz.

1. 1.0 : where an irrigation of 75 mm was applied when evaporation from a Class A pan totalled 75 mm;
2. 0.75 : where an irrigation of 75 mm was applied when evaporation from a Class A pan totalled 100 mm;
3. 0.6 : where an irrigation of 75 mm was applied when evaporation from a Class A pan totalled 125 mm;
4. 0.5 : where an irrigation of 75 mm was applied when evaporation from a Class A pan totalled 150 mm;

Two further treatments were applied, where irrigations of 75 mm were applied on the basis of variable crop factors and where the largest factor coincided with full bloom, viz.

5. 0.6 : followed by 0.75 and
6. 0.6 : followed by 0.75 and 1.0.

Irrigation levels were applied as main treatments while population densities of 50 000, 325 000 and 600 000 plants per hectare of the cv. Acala 1517-70 were planted. Three replications were planted over four growing seasons, resulting in 72 different sets of data. The field trials were conducted on a sandy soil with an average clay content of 11 per cent, fine sand content of 71 per cent and coarse sand content of 17 per cent; the profile was 1.8 meter deep, deposited on a calcareous substratum (Hutton form, Mangano series).

Seed cotton yields were harvested by hand in three pickings after removing the affected border around each sub-plot. The net sub-plots measured 6.0 X 3.4 m. Lint percentages were determined on samples taken from each picking on each sub-plot from which the corresponding lint yields were determined. Lint percentage was obtained by mechanically delinting a previously weighed sample of seed cotton.

The total number of bolls harvested on each sub-plot was counted and bolls cut off. This was done for each picking separately. The actual number of plants harvested was counted and from this the average number of bolls harvested per plant was calculated for each sub-plot. Boll mass was expressed as the average mass of the bolls harvested on each sub-plot. This was done by dividing the seed cotton yield by the number of bolls harvested.

Micronaire values, which indicate fineness and maturity of the fibre, were determined on samples taken of each picking on every plot. This was done by the Speedar method as described by Brown & Ware (1958).

The daily calculated values for leaf water potential below -1.7 mPa were summed for periods which De Kock *et al.* (1990) identified as sensitive to water stress, viz. 66-82, 88-117, 129-141 and 145-156 days after seedling emergence, corresponding to early flowering, flowering peak, peak boll development and boll ripening, respectively.

Correlations were determined between totals of daily leaf water potential values below -1.7 MPa for each sensitive period and the different yield criteria. In order to explain the effect plant water stress has on yield and yield-related properties, correlation coefficients were not only determined for seed cotton and lint yields, but also for boll mass, number of mature bolls produced per plant, lint percentage and micronaire values. This was done for all treatment-year combinations in the irrigation experiments. Coefficients below the significance level of $P = 0.05$ were disregarded.

Results

Seed cotton yield

The effect of water stress during the reproductive phase on seed cotton yield, which ranged between 1 500 to 3 900 kg ha^{-1}, is illustrated in Figure 1. From this it is clear that water deficits during early flowering (66-82 days after emergence) had a slightly more consistent negative effect on seed cotton yields than during peak flowering (88-117 days after emergence). Correlation coefficients for these two periods

were -0.50 and -0.47, respectively. Stress, however, explained the greatest variation in yield when occurring during boll development (129-141 days after emergence) with a correlation coefficient of -0.52. Ripening of the bolls was consistently hastened by water deficits which resulted in stress after opening of the first bolls (145-156 days after emergence). This led to increased seed cotton yields. The beneficial effect of stress during boll ripening ($r = +0.60$) surpassed all earlier negative effects indicated by negative correlation coefficients.

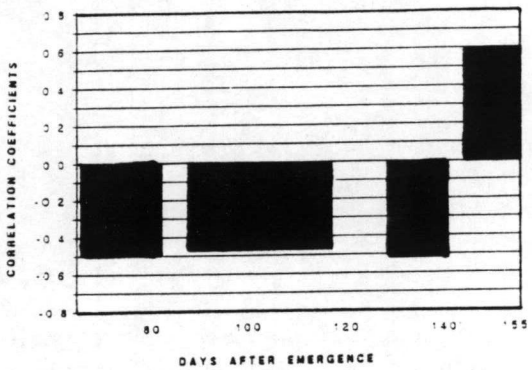


Figure 1 The effect of water stress during the reproductive phase on seed cotton yields as expressed by correlation coefficients between yields and plant water potential values

Lint yield

The effect of water stress during the reproductive phase on lint yields was very similar to the effect it had on seed cotton yields (Figure 2). The correlation coefficients between plant water stress and lint yields were in fact nearly identical during the different periods considered to those obtained for seed cotton yields, viz. -0.49, -0.45, -0.52 and +0.61 for early flowering, peak flowering, peak boll development and boll ripening, respectively.

Lint percentage

Although water stress affected seed cotton and lint yields in an equally consistent manner, this may suggest that lint percentage was not affected. Figure 3, however, indicates that lint development was actually enhanced by water stress during peak flowering and boll ripening.

Boll number

The effect of soil water deficits on the number of bolls to reach maturity is illustrated in Figure 4. During early flowering stress probably increased boll shed since it decreased the number of bolls to reach maturity. Stress during the later growth stages, however, had no effect on the number of mature bolls per plant.

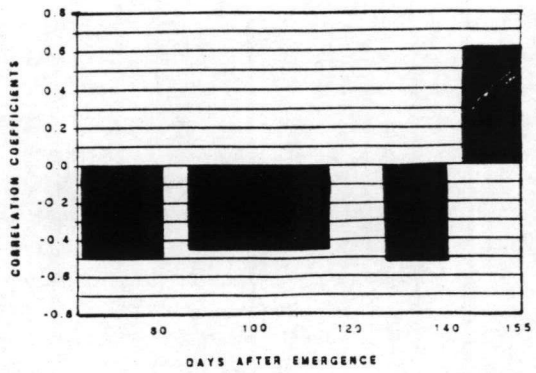


Figure 2 The effect of water stress during the reproductive phase of cotton on lint yields as expressed by correlation coefficients between yields and plant water potential values

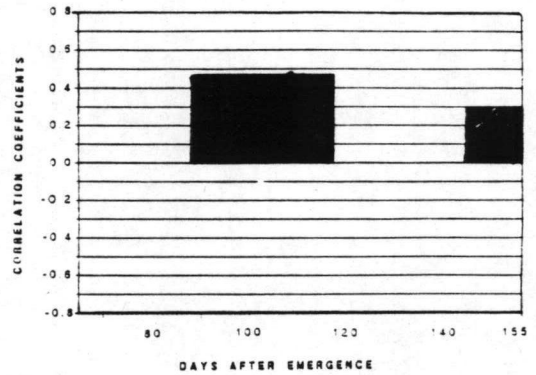


Figure 3 The effect of water stress during the reproductive phase of cotton on lint percentages as expressed by correlation coefficients between lint percentages and plant water potential values

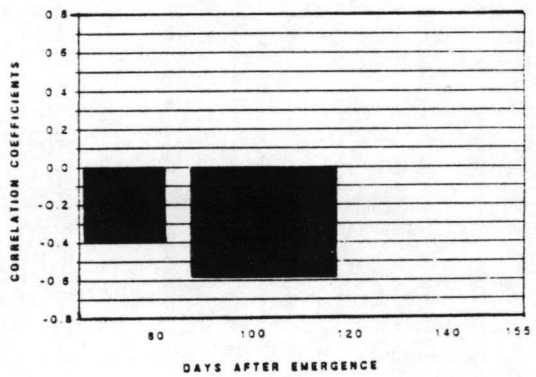


Figure 4 The effect of water stress during the reproductive phase of cotton on the number of bolls borne by a single plant as expressed by correlation coefficients between boll number and plant water potential values

Boll size

The average size of a boll was not affected by water stress during early or peak flowering (Figure 5). Water stress during peak boll development (129-141 days after emergence) increased boll size (correlation coefficient +0.40) but during boll ripening (145-156 days after emergence) decreased boll size (correlation coefficient = -0.042).

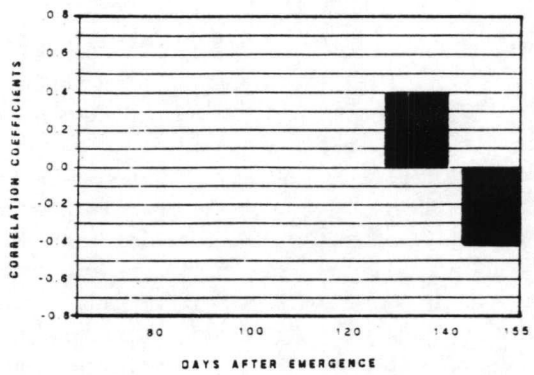


Figure 5 The effect of plant water stress during the reproductive phase of cotton on individual boll size as expressed by correlation coefficients between boll mass and plant water potential values

Fibre quality

The effect of water stress on fibre quality, as indicated by the fineness of the fibre in micronaire values, is illustrated in Figure 6. Stress again had no effect during early and peak flowering, but during peak boll development it inhibited fibre diameter while it enhanced micronaire values when occurring during the ripening phase of the bolls.

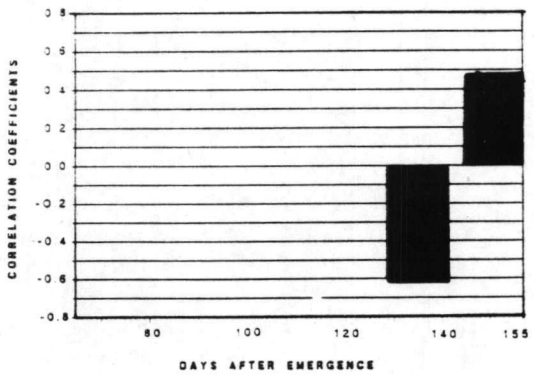


Figure 6 The effect of plant water stress during the reproductive phase of cotton on fibre quality as expressed by correlation coefficients between micronaire values and plant water potential values

Yield predictions

Equations for predicting water stress affected seed cotton and fibre yield for the Vaalharts irrigation area were obtained by stepwise regression. To predict seed cotton yield S (kg ha^{-1}):

$S = 2360.35 - 0.56A - 1.58B - 2.87C + 2.72D$

$R^2 = 72.6\%$; SE = 369.7; df = 52.

For lint yields L (kg ha^{-1}):

$L = 924.82 - 0.32A - 0.51B - 1.12C + 1.10D$

$R^2 = 72.7\%$; SE = 142.8; df = 52.

The independent variables are daily leaf water potentials below -1.7 MPa at 14:00, summed for the periods: early flowering (66-82 days after emergence); peak flowering (88-117 days); peak boll development (129-141 days); boll ripening (146-156 days after emergence).

These equations indicate that accumulated water stress during early and peak flowering had a smaller inhibiting effect on yields than during boll development, while yields were enhanced by stress during the boll ripening period.

Discussion and Conclusions

From this study, it is clear that water stress during early flowering resulted in a smaller number of bolls reaching maturity, although individual boll size was unaffected. It is generally accepted that water stress in the early flowering stages stimulates excessive shedding of squares and flowers which result in decreased yields (Constable & Hearn, 1981; Cull *et al.*, 1981a). Although flower shedding was not monitored in the present study, it may be assumed that the smaller number of bolls that matured was due to a larger percentage of squares and flowers that were shed during early flowering. Although boll size may be dependent on plant population, this effect was not addressed. Boll size, fibre thickness and lint percentage were not affected by water stress during early flowering. It is therefore clear that lint growth on the seeds was not influenced by water stress during early flowering. Seed cotton and lint yields were therefore inhibited by water stress during early flowering solely because stress caused more flowers to be shed.

Water stress during peak flowering also resulted in fewer mature bolls borne on a single plant. Stress during this growth stage did not affect the average size of a single mature boll nor did it influence the fineness of the fibre produced. It did, however, enhance the lint percentage. Since water stress during peak flowering inhibited both seed cotton and lint yields, while also reducing the number of mature bolls produced, it can be inferred that this was due to more flowers being shed. Fewer flowers borne on a single plant which produced fewer mature bolls probably experienced better water and nutritive conditions and this may be the reason why these bolls produced more lint per seed than under unstressed conditions.

During the main boll development period, stress no longer caused shedding, but reduced individual boll size by inhibiting lint to seed development as well as fibre diameter and consequently the average mass of a boll. Similarly, Howell *et al.* (1984) reported fibre length and micronaire values to diminish under water stress conditions.

While it is imperative that bolls develop fully and that few are shed in order to obtain maximum yields, Constable & Hearn (1981) point out that irrigation may delay ripening of the bolls and result in lower yields in areas where severe frost is to be expected towards the end of the growing season. At Vaalharts where reproduction is terminated by early frost, stress during boll development consequently caused more bolls to reach maturity before the plants were killed off by severe frost. Results from the present study therefore confirm the results obtained by Constable & Hearn (1981), by identifying an advantageous effect of stress on yields during boll development (Figures 1 & 3).

From the duration of each sensitive period and average daily pan evaporation and crop factors for the corresponding periods, the evapotranspiration, and thus the irrigation needs, were calculated. Optimal water requirements are 147 mm for 16 days during early flowering, 223 mm over 29 days during peak flowering and 75 mm for 15 days of boll development.

According to Vaalharts' long term average rainfall data, 31.1 and 70.5 mm rain may be expected during early and peak flowering, while an average of 27.1 mm has been recorded during boll development. The amount of rain received over a short period (i.e. a pentad) will, however, determine whether rain can replace or delay an irrigation application. The average distribution of rain during early flowering, peak flowering and boll development is in fact such that no pentad has an average rainfall of more than 12 mm. Since the average pan evaporation and evapotranspiration over a 5-day period exceeds 45 and 36 mm, respectively, it cannot be expected that the occurrence of rain will eliminate the need for any of the scheduled irrigation applications during the stress-sensitive stages at Vaalharts. Consequently it should be planned to replenish the total water use by irrigation during each of the sensitive stages.

When irrigating cotton, care should be taken to replenish soil water before the onset of the first stress sensitive period commencing 66 days after emergence. During early and peak flowering (66-82 and 88-117 days after emergence), irrigation has to be applied, starting a few days before the onset of each sensitive period. Care should also be taken that the available water is not depleted towards the end of the latter period, as moisture sensitivity, according to De Kock *et al.* (1990), peaks at 114 days after emergence. The final irrigation should be applied after the end of effective flowering during peak boll development (129-141 days after emergence) and it is most important to provide for sufficient water for this 12 day period. When the first bolls open, it is important to withhold water, especially at Vaalharts where frost occurs and where the productive phase of the plant is limited to one season only. This will hasten the ripening of bolls and enhance yields, but may inhibit fibre maturity and fibre tenacity.

The water retention properties of the sandy soils of the Vaalharts irrigation area are such that 108 mm of water can be absorbed by the plant between field capacity and a soil water potential of -60 kPa (Burger & Bennie, 1979). The amount of water which should be effectively applied for irrigation during the reproductive phase of the plant, when root development is expected to enable utilization of the full soil profile depth of 1.8 m, is therefore 108 mm. This implies that three to four such irrigations will be required to supply water during the early and peak flowering period and one irrigation would satisfy the requirements of the cotton plant during boll development. However, should the amount applied be an effective 23 mm, as typically in the case of a centre pivot, seven irrigations will be required during early flowering, ten during peak flowering and more than three during boll development.

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THE VALUE OF IRRIGATION FACTORS IN IRRIGATION SCHEDULING OF CITRUS

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Abstract

The purpose of this investigation was to determine the value of using irrigation factors (Fi) and Class A pan evaporation data as a method for scheduling the irrigation of mature citrus trees. This method was compared over several seasons with tensiometer scheduling at Nelspruit in the Eastern Transvaal and Addo in the Sundays River Valley of the Eastern Cape. Monthly irrigation factors were calculated for each area based on long term water use data obtained for mature citrus trees grown in weighing lysimeters at the Sundays River Valley Experimental Station and long term Class A pan evaporation data from both areas. Tensiometer scheduling gave a larger yield than the Fi method in 2 out of 4 seasons at Nelspruit but no significant differences were recorded at Addo. Fruit size was comparable between treatments in both experiments with tensiometers giving larger fruit in one season only at Addo. No consistent difference in volume of water applied between methods and seasons was observed. Rainfall had less influence on irrigation schedules in Addo than in Nelspruit. In both areas the water use of mature Valencia trees was comparable if expressed on a canopy area basis, to compensate for tree size. It appears that irrigation factors provide a good alternative to tensiometers for irrigation scheduling, provided that monthly varying factors are determined for each area.

Introduction

The use of the Class A pan evaporation data and crop or pan factors for irrigation scheduling is a well known practice in irrigation farming (Fuchs & Stanhill, 1963; Bredell & Barnard, 1977; Doorenbos & Pruitt, 1977; Burgers, 1982; Methochis, 1989; Castel & Buj, 1990). Although this factor varies throughout the season for citrus (Van Bavel, Newman & Hilgeman 1967; Kalma & Stanhill, 1969; Castel & Buj, 1990), a constant factor was proposed by several researchers (Bredell & Barnard, 1977; Scheepers, 1980; Yagev & Horesch, 1981 and Obreza & Pitts, 1989).

The validity and accuracy of crop factors for irrigation scheduling purposes, have been questioned by several researchers. Green & Moreshet (1979) maintained that the crop factor for citrus required a correction for atmospheric resistance variations and in order to use crop factors established in one location for another, corrections for Class A pan evaporation and wind conditions would have to be made.

Du Plessis (1988) showed that crop factors not only varied throughout the season, but also from season to season and that the variation between seasons for the same month could be much higher than between months. Green & Du Plessis (1982) stated that the crop factor will also be affected by orchard layout and irrigation method. They claimed that the crop factor varied from a high value at low Class A pan evaporation to a low value at high evaporative demand, which is in agreement with the fact that humid areas have much higher crop factors than dry areas (Doorenbos & Pruitt, 1977). Kalma & Stanhill (1969) demonstrated the effect of irrigation method and matric potential of the topsoil on evapotranspiration of citrus and thus the crop factor.

By using long term monthly water use data obtained from a mature citrus tree grown in a weighing lysimeter and long term average monthly Class A pan evaporation figures for different areas, Du Plessis (1988) calculated crop factors for citrus in these areas. These factors were calculated on a wetted area of 18 m^2 $tree^{-1}$ or two-thirds of the total orchard area (typical for localized irrigation). Since these factors can be higher than 1.0, they were called irrigation factors to eliminate confusion with the traditional smaller crop factors calculated on the total surface area. These factors differ extensively between areas, being relatively high in humid areas and low in dry areas, corresponding to the predictions of Doorenbos & Pruitt (1977).

The purpose of this investigation was to test the usefulness of these irrigation factors for irrigation scheduling of mature citrus trees in two different areas. For evaluation purposes tensiometer scheduling was used as the norm in both areas. Scheduling by means of tensiometers has resulted in consistently good production and fruit size for Valencias over many seasons (CSFRI, Unpublished report).

Materials and methods

Two irrigation experiments, one located at the Citrus and Subtropical Fruit Research Institute at Nelspruit and the other one at the Sundays River Valley Experimental Station at Addo, on mature Valencia trees, were used for this purpose.

Nelspruit experiment: This experiment consisted of 7 treatments with 4 replicates and 4 trees per plot. Water was applied with two microjets per tree, delivering 100 ℓh^{-1} in total and wetting approximately 18 m^2 $tree^{-1}$. Water applications were controlled with an irrigation controller and the volume of water applied was registered on a water meter and recorded after each irrigation treatment. Yield was measured on a per tree basis and the fruit sized according to

commercial sizes (expressed in kg count^{-1} i.e. number of fruit per 15 kg carton). Only the results of two relevant treatments, tensiometer scheduling and irrigation factor scheduling are reported in this paper. In the case of tensiometer scheduling 900 litres of water tree^{-1} was applied whenever the average readings on tensiometers at a depth of 300 and 600 mm were -30 kPa. Irrigation factors (Fi) used (Table 1) varied on a monthly basis. Water was applied once per 7 day cycle. The volume of water applied varied according to the accumulated total of Fi x Eo (Where Eo is the daily Class A pan evaporation in mm). The water holding capacity (WHC) of the trial site soil was determined from retention curves obtained from pressure plate analysis similar to the method described by Richards & Weaver, 1944).

Table 1 Irrigation factors (Fi)* used throughout the season at the two localities.

Month	Locality	
	Nelspruit	Addo
August	0.59	0.87
September	0.51	0.75
October	0.68	0.76
November	0.90	0.75
December	0.94	0.73
January	0.98	0.82
February	1.00	0.94
March	1.10	1.10
April	1.10	1.25
May	0.93	1.20
June	0.82	1.10
July	0.67	0.93
Average	0.86	0.93

* Based on the long term average monthly water use of a mature citrus tree in ℓ tree^{-1} and the long term Class A pan evaporation data (in mm) for each area, expressed in terms of the wetted area of 18 m^2 tree^{-1} or two-thirds of the total orchard area. (Du Plessis, 1988).

Addo experiment: This experiment consisted of 5 treatments with 4 replicates and 3 trees per plot. Results from only two of these treatments namely tensiometer scheduling and irrigation factor scheduling are used in this paper. In this case water was applied (690 ℓ tree^{-1}) when a tensiometer reading of not less than -50 kPa at 300 mm depth or -30 kPa at 600 mm depth was reached. Irrigation factors used in the other treatment differed from those used in the Nelspruit experiment (Table 1). In this case 990 ℓ tree^{-1} was applied when the accumulated total of Fi x Eo reached 50 mm.

Irrigation factors (Fi) shown in Table 1 were calculated for each area on a monthly basis as follows: Fi = Et/Eo, where Et is the average monthly long term water use data, obtained from mature trees grown in weighing lysimeters at the Sundays River Valley Experimental Station. Eo is the long term monthly average Class A pan evaporation data obtained from both Addo and Nelspruit. Fi was calculated for the wetted area (initially 18 m^2 tree^{-1} in both cases, with the wetted area for Addo being increased to 19.75 m^2 tree^{-1} during 1987, and with Fi left unaltered). In both areas the weather stations were located within 500 m of the experimental orchards. WHC of the trial site soil was determined in the same way as for the Nelspruit site.

Results and discussion

A general comparison between the soils and trees of the two experimental sites is shown in Table 2. The soil at the Addo site has a larger fine fraction than at Nelspruit with a consequently larger water holding capacity. The trees in the Addo experiment are approximately 35% larger than those in the Nelspruit experiment.

Nelspruit experiment: Data over a period of 4 seasons were available from this experiment. Table 3 shows a

Table 2 General information on the two experimental sites.

Factor description		Experimental site	
		Nelspruit	Addo
Soils:	Clay (%)	21	19
	Silt (%)	8	13
	Fine Sand (%)	32	41
*WHC (mm/600 mm)			
Total		53	60
-50 kPa		47	35
-30 kPa		38	22
Planting distance (m)		7 x 7	6.7 x 5.8
Planting date		1968	1961
Drip-area/tree (m^2)		16.4	22.2
Wetted area/tree (m^2)		18.0	19.75

* WHC is water holding capacity
Total WHC is water held between field capacity (-10 kPa) and -100 kPa matric potential in the rootzone (0-600 mm).
-50 kPa: Refers to water held between -50 kPa and field capacity in the root zone.
-30 kPa: Refers to water held between -30 kPa and field capacity in the root zone.

comparison between yield and fruit size for the two methods of scheduling. Only during the last two seasons (1988/89 and 1989/90) did tensiometer scheduling increase the yield significantly above those of the irrigation factor method of scheduling. This difference was approximately 23%. The methods of scheduling did not affect the fruit size significantly, although the irrigation factor method tended to produce smaller fruit during the 1987/88 season. The fact that yield was higher during the 1988/89 and 1989/90 seasons for the tensiometer method without increasing fruit size, means that more fruit were probably produced. Therefore, inadequate irrigation probably prevailed in the case of the irrigation factor method of scheduling during the flowering and fruit set period (September to November). This could be due to the fact that a fixed irrigation cycle (7 days) was used in this treatment, causing progressive drying out of the soil in the deeper layers, where a large portion of roots are situated.

Table 3 Comparison of the irrigation factor (Fi) and tensiometer (T) methods of scheduling on yield and fruit size (Count ≥88) for Valencias over 4 seasons in the Nelspruit area.

Method	Season							
	1986/87		1987/88		1988/89		1989/90	
	Yield (kg/tree)	Count≥88	Yield (kg/tree)	Count≥88	Yield (kg/tree)	Count≥88	Yield (kg/tree)	Count≥88
Fi	208,1	117,4	155,6	107,0	241,3	156,0	238,1	176,9
T	224,7	126,4	213,7	159,9	299,7	171,9	290,6	174,6
LSD (5%)	NS	NS	NS	NS	52,1	NS	40,6	NS
CV (%)	10,5	21,2	17,0	23,9	14,8	24,7	10,4	19,4

Water use: The volume of water applied per treatment and the rainfall figures are shown in Table 4. No attempt was made to determine the efficiency of the rainfall, and for calculation of water use it will be taken as 60%. No consistent differences were obtained between the two methods of scheduling as far as water application was concerned. On average the same volume of irrigation water was needed whether tensiometers or irrigation factors were used for scheduling purposes. Rain played a significant role in this experiment, on average supplying 17 m^3 of water $tree^{-1}$ per annum as compared to the 12 m^3 $tree^{-1}$ per annum from irrigation. The volume of rain water was calculated on the wetted area of 18 m^2 $tree^{-1}$, but could even be more since the total root area would be larger.

Addo experiment: Data for three seasons were available from this experiment. No significant differences in yield (Table 5) were obtained between the two methods of scheduling. Fruit size however, showed a significant difference in the last season with the tensiometer method being superior. This difference could be due to a lack of water during the active fruit growth phase (December to mid-April) in the case of the irrigation factor method of irrigation, or a larger number of fruit per tree resulting in smaller fruit.

Water use: The volume of water applied (Table 6) differed from season to season between the two methods of scheduling, with the tensiometer method needing more water in two of the three seasons. Rainfall played a much smaller role in this experiment than was the case in the Nelspruit experiment. Only 7.5 m^3 of water $tree^{-1}$ per annum originated from rainfall against more than 25 m^3 $tree^{-1}$ per annum from irrigation water.

Comparison of water use of citrus grown in Nelspruit and the Sundays River Valley: If rainfall is taken as 60% effective, water use per tree is 30 m^3 $annum^{-1}$ for Addo and 22.2 m^3 $annum^{-1}$ for Nelspruit (tensiometer scheduling method plus 60% of average rainfall). Taking the tree size into account (drip area, Table 2) a mature tree in Addo will use 1.35 m^3 of water per m^2 of drip area (30.0/22.2 = 1.35%) and the same in

Table 4 Comparison of the irrigation factor (Fi) and tensiometer (T) methods of scheduling on volume of water applied* per season at Nelspruit.

Season	Water applied (m^3/tree)		Rainfall (m^3/tree)
	Fi	T	
1987/88	14.6	13.0	13.8
1988/89	8.1	11.6	17.2
1989/90	12.7	15.2	15.6
1990/91	12.7	8.0	21.2
Average	12.0	12.0	17.0

* Wetted area of 18 m^2/tree

Table 5 Comparison of the irrigation factor (Fi) and tensiometer (T) methods of scheduling on yield and fruit size (Count ≥88) over 3 seasons at Addo

Method	Season					
	1986/87		1988/89		1989/90	
	Yield (kg/tree)	Count ≥88	Yield (kg/tree)	Count ≥88	Yield (kg/tree)	Count ≥88
Fi	178.7	141.7	240.7	191.5	189.0	67.9
T	209.4	144.6	238.6	198.8	201.9	104.7
LSD 5%	NS	NS	NS	NS	NS	28.8
CV (%)	14.4	21.9	13.9	15.1	11.5	20.2

Nelspruit (22.2/16.4 = 1.35%). On a hectare basis with 400 trees ha^{-1} (7 x 3.5 m) and a canopy area of 67% of the total area (6 700 m^2) the water use will be 9 045 m^3 $annum^{-1}$ in Nelspruit (54% of total water use from irrigation) and 7 700 m^3 $annum^{-1}$ at Addo (85% of water use from irrigation).

Table 6 Comparison of the irrigation factor (Fi) and tensiometer (T) methods of scheduling on volume of water applied * per season at Addo.

Season	Water applied (m^3/tree)		Rainfall (m^3/tree)
	Fi	T	
1986/87	39.7	23.0	6.5
1988/89	24.8	25.9	6.9
1989/90	21.1	27.5	9.0
Average	28.5	25.5	7.5

* Wetted area of 19.75 m^2/tree

Conclusion

Irrigation scheduling of mature Valencia trees by means of the Class A pan evaporation and relevant irrigation factors was shown to be a viable proposition, although not as accurate as scheduling by means of tensiometers. It is important to use variable factors throughout the season and the factors should be related to the evaporation data of the specific area.

Although the effectiveness of the rainfall could not be determined it seems that a tree of comparable size will use the same volume of water per annum in Nelspruit as at Addo.

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IRRIGATION TIMING USING LEAF WATER POTENTIAL OF WHEAT

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Abstract
Irrigation scheduling, using a range of estimated midday leaf water potential (LWP) thresholds was applied to wheat at Roodeplaat Experiment Station near Pretoria to investigate the suitability of LWP as an irrigation timing criterion. Based on the predictability of LWP and its strong relationships with grain yield, grain quality and total as well as peak rate of evapotranspiration, it is concluded that LWP is an excellent index for the timing of irrigation. Indications are that attainment of yields near the upper limit of the evapotranspiration-yield-relationship is ensured by applying this technique.

Introduction

Irrigation scheduling is concerned with two well known questions, namely when to irrigate and how much to irrigate. The second question is relatively easily answered by measuring the soil water deficit or by estimating it with proven formulae and models. The first question concerning irrigation timing, however, is much more difficult to answer as it is linked to goals set by the irrigator. An aim of the irrigator could be to obtain a certain crop yield or quality, or more often to maximize yield for the most limiting asset, for instance land area or volume of water available for irrigation. Present irrigation timing techniques offer limited or no flexibility for different scheduling aims since they merely try to prevent the onset of water stress or maximize yield per unit of water applied.

Irrigation timing techniques which ensure the attainment of upper boundary values on the water-yield relationship are of primary importance because they minimize irrigation inputs, whatever the target yield. Irrigation timing based on the crop water status was found to be promising in this regard (Stegman, Schiele & Bauer, 1976). Routine measurements of crop water status variables such as the midday stomatal diffusive resistance and leaf water potential (LWP) are difficult and therefore impractical for irrigation timing. LWP will only be implemented as a criterion for irrigation timing if it can be reasonably accurately estimated using physically-based or locally-calibrated empirical models (Stegman, 1983). Little attention has thus previously been given to the establishment of relationships between LWP threshold and crop yield, or any other important parameters such as grain quality, seasonal evapotranspiration, and peak evaporation rate.

An empirical model which estimates the LWP from the soil water deficit and evaporative demand of the atmosphere was developed by Nel & Berliner (1990) for wheat at Roodeplaat. However, the performance of the model in estimating LWP for the purpose of irrigation timing was not determined.

The aims of this study were to evaluate the estimated LWP as an irrigation timing criterion at Roodeplaat by:

i) testing the perviously developed model for LWP prediction, and
ii) seeking relationships between grain yield, grain protein content, seasonal evapotranspiration, peak evapotranspiration and LWP threshold.

Materials and methods

The soil of the experimental site at Roodeplaat (latitude 25°35′ south, longitude 28°21′ east) is classified as a Shorrocks series of the Hutton form with a clay content of 12% in the A horizon increasing to 21% in the B horizon. The 1.9 m profile has a 198 mm plant available water capacity as determined *in situ*.

Superphosphate (10.5% P) was broadcast at a rate of 28 kg P ha^{-1} and limestone ammonium nitrate (28% N) at a rate of 51 kg N ha^{-1}, and the whole experimental field was rotovated to a depth of 0.2 m. Spring wheat (*Triticum aestivum* L. cv SST66) was planted on 8 June 1988 at a seeding rate of 64 kg ha^{-1} in rows spaced 0.25 m apart. A top-dressing of 100 kg N ha^{-1} (LAN 28% N) was applied 47 days after planting.

Prior to fertilization and planting, the profile had been brought to field capacity and, after planting, another 20 mm of water was applied to ensure good germination and seedling establishment. After top-dressing the whole field was brought to field capacity again and subsequent irrigations applied according to individual plot treatments.

After emergence, 21 plots, each 10 x 5 m in size, were measured out in a randomized block design with three replicates. Soil water content was measured twice a week by means of a neutron moisture meter, the access tube being installed in the centre of each plot. Measurements were taken at 0.15 m intervals to a depth of 1.8 m. On certain cloudless days during which soil water determinations were made, the mean midday LWP of each plot was also measured. This was done by sampling three randomly chosen fully-expanded upper leaves and applying the pressure chamber technique described by Turner (1981). An area of 2 m^2 close to the access tube, where no destructive sampling occurred, was used for yield determination at the end of the season.

Seven irrigation timing treatments were applied using estimated LWP threshold values of -1.2; -1.4; -1.6; -1.8; -2.0; -2.2 MPa. The model of Nel & Berliner (1990) was used to estimate leaf water potential:

$$LWP_p = -0.1024(Epan) - 0.01383(SWD) - 0.0141 \quad (1)$$

where LWP_p = the estimated midday leaf water potential in MPa
Epan = the daily A-pan evaporation in mm,
SWD = the measured soil water deficit as a percentage of the plant available water capacity of the profile.

As the soil water content was determined only twice a week, the frequency of measurement of ET rate and LWP, and of decisions whether to irrigate or not, were also limited to two per week.

The accuracy and uniformity with which water was applied were assumed to have no influence on results since a specially designed plot irrigator, fitted with an accurate water meter and an oscillating boom with herbicide sprayer type nozzles, was used. Uniformity of application exceeded that of commercial irrigation systems.

Seasonal evapotranspiration (ET) for each plot was calculated from the following equation:

$$ET = R + I + S + W - (RO + D) \quad (2)$$

where R = total rainfall
I = total irrigation
S = net change in soil water deficit between the beginning and end of the season
W = water supplied by upward flux from a shallow water table
RO = surface runoff; and
D = deep drainage.

No surface runoff occurred during irrigation or rainfall, and RO was thus assumed to be zero in calculating the seasonal ET. To minimize deep drainage, plots were irrigated back to 95% of field capacity and, in calculating the seasonal water use, losses due to deep drainage were assumed to be negligible compared to water use by evapotranspiration. A shallow water table was absent; therefore W was assumed to be zero. Peak ET is the highest increase in soil water deficit between two days of soil water measurement, expressed in mm day^{-1}.

At the end of the season an area of 2 m^2 per plot was harvested, the ears threshed and grain yield determined after oven drying at 60°C for 48 hours. The protein content analyses were done by the South African Wheat Board.

Results and discussion

Estimated versus measured leaf water potential

For LWP values above -2 MPa (the lower limit of the range for which the equation of Nel & Berliner (1990) was derived) estimated and measured values yielded a correlation coefficient of 0.73 and a regression coefficient of 0.63, indicating some over-prediction. For measured values below -2M Pa, the correlation ($r = 0.70$) was equally good but the smaller regression coefficient of 0.3 indicated an even greater over-prediction in this range. The greater over-prediction at lower LWP suggests that the relationship between LWP, soil water deficit and atmospheric evaporative demand is not linear.

By using nonlinear regression, 198 observations of leaf water potential were related to pan evaporation and soil water deficit, resulting in a r^2 of 0.96, and a Durban-Watson value of 1.29. The regression equation obtained was:

$$LWP = -0.15568Epan - 0.000247(SWD^2) \quad (3)$$

where LWP = the midday leaf water potential in MPa
Epan = the daily A pan evaporation in mm
SWD = the measured soil water deficit as a percentage of the plant available water capacity of the profile.

The relationship is displayed graphically in Figure 1. What is of significance is that the data were collected from 60 days after planting to the hard dough stage, thus ensuring that the regression equation is applicable for the larger and more important part of the season.

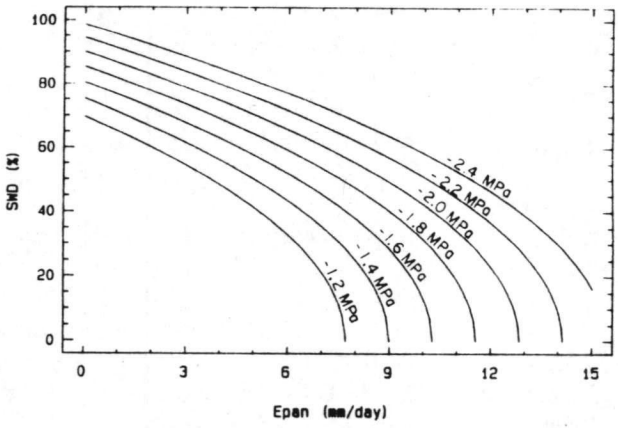


Figure 1 Relationship between soil water deficit (SWD), class A pan evaporation (Epan) and midday leaf water potential of wheat at Roodeplaat.

As the irrigation timing was based on over-estimated LWP thresholds (obtained using Equation 1), the real values were derived using linear regression equations of measured values on predicted values for each plot to get an indication of the consistency of LWP threshold prediction over the experimental site. Table 1 provides the predicted LWP threshold used for irrigation timing, the corresponding real LWP

threshold derived from the regression equations (not shown) and the coefficient of variation of real LWP thresholds between plots of the same treatment. The low coefficients of variation found between replicates which were some 50 m apart indicate that a reasonably consistent prediction of leaf water potential was possible for this experimental site.

Table 1 Predicted leaf water potentials used as threshold values for irrigation timing (LWP_p), corresponding derived real leaf water potential threshold values (LWP_r) and coefficients of variation of measured leaf water potentials for treatments.

(MPa)		Coefficient
LWP_p	LWP_r	of variation (%)
-1.20	-1.30	*
-1.40	-1.45	2
-1.60	-1.71	7
-1.80	-2.37	6
-2.00	-2.89	8
-2.20	-3.20	2
-2.40	-4.12	5

* Only two replicates available

Grain yield, grain protein content, seasonal evapotranspiration and peak evapotranspiration as related to the real leaf water potential threshold.

Figure 2 consists of four scatter diagrams relating grain yield (Figure 2A), protein content of the oven dried grain (Figure 2B), seasonal evapotranspiration (Figure 2C), and peak evapotranspiration (Figure 2D) to the real LWP threshold. The trend lines are the best fit (highest r^2) for different curvilinear regression analyses tried.

The resulting equation, expressing grain yield at 13 % moisture content (Y) as a function of LWP threshold (X) was $Y = -47362 + 1.035*10^5(-X)^{0.5} + 5.3084*10^4(X) + 3467(X)^2$, with a coefficient of determination of 0.97. Levelling off of yield occur at threshold potentials below approximately -3.5 MPa and above -1.5 MPa. The equation predicts a maximum yield of 7 786 kg ha^{-1} at a leaf water potential threshold of -1.44 MPa. For threshold values between -3.5 and -1.5 MPa the relationship is linear and agrees in this respect with the results of Sjoka, Stolzy & Fischer (1981).

For protein content the equation was $Y = 12.872 (-X)^{0.29889}$ ($r^2 = 0.92$), where Y represents the grain protein content and X the LWP threshold. This rather strong relationship is supported by the findings of Stone & Tucker (1969), that grain N content declines linearly with increasing amounts of water applied to the crop. N fertilization, however, was equal for all treatments despite lower expected yields for lower LWP thresholds. These treatments therefore received more N than was needed to satisfy their yield requirements. Whether this extra N was beneficial for protein content cannot be deduced from this experiment. However, conclusions such as that from Chevalier (1975) that environmental factors may be dominant over N-fertility in determining the protein content, suggest that the protein content was mainly determined by the leaf water potential threshold applied.

The equation for seasonal evapotranspiration was $Y = 796.7(-X)^{-0.7268}$ ($r^2 = 0.97$) and for peak evapotranspiration rate was $Y = 16.373(-X)^{-1.525}$ ($r^2 = 0.95$), where Y represents the seasonal ET and peak ET rate respectively and X the LWP threshold. For both equations the slope increased with increasing LWP threshold. These two relationships may be explained by the findings of Oosterhuis & Walker (1987) that changes in stomatal diffusive resistance corresponded with the first changes in LWP of wheat. As LWP threshold increased, diffusive resistance decreased, allowing transpiration at higher rates and for longer periods of time and resulting in higher peak evapotranspiration rates and higher accumulated seasonal evapotranspiration.

The relationship between the LWP threshold and peak evapotranspiration rate emphasizes the need for a sufficiently large irrigation system capacity to maintain leaf water potentials associated with high yields as well as to facilitate irrigation management.

Grain yield as related to seasonal evapotranspiration

Irrigation timing regimes that ensure a close approach to the maximum possible yield (yield limit) for any given value of total seasonal ET are of primary interest because they permit optimal use of irrigation water (Stegman, 1983). The relationship between the grain yield and seasonal ET was found to be described well by a modified Mitscherlich function (Wood, 1980) with $R^2 = 0.95$ and function : $Y = -4025 + 23.09(X) - 5.205(1 + e^{0.01X})$ where Y represents grain yield and X seasonal ET. Figure 3 shows a scatter diagram of the data and the fitted curve. The function predicts a maximum yield of 7 734 kg ha^{-1} with an evapotranspiration of 609 mm. The corresponding threshold potential derived from the evapotranspiration LWP threshold (Figure 2C) is -1.45 MPa.

It is remarkable that the leaf water potential thresholds for maximum yield and evapotranspiration are approximately similar. This critical value of approximately -1.45 MPa corresponds well to the -1.5 MPa measured by Sjoka *et al*,. (1981), the -1.57 MPa estimated by Shimshi (1979) for sharp changes in leaf permeability and the -1.0 to -1.7 MPa found by Oosterhuis & Walker (1987) for sharp changes in stomatal diffusive resistance.

Probably more important than maximum yield per

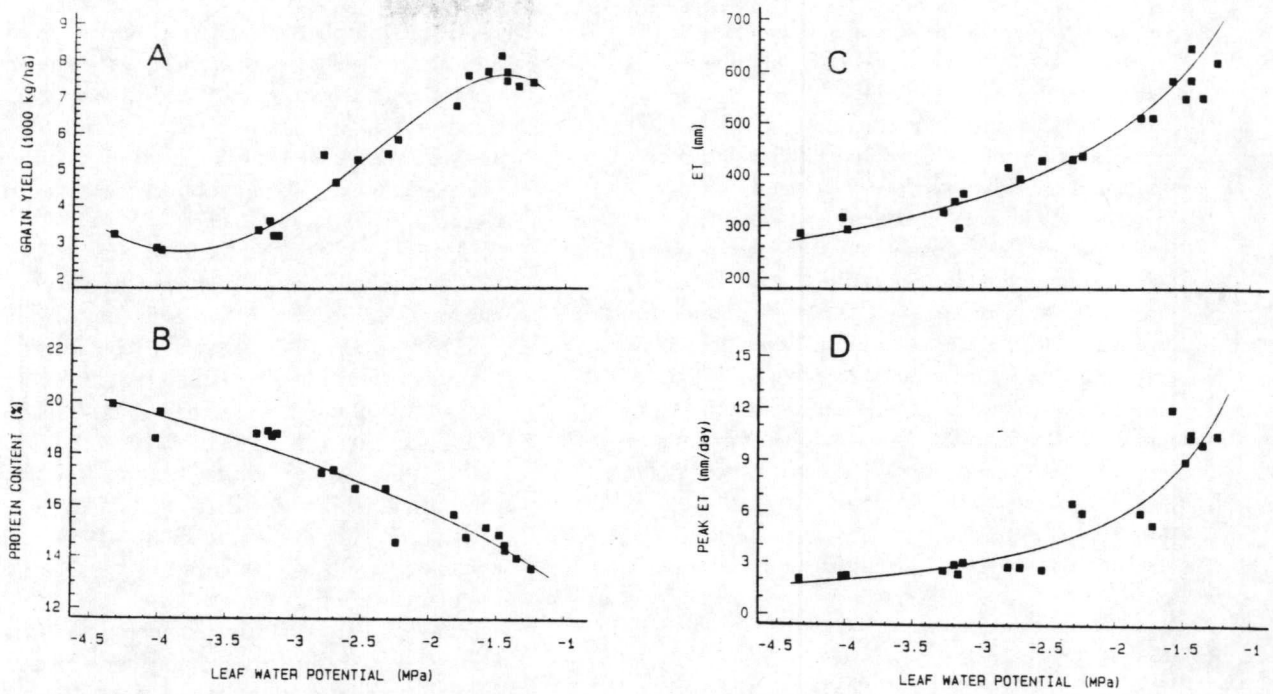


Figure 2 Grain yield, grain protein content, seasonal evapotranspiration and peak evapotranspiration as related to the real leaf water potential threshold.

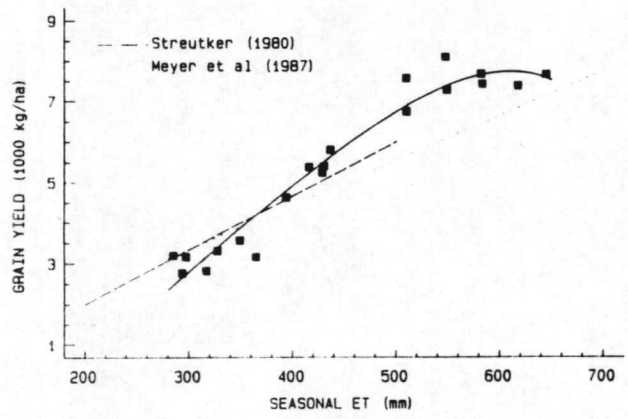


Figure 3 Grain yield (13% moisture content) as related to seasonal evapotranspiration.

unit area is maximum yield per unit water applied, or maximum water use efficiency (WUE), for this is the target of most irrigation scheduling techniques. The slope of the yield - evapotranspiration curve (Figure 3) represents WUE. The WUE reaches a maximum of 13.53 kg mm^{-1} ha^{-1} when water used is 521 mm at a yield of 7047 kg ha^{-1} and at a threshold leaf water potential value of approximately -1.82 MPa.

In comparison with upper limit yield - water use curves for Roodeplaat (Figure 3) previously determined by Streutker (1980) and Meyer, Oosterhuis, Berliner, Green & van der Merwe (1987), the regression curve fitting the present results suggests that higher yields per unit water are attainable than previously thought possible. The earlier data resulted from timing regimes based mainly on soil water status. Although a strict comparison is not possible, indications are clear that irrigation timing using midday LWP ensures near upper limit yields, resulting in more efficient water use no matter what the target yield. This supports the findings of Stegman *et al.* (1976).

Attaining upper limit yields with irrigation timing based on midday LWP is most likely the result of achieving the lowest possible irrigation frequency by allowing the drying cycle to continue to the selected threshold or level of crop water stress. This in turn allows the ET/Epan ratio to drop to a level as low as possible due to increasing stomatal diffusive resistance. The lowest allowable irrigation frequency is also accompanied by the highest possible soil water deficit, which will maximize the opportunity for the use of rainfall during the season and further minimize the use of irrigation water.

Conclusion

The midday leaf water potential can be considered an excellent irrigation timing criterion for the following reasons:

i) between 92 and 97% of the variation in grain yield, grain protein content, seasonal evapotranspiration and peak rate of evapotranspiration could be attributed to the LWP threshold applied,

ii) indications are that attainment of yields near the upper limit of the ET-yield relationship is ensured,

iii) acceptably accurate prediction (coefficient of determination of 0.96) of the midday leaf water potential on cloudless days from easily measured weather and soil variables was found to be possible for the greater part of the growing season, including the grain-filling stage and,

iv) the low coefficients of variation found for measured leaf water potential between treatment replicates indicate acceptable repeatability over distance in relatively homogeneous soil.

Estimated midday leaf water potential therefore creates the opportunity of scheduling for specific target yields from easily measured or estimated weather and soil variables. However, further investigation on the repeatability over seasons, locations and cultivars is needed.

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COMPARISON OF WATER USE OF WHEAT SUBJECTED TO DIFFERENT IRRIGATION SCHEDULING METHODS

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Abstract

Excessive or inadequate irrigation is a common problem in the cultivation of crops under irrigation. It is important that scientifically based irrigation scheduling methods, which consider the soil-plant-atmospheric continuum, be used to obtain maximum production per unit of water use. Six scheduling strategies, which include two options each of two locally developed scheduling models (BEWAB-optimum and -suboptimum and PUTU-optimum and -suboptimum), were compared. The other two strategies were a wet treatment (profile filled to field water capacity each time the soil water potential reached a value of -30 kPa at 30 cm soil depth) and a treatment where the profile was filled to field water capacity each time visible stress was observed during the vegetative stage and when the soil water potential reached a value -30 kPa at 30 cm soil depth during the reproductive stage. Although large differences in water use as well as water use efficiency between methods were obtained, few significant differences in grain yield between methods were obtained. It was found that both locally developed scheduling models (BEWAB and PUTU), with their different options (optimum and suboptimum), can be used successfully in practice.

Introduction

Water for irrigation purposes will become less available and more expensive in future. It is therefore necessary to strive towards obtaining maximum production from limited water supplies. As with poor cultivation practices, poor irrigation management, including e.g. untimely or inadequate irrigation, is responsible for major losses in production. Excessive irrigation, resulting in deep percolation losses from the root zone, is a prime cause of water wastage. There is strong support for scheduling irrigation according to atmospheric demand which will contribute to the alleviation of both crop yield and irrigation water losses (De Jager, Van Zyl, Kelbe & Singels, 1987).

Climatic conditions, and especially the atmospheric evaporative demand, have an influence on the rate at which the the soil water reservoir is depleted by the crop. Knowledge of all relevant aspects of the soil-plant-atmosphere continuum is essential for the effective management of the level of plant available soil water. To control the level of the plant available water in the soil reservoir, it is also neccesary to know the reservoir volume (Bennie, Coetzee, Van Antwerpen, Van Rensburg & Burger, 1988).

The efficient and economic use of water in agriculture is becoming a prime factor in agricultural management. The concept of water use efficiency, defined as the crop yield per unit of water used to produce the yield, is becoming more widely used as a means of judging the effectiveness of irrigation scheduling. To improve water use efficiency, a clear understanding of how plants use water and respond to shortages is needed (Oosterhuis, 1983); irrigation scheduling not based upon such understanding is unlikely to be effective.

In this study the influence of six different irrigation scheduling strategies on grain yield, water use and water use efficiency of wheat was investigated.

Procedures

The wheat cultivar, Gamtoos, was planted on 13 June 1989 at a seeding rate of 100 kg ha^{-1} at the Rietrivier Research Station (29°07'S, 24°36'E). The soil was classified as a Mangano series of the Hutton form with a depth of 1 800 mm. The clay percentage for the 300, 600, 900, 1 200, 1 500 and 1 800 mm layers are 11.7; 14.7; 16.0; 15.1; 14.1 and 12.7 respectively. Fertilizer applications of 75 kg N, 50 kg P and 25 kg K ha^{-1} were given at planting and 75 kg N ha^{-1} four weeks after planting. Individual plots were 10 m long and 7.2 m wide, of which 8 m × 5.6 m were harvested. Irrigation water was applied to the plots by means of microjets to achieve even distribution of the water. As a result of the high output of the jets, the irrigation can be considered as simulated flood irrigation. The trial was laid out in a 6 × 6 latin square design. The six irrigation scheduling strategies consisted of the following:

A) Profile filled to field water capacity each time the soil water potential reaches a value of -30 kPa at 30 cm soil depth.

B) BEWAB - optimum. Irrigation is scheduled according to the water balance approach of Bennie *et al.* (1988). The aim with this treatment is both to start and end the season with a wet profile.

C) PUTU - optimum. Irrigation is scheduled according to a computerized weather-based crop growth model (De Jager *et al.*, 1987). The model uses the Penman-Monteith equation for estimating total evaporation. The aim with this treatment is to prevent any plant water stress during the growing season.

D) BEWAB - suboptimum. As for B), except that this treatment aims to end the season with a dry profile.

E) PUTU - suboptimum. As for C), except that

allowance is made for the occurrence of moderate plant water stress.

F) Profile filled to field water capacity each time visible stress is observed between 10:00 and 11:00 during the vegetative stage and when the soil water potential reaches a value of -30 kPa at 30 cm soil depth during the reproductive stage.

Irrigation scheduling using methods B and D is described by Bennie *et al.* (1988), while that using methods C and E is based on weather data obtained from an automatic weather station and is described by De Jager *et al.* (1987). The soil water potential of -30 kPa was indicated by means of tensiometers. Soil water content was monitored by means of neutron soil water meter readings at 300 mm increments to a depth of 1 800 mm twice a week.

Analyses of variance were done on the quantifiable water used (rain + irrigation + difference in profile water content at the beginning and end of the season) during the growing season, the grain yield obtained and the water use efficiency (yield ÷ water use) for each of the six scheduling strategies. A regression analysis, with yield the dependent and water use the independent variable, was used to obtain an equation for predicting the grain yield for a specific amount of water consumed (Y=aX^b).

Results and Discussion

The quantifiable water use, grain yield and water use efficiency are shown in Table 1 for the different irrigation scheduling methods.

The water use figures for the different treatments, especially those of A and F, were low in relation to the grain yields obtained. This was also reflected in the water use efficiencies (Table 1). This can be ascribed to the existence of a water table after the flood of 1988. Water, obtained by the crop from the water table, could not be quantified. As a result, rather high water use efficiency figures were obtained. Water use efficiency figures recorded by Meyer, Oosterhuis, Berliner, Green & Van der Merwe (1987) ranged from 6.54 to 13.5 kg ha^{-1} mm^{-1}. Botha, Bennie & Burger (1983) obtained water use efficiencies ranging from 6.86 to 8.71 in terms of kg grain ha^{-1} mm^{-1} water applied.

Table 1 Water use (mm), grain yield (kg ha^{-1}) and water use efficiency (kg ha^{-1} mm^{-1}) for six irrigation scheduling methods.

Scheduling method	Quantifiable water use	Grain yield	Water use efficiency
A (No stress)	335	6601	19.99
B (BEWAB-opt)	651	8116	12.44
C (PUTU-opt)	501	7983	15.95
D (BEWAB-subopt)	550	7806	14.18
E (PUTU-subopt)	452	7426	16.43
F (Vegetative stress)	332	6963	21.01
Mean	470	7483	16.67
LSD_T (0,05)	43	1387	2.85
CV (%)	5.1	10.2	9.4

Although significant differences in water use as well as water use efficiency between most of the irrigation methods were obtained, the grain yield of only two of the methods (B = BEWAB-optimum and A = -30 kPa at 30 cm soil depth) differed significantly from each other. B gave a significantly higher grain yield than A. The grain yields of treatment B were between 6 767 and 8 679 kg ha^{-1}, except for one replication which yielded 10 823 ha^{-1} (Figure 1). If this yield is disregarded, it is possible that no significant differences between treatments will occur.

Method C used 23 percent less water than B, while the average grain yield of C was only two percent lower than that of B. The water use efficiency of C was 28 percent higher than that of B. Choudhury & Kumar (1980) observed that additional water supply in no-stress periods increased water use and grain yield of wheat proportionately without any increase in water use efficiency. The aim with B must however be borne in mind. This method starts with a wet profile and also ends with a wet profile. This means that a lot of water is carried over to the summer season and little water is needed to plant a summer crop.

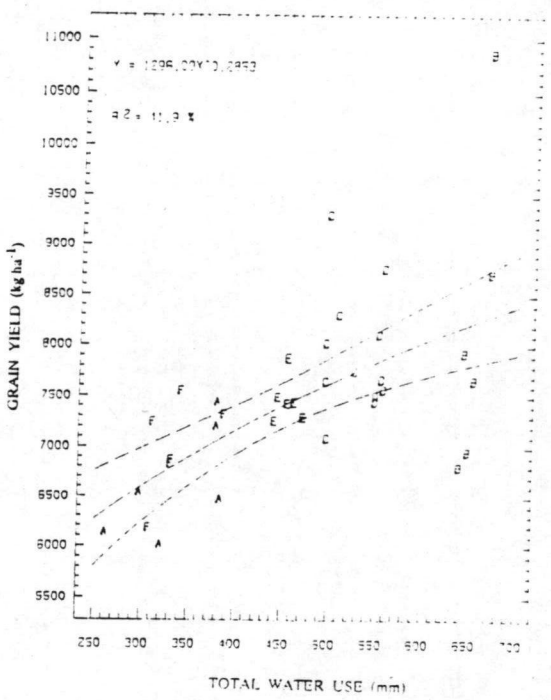


Figure 1 The influence of water use (mm) of six irrigation scheduling methods on grain yield (kg ha^{-1}) of wheat.

When methods D (BEWAB-suboptimum) and E (PUTU - sub-optimum) are compared, Table 1 shows that method E used 18 percent less water than D, while the grain yield of E was five percent lower than that of D. The water use efficiency of E was 16 percent higher than that of D.

Despite the water stress imposed during the vegetative stage in treatment F, A and F used approximately the same quantity of water (335 and 332 mm) to give only marginally (not significantly) different grain yields (6 601 and 6 963 kg ha^{-1}) and water use efficiences (19.99 and 21.01 kg ha^{-1} mm^{-1}). Previously reported work suggests that a considerable increase in the water use efficiency of wheat and barley should be possible, by scheduling irrigation at critical growth stages, as was observed by Singh & Kumar (1981).

The influence of the water used by the different irrigation scheduling methods, on the grain yield of wheat, is shown in Figure 1. A regression equation, Y = 1296.09X^0.2853, where Y = grain yield in kg ha^{-1} and X = water use (mm), was obtained for the prediction of grain yield. Only 41.9 percent of the variation in grain yield can be attributed to water use (Figure 1) which is rather low. Factors responsible for the rest of the variation in grain yield were not investigated, although differences in unquantifiable water usage from the water table are likely to be involved. The regression line is non-linear, which indicates that the increase in grain yield per unit water will be lower at high than at low water applications.

When weather data from an automatic weather station as well as sufficient water are available, PUTU-optimum is a good irrigation scheduling option. However, if there is a possibility of restricted water supply, PUTU-suboptimum can be used to achieve optimal water use efficiency of wheat. When no weather data from an automatic weather station are available, BEWAB is a favourable option. If sufficient water is available and wheat is followed by another crop in summer, BEWAB-optimum (which leaves the profile wet at the end of the growing season) will be the obvious choice. If wheat is the only crop per year, however, BEWAB-suboptimum is preferable for the irrigation scheduling of wheat since less water is used than with BEWAB-optimum and the soil profile is not left unnecessarily wet at the end of the season.

Conclusion

Both options (optimum and suboptimum) of both local developed irrigation scheduling methods (BEWAB and PUTU) can be used in practice for the irrigation scheduling of wheat depending on the availability of water, weather station data and the option of one or two crops per year. No significant difference in grain yield between B (BEWAB-optimum), C (PUTU-optimum), D (BEWAB-suboptimum) and E (PUTU-suboptimum) were obtained. All of them are scientifically-based irrigation scheduling methods. As a result of the lower quantifiable water use of the two options of PUTU, treatments C and E gave a significant higher water use efficiency than B. Data from a weather station are however not always available for the use of PUTU as an irrigation strategy.

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SCHEDULING OF DEFICIT IRRIGATION FOR IMPROVED WATER USE EFFICIENCY

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Abstract

The effect of deficit irrigation scheduling on soil water depletion, growth, fruit yield and water use efficiency of fresh market tomatoes (*Lycopersicon esculentum* Mill cv Flora Dade) was studied on deep soils of different texture at the Agricultural Experimental Station of the University of Pretoria from 1986 to 1990. Particular attention was given to the effects of soil type, the quantity and frequency of water application and cessation thereof during different growth stages. The results indicate that high frequency deficit drip irrigation applied during the day near the plants was most effective in maintaining high tomato yields of good quality despite high soil water depletion. The plants were able to utilise soil water more effectively and with less detrimental yield and growth effects than under low frequency overall deficit irrigation. Periodic waterstressing during the early growth stages resulted in supplementary growth which reduced or prevented potential yield reductions. By maintaining sufficient reserve soil infiltration capacity under deficit drip irrigation rain water utilisation could be improved substantially, thereby increasing water use efficiency.

Introduction

Deficit irrigation implies the application of reduced amounts of irrigation water, either by applying less water than evapotranspired on a regular basis or by allowing more complete soil water depletion during the whole or part of the growing season. This may be necessitated in practical farming by limited irrigation water availability, irrigation bottle-necks or an endeavour to maintain a sufficient soil water reserve capacity to utilise natural rainfall. To achieve high yields of a particular crop under deficit irrigation, a good understanding of the behaviour of that crop under varying degrees of available soil water deficits is essential.

Research with wheat (Hang & Miller, 1983), dry beans (Miller & Burke, 1983), cabbage (Fischer & Nel, 1987), maize (Stockle & James, 1989) and cowpeas (Ziska & Hall, 1983) showed that near maximum yield and, therefore, improved water use efficiency (WUE) could be obtained with deficit irrigation on fairly deep soils with acceptable water holding characteristics. However, in other experiments yields of fresh market tomatoes (Sammis & Wu, 1986), cabbage (Sammis & Wu, 1989) and oranges (Castel & Buj, 1990) were reduced by deficit irrigation. Generally it appeared that large soil water holding capacity, high soil water at planting and deep root exploration were important prerequisites for successful implementation of deficit irrigation.

Tomatoes have a well developed root system (Portas & Dordio, 1980) and should therefore perform well under deficit irrigation on deep soils with good water retaining properties. In this paper several years' research on the effect of various deficit irrigation schedules on water use, yield and water use efficiency (WUE) by market tomatoes are presented and discussed with a view to optimising irrigation and rain water use efficiency.

Materials and methods

The effect of deficit irrigation scheduling on soil water depletion, fruit yield and WUE of the table tomato cultivar, Flora Dade, was investigated from 1986 to 1990. Particular attention was given to the effect of soil type, the quantity and frequency of water application and cessation thereof during different growth stages.

The research was done on two experimental sites each fitted with a rain shelter which automatically covered the whole experimental area shortly after commencement of rain showers, thus ensuring strict control over water applications. The first site consisted of 12 plots which were completely randomised with respect to three different soil types (light brown sandy loam, red sandy clay and black clay, disturbed several years ago to a depth of 2 m and containing, respectively, 15%, 37% and 42% clay in the top 0.8 m) and two or four irrigation treatments. The plots were sealed on all four sides with brick walls covered with plastic sheeting and were underlain by sandy clay soil of indefinite depth. The second site consisted of 16 unsealed plots of similar sandy clay soil of indefinite depth. The first site was used for investigating varying frequencies and levels of drip and microjet irrigation on the three soil types. On the second site the effects of water stressing during the vegetative, fruit growth and ripening stages were investigated.

Plants of the cultivar Flora Dade were planted in early summer (November) 0.4 m apart in 1.5 m rows. Various spray (microjet) and drip irrigation schedules were applied. Spray irrigation, used to replenish soil water in the top 0.8 m of soil to field capacity, was applied by microjets (spaced 0.3 x 0.6 m on polythene piping) when each of four pre-determined levels of plant available water depletion (40, 65, 90 and 100% PAWD) in that layer had been reached. Drip irrigation was applied with Agriplas in-line drippers spaced 0.6 m apart

on plastic pipes placed 0.25 m from each tomato row. A USWB Class A pan was placed in the open on a level grass area approximately 30 m from the experimental sites and pan evaporation measurements (Ep) were used to determine quantities of water to be applied by drip irrigation. Water stress was induced during different growth stages by withholding irrigation until stressed plots could be visually distinguished, at midday, from unstressed plots for at least one week. Tomato fruits were harvested in weekly intervals from approximately 80 days after planting (DAP).

Experimental sites, crop cultivation and harvesting techniques are fully described by Fischer (1990). Soil water was monitored at approximately weekly intervals (usually before weekly irrigations were due) with a CPN 503DR neutron water meter (manufactured by Campbell Pacific Nuclear Corp., Pacheco, U.S.A.). The neutron probe access tubes were installed next to the dripper lines, 0.25 m from the tomato rows.

Results and discussion

Low frequency mircrojet irrigation

Soil water deficit profiles and tomato yields for treatments on the sandy loam are shown in Figure 1. At the four depletion levels, 16, 11, 6 and 2 irrigations were applied which corresponded to average irrigation intervals of approximately 9, 13, 23 and 70 days, respectively. Similar fruit yields were obtained at the 40% and 65% PAWD levels. At the 90% and 100% depletion levels, however, significantly less fruit was harvested. Results of earlier trials (Fischer, 1990) suggest that yield reductions could be expected after 70% PAWD. Similar trends were obtained on the heavier soils, although peak soil water depletion occurred later and the magnitude of yield reduction was slightly lower than in the sandy loam soil. In all soils more water was extracted from the deeper soil layers (0.8-1.2 m and 1.2-1.6 m) at the 90 and 100% PAWD levels then at the 40 and 65% levels. Water extraction from these layers commenced approximately six to seven weeks after planting. This coincided with the beginning of fruit growth. The lower fruit yields at the higher depletion levels were primarily due to a decrease in fruit size.

The results show that tomato fruit yield under low frequency irrigation is adversely affected if more than 70% PAW in the top 0.8 m is extracted.

Drip frequency at suboptimum (deficit) level

Weekly and two-daily drip irrigation, at a rate equivalent to 50% of Ep, was applied from 36 to 126 DAP. Soil water depletion curves, as shown in Figure 2, illustrate a sharp increase in soil water deficit from 36 to 100 DAP, reaching a maximum between 98 and 126 DAP. During this period virtually all PAW in the top 1,6 m had been extracted by the tomatoes. Tomatoes were solely dependant on the two-daily and weekly deficit irrigations and on water extracted from below 1.6 m. This extreme soil water depletion pattern was maintained for approximately one month until 126 DAP. When the plants became visually stressed (from 127 DAP onwards) the irrigation rate was increased to 75% of Ep. This was followed by an additional water application when, due to a faulty rain shelter mechanism, an unknown portion of 117 mm of rain which fell betv 133 and 137 DAP wetted the plots and effectively terminated the deficit irrigation treatment.

Soil water status in the 0-0.8 m layer varied under two-daily than under weekly drip (Figure 2). Under weekly drip high water stress occurred during the last few days of the weekly irrigation interval as observed by lowered leaf water potential and reduced leaf growth (Fischer, 1990). Furthermore, since all irrigations were applied during the day when evaporative demand was high, tomatoes under two-daily drip were subjected to lower but more regular variations in plant water stress than under weekly drip. This created favourable conditions for the occurrence of osmotic adjustment (Turner & Jones, 1980), which had previously been identified in tomatoes by Oosterhuis & Wullschleger (1989). Siadat (1980) also found that plant water stress accompanied by deep soil water extraction could be avoided by deficit irrigation applied during periods of high evaporative demand. Despite the difference in the plant stress cycle and the effects on leaf growth, Figure 2 shows that similar high fruit yields of approximately 140 t ha^{-1} were obtained from both treatments.

It is concluded that under high frequency deficit drip irrigation all PAW in the top 1.6 m may be extracted without materially affecting growth and fruit yield, provided this high extraction level is maintained for a limited period only. In unsheltered conditions this could be achieved by occasional rain, thus ensuring maxi efficiency of irrigation and rain water use.

Drip frequency at optimum level

Twice-daily and weekly drip application of optimum irrigation levels for tomatoes were compared on three soil types. Under optimum irrigation the total soil water deficit, as estimated from USWB Class A pan measurements and crop factors since the previous irrigation, was replaced with each irrigation. Soil water depletion and tomato yields (average for three soil types) are shown in Figure 3. These show that during the late fruit growth phase (60 to 100 DAP) considerably higher water deficits occurred in the 0-0.4 m and, to a le degree, in the 0.4-0.8 m soil layers under weekly than under twice-daily drip. This resulted in a slight, though non-significant, decrease in fruit yield. In the 0.8-1.6 m soil depth, however, higher soil water deficits occurred under twice-daily drip during the same period. This

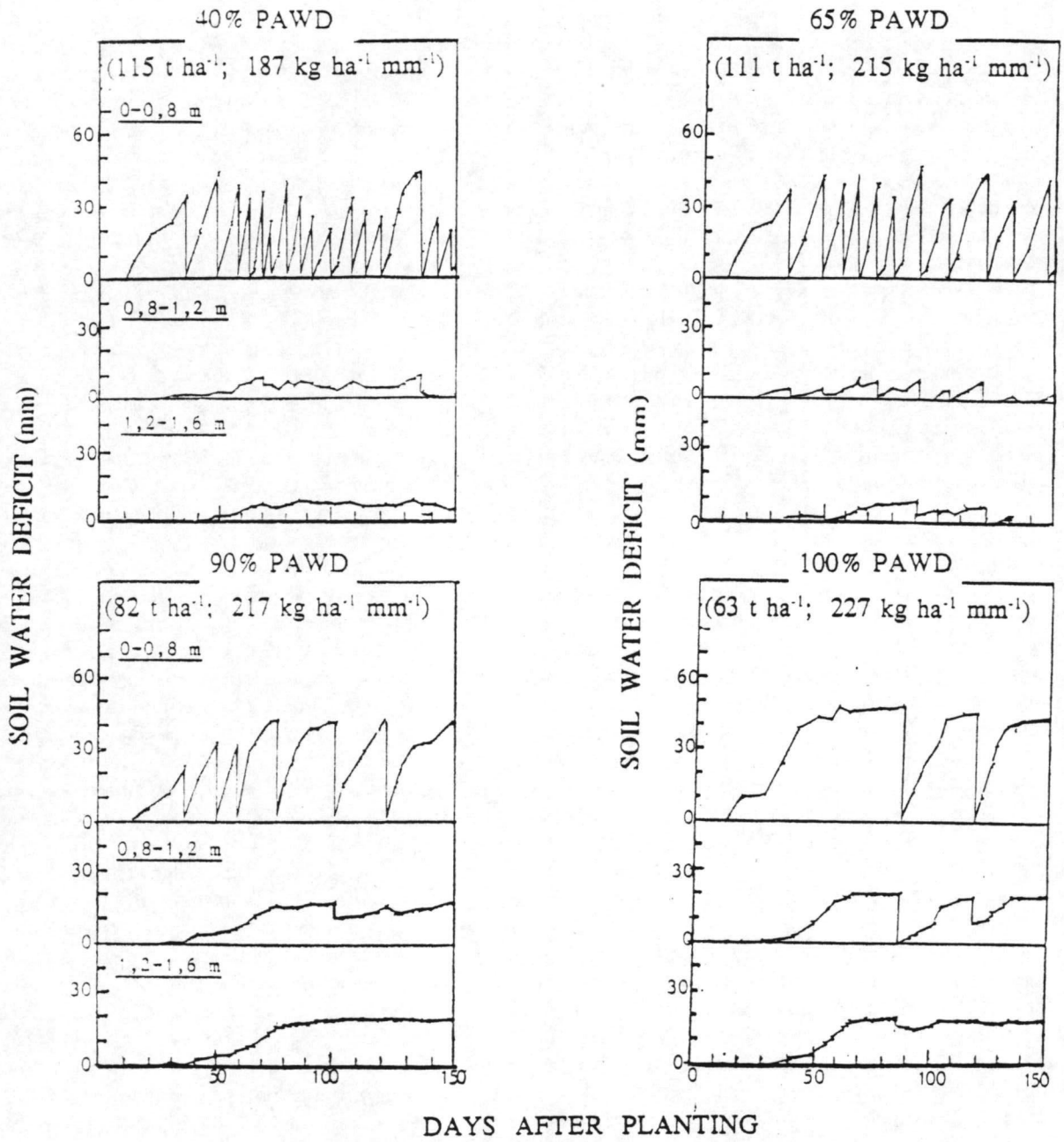


Figure 1 Water depletion by tomatoes at three depths of sandy loam soil which was spray-irrigated to field capacity at four levels of PAWD in the top 0.8 m. Fruit yields and water-use efficiencies obtained are shown in parenthesis.

may have been due to, either, improved utilisation of deep soil water under high frequency drip, or to less efficient wetting of the deeper soil layers by the lower half-daily irrigation quantities as a result of higher evaporation losses associated with the higher irrigation fequency, or both.

The results suggest that the lower fluctuations in soil water status in the top 0.8 m associated with high frequency drip irrigation at optimum levels slightly improved fruit yield and therefore WUE, despite higher soil water depletion in deeper soil layers.

Stressing tomatoes during different growth stages

On the sandy clay soil of the second experimental site tomatoes on the unstressed control plots were drip irrigated daily at optimum levels from planting until

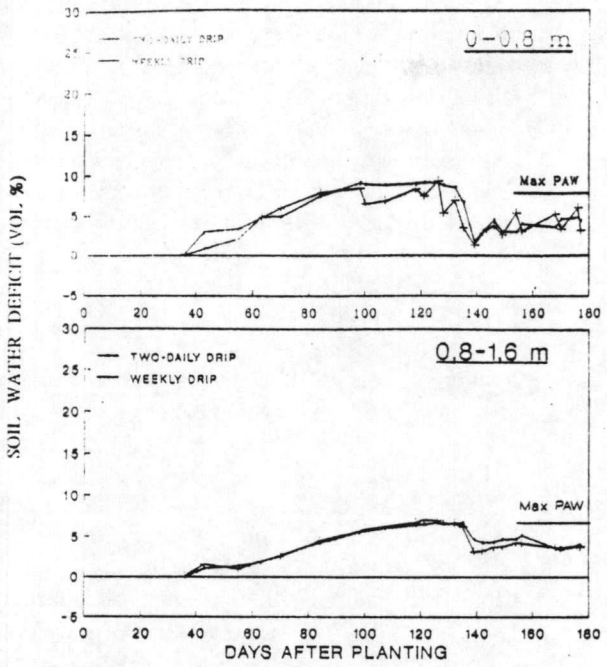


Figure 2 Soil water depletion by tomatoes at two depths under two-daily (·) and weekly (+) deficit irrigation. Total fruit yields and water-use efficiencies were (a) for two-daily drip, 143 t ha^{-1} and 262 kg ha^{-1} mm^{-1} and (b) for weekly drip, 139 t ha^{-1} and 255 kg ha^{-1} mm^{-1}, respectively.

harvesting. On the other three of the four sets of plots tomatoes were stressed either by withholding irrigation during the vegetative, fruit growth or ripening stages. The effect thereof on soil water status, fruit yield and WUE are shown in Figure 4. These show that soil water deficits increased sharply after irrigation was terminated. Maximum soil water deficits of approximately 11% by volume were measured during the vegetative and fruit growth stages. Assuming no horizontal soil water variation this represents nearly all PAW in the 0-1.4 m layer. Tomatoes stressed during ripening did not deplete soil water to the same extent and exhibited visible stress symptoms sooner. Despite high depletion rates fruit yields did not differ significantly. This is ascribed to supplementary growth which occurred after re-watering of tomatoes that were stressed during the vegetative and early fruit growth stages (Fischer, 1990). Tomatoes stressed during the late fruit growth and ripening stages produced slightly smaller fruit, though this did not affect total fruit yields significantly.

These results show that periodic plant water stress, particularly when experienced during the early growth stages, may not necessarily affect tomato yields detrimentally.

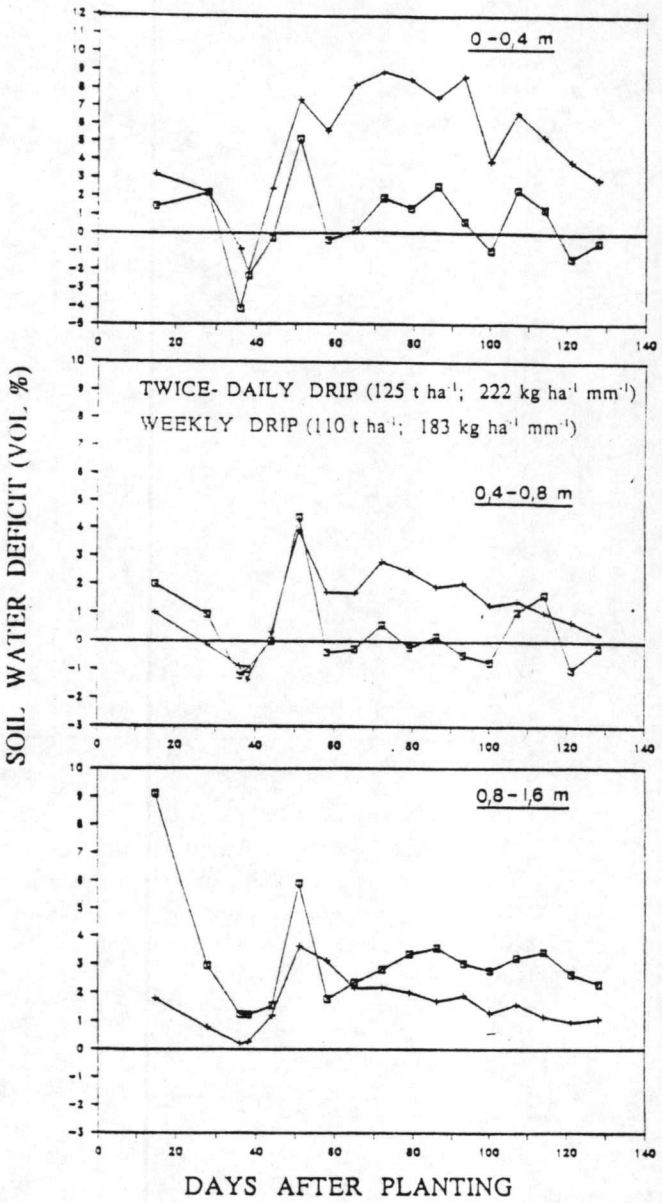


Figure 3 Soil water deficits at three soil depths under twice-daily (□) and weekly (+) optimal drip irrigation. Total fruit yields and water use efficiencies in parenthesis.

Water-yield relationship

Water-yield curves presented in Figure 5 show that market tomatoes grown on deep soils can attain maximum fruit yields of approximately 140 t ha^{-1} with a total water use of 400 mm under optimal growing conditions and irrigation practices. Unfavourable climatic and soil conditions, as well as poor irrigation and production practices can lower yields substantially, even with relatively high water applications.

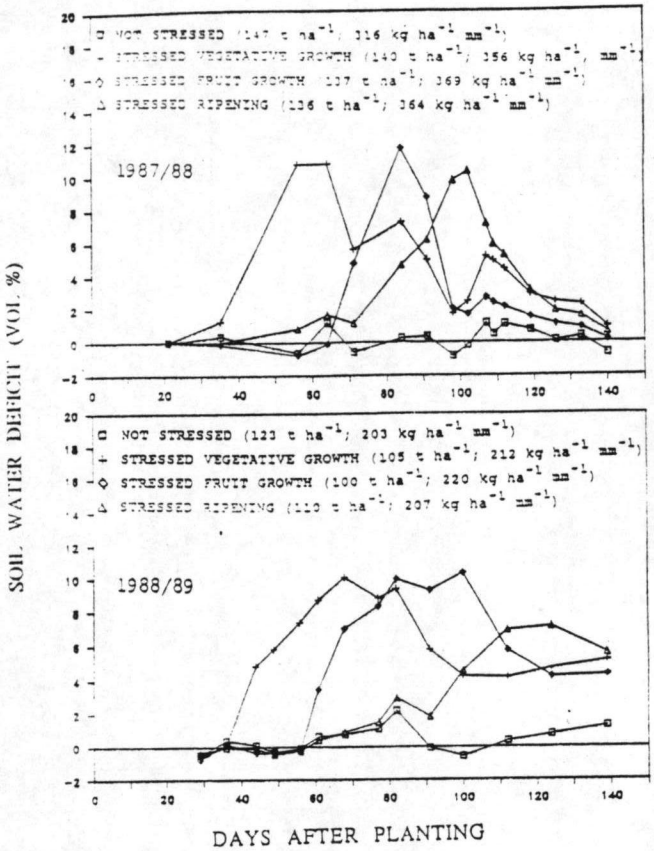


Figure 4 Soil water depletion by tomatoes during 1987/88 (0-0.2 m) and 1988/89 (0-1.4 m) as influenced by terminating irrigation during various growth stages. Total fruit yields and water-use efficiencies in parenthesis.

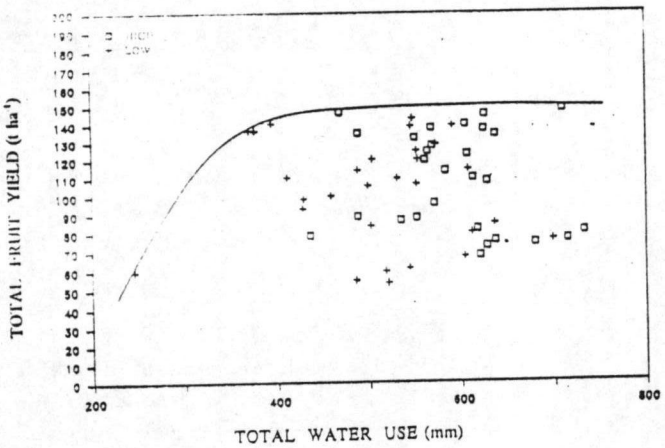


Figure 5 Water yield relationship at high and low irrigation levels.

Conclusion

It is concluded that near maximum tomato yields can be obtained with high frequency deficit drip irrigation on deep soils, thus improving water use efficiency and rainfall utilisation. The effectivity of this practice will depend on soil water storage capacity, climatic and general growth conditions, crop characteristics and a need to consider alternative uses of some of the available irrigation water. Periodic severe plant water stress not necessarily lower fruit yields under conditions similar to those of the experiment.

Acknowledgement

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THE ECONOMICS OF IRRIGATION: PRESENT RESEARCH AND FUTURE CHALLENGES

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Abstract
The problem in the economics of irrigation is choice between alternatives for the optimal allocation and use of scarce resources. Applied research must provide solutions which maximize or at least improve individual utility and social welfare. Based on the systems approach, the field of research is divided into the economics of crop production, resource allocation, irrigation farming, regional development and water policy. An overview is given of the present state of knowledge and future research challenges. Progress has been made in addressing relevant questions and presenting practically useful answers. This comprises reliance on detail and correct data and use of suitable methodologies. In particular crop growth simulation models, dynamic linear programming models, input-output tables and benefit-cost analysis have been successfully applied. Challenges at the level of irrigation farming and water policy are identified. These include increased efficiency in water and energy use through scheduling; use of appropriate technology; analysis of decision processes, utility profiles and risk preferences of managers; dynamic-stochastic modelling; quantifying the social, economic and environmental impact of irrigation on regional development; deriving regional production functions and demand for water; and a study of institutional alternatives for the creation of a market for and pricing of water. This research must be undertaken based on an awareness of real life needs and multi-disciplinary teamwork.

"In the process of identifying and assessing the potential contribution of economics and economists to research on water problems, it is necessary to identify the nature of continuing and emerging water problems to which economic theory and methods can be applied" (John F. Timmons, 1983).

Introduction

Irrigated agriculture in South Africa uses approximately 51 per cent of the total water resources. In the past it has contributed an estimated 25 to 30 per cent of gross agricultural production (Department of Water Affairs, 1986: 2.4 and 2.7). However, water supplies are variable and together with increasingly competitive uses, water is a scarce resource. Furthermore, with the possible exception of vegetables, fruit and industrial crops, other sources of crop and livestock products are available to satisfy market demands. This raises the complex question of both effective and efficient water utilization.

The answer is neither obvious nor straightforward but requires knowledge of the economics of water resources. This knowledge is acquired by means of applied research to determine the alternatives for decisions regarding the optimal allocation and use of water for irrigation. In order to be of practical value to the farming community, this research effort must provide solutions that will maximize or at least improve utility of individual farmers and welfare of society as a whole (Groenewald, 1973: 4-13).

In this paper a brief overview is given of applied research which has been completed or is presently being undertaken. Emphasis is placed on future challenges which face agricultural economists specializing on water resource problems. Within the context stated above, experienced or expected problems are defined as the non-existence of knowledge or the deviation from some relevant optimum (Groenewald, 1973; Timmons, 1983: 187).

Past research contributions

As is the case in many other countries, the development of water resources in South Africa has been characterized by social and political influences (Van der Post, 1937: 219). This fact as well as the apparent surplus of water and capital resources probably explains why initially relatively little agricultural economic research was done. Obviously the responsibility to critically analyse the economic policy of rural development, land and irrigation settlements has not thereby been excluded. An important and incisive contribution in this regard was made by Van der Post, (1937: 217-289) and principles applied then are still valid today. Other noteworthy examples are the application of economic principles for solving problems of water utilization (Van Wyk, 1964) and also include mainly farming surveys (cf. De Swardt, 1929; Retief *et al.*, 1960) and studies of settlers in river basins or irrigations schemes (cf. Hattingh, 1965; Van Zyl, 1965).

At the time of the National Irrigation Symposium during 1967 a description was given of important economic features and relationships in irrigation farming. The principles of production economic theory with respect to irrigation practices were clearly illustrated. Mention was made of a lack of attention to economic considerations with planning of government water schemes and irrigation board schemes.

Arguments were given in favour of more efficient use of water on existing irrigation schemes and elimination of uneconomic small farming units rather than horizontal expansion of irrigated land. A specific conclusion was that "vertical expansion should therefore be given priority, so that the existing resources can be utilized more efficiently through adopting well-planned farming systems and farming techniques" (Siertsema, 1968: 13-19) and this is equally relevant under present circumstances.

Outline of the field of research

Problem-solving and subject matter research in agricultural economics is holistic, mostly multi-disciplinary and requires simultaneous attention to all variables (Johnson, 1987: 88-89). The systems approach is a way of thinking in terms of the whole (Spedding, 1979: 18-19) and therefore helpful in delineating the fields of study in irrigation economics. Based on systems theory, irrigation can be defined as a purposeful, open, dynamic and stochastic system, with one of the primary goals to produce food and fibre by means of agricultural resources (Dillon, 1978). This implies amongst others that developments are due to the purpose that is being served (i.e. the teleological view); that the environment influences efficiency in one way or the other but cannot be controlled; that situations change over time; that the outcome of events is uncertain; that irrigation is a man-biological-machine system which is consequently more complex than plant, soil, climate, animal and machine systems. Finally the efficiency of irrigation cannot be evaluated by analyzing the components separately. The analysis must be done by giving full recognition to the relationships between components and sub-systems, the functioning of the system as a whole in relation to the environment and other systems in the same environment. Because of the purposeful nature of the system, it is subject to the management principles adhered to by decision-makers and therefore human resources perform a central function.

A number of systems and sub-systems can accordingly be identified. These consist of e.g. the crop enterprise sub-system; various resource sub-systems; the farming system; the river basin or regional system; and the national water system (Backeberg, 1990). Farming systems can of course also be described as sub-systems of the regional system which in turn are sub-systems of the national water system.

Systems can therefore be subdivided into sub-systems which "have this property that they possess an integrity of their own, such that when studied in relative isolation the resulting increased knowledge about them can be fitted back into the whole system from which they were derived and contribute to understanding of the latter" (Spedding, 1975: 14, quoted by Van Rooyen, 1983: 107).

It is clear that systems occur at different levels within the agricultural economy, but this is not necessarily a reflection of the complexity of the system. Interactions take place between sub-systems and systems and this underlines the importance of defining conceptual boundaries. A simplified representation of these relationships is given in the figure below.

Key: a. Soil-crop-water sub-systems
b. Capital sub-system
c. Labour sub-system
d. Management sub-system
1. Farming system
2. Regional system
3. National water system

Goal 1: Maximize individual utility

Goal 2: Maximize social welfare

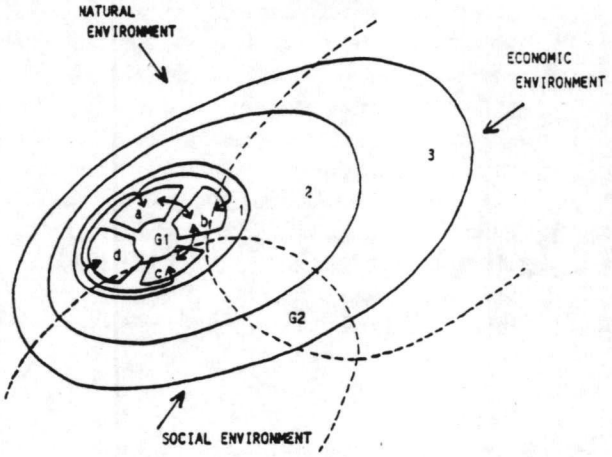


Figure 1 Systems delineating the field of research in irrigation economics.

For each system or sub-system models can be constructed which rely upon knowledge from the economic and sociological disciplines, applied natural sciences and engineering professions. In addition, the problem-solving model may contain spatial, dynamic and probabilistic features (see also Johnson, 1987: 101-105 for a discussion of important characteristics of problem-solving models).

Following this approach it is apparent that water resources cannot be researched in isolation from human, capital and land resources in the production process. Because of the high requirements of managerial capability and intensive capital investment for economically feasible irrigation, it is similarly not a foregone conclusion that water is the only or the most scarce resource in agriculture (cf. Van der Post, 1937). Research of economical optimal resource allocation must consequently provide a solution to the problem of relative scarcity and consider both beneficial and detrimental consequences of water use.

Present research and future challenges

Research being undertaken within each system or sub-system will now be discussed.

Economics of crop production

The transformation of water resource inputs to crop outputs is the basic relationship in the research of irrigation economics. Two problems are experienced by farmers in the production process in their efforts to increase irrigation efficiency (Bosch, Eidman & Oosthuizen, 1987). Firstly returns from irrigation are uncertain because of the uncertainties about weather, soil water levels and crop water requirements; secondly the timing of water applications largely determines crop response and increased yield through irrigation. The handling of these problems requires a dynamic approach in which the interactions between atmospheric, plant, soil and management variables are considered in determining when water stress occurs and plant growth affects yield. This implies that economic analysis depends on clarification of the physical-biological relationships and co-operation by soil scientists, agronomists, agrometeorologists and agricultural engineers. The economic evaluation of climate-crop-soil-water-management relationships further requires multi-disciplinary teamwork.

Various valuable irrigation management concepts have been formulated by biological scientists. Specific reference can be made to water use efficiency standards which can be employed to compare crop production per unit of water for dryland, supplemental and full irrigation (Green, 1985; Dent, Schulze & Angus, 1988; Bennie, Coetzee, Van Antwerpen, Van Rensburg & Burger, 1988; Gilley, Martin & Supalla, 1985; De Jager, 1978). The term irrigation efficiency is currently interpreted in a systems context because of greater understanding of the interactions between irrigation practices and the climatology and hydrology of a drainage area.

Significant research has been carried out with respect to the essential soil-water-plant-climate relationships (Bennie *et al.*, 1988; Human & Pretorius, 1991; De Jager, Van Zyl, Kelbe & Singels, 1987). Improved methods and instruments have been developed to monitor soil water and weather information. Useful research results and data about the physiological efficiency of crops have become available, specifically in respect of the influence of crop water stress on crop yields during critical growth stages.

Progress has been made by agricultural economists during the last few years in the approaches and methods followed to clarify the above mentioned basic problems of irrigation farmers. This refers to the extent, reliability and detail of data on soil, crops and climate; the integrated use of the data by means of computerised crop growth models; and the participation in multi-disciplinary research.

Solutions have been provided, amongst others, to the following questions with the help of crop growth models and the method of stochastic dominance (Virag, 1988; Botes, 1990):

(a) When and to what degree can irrigation of a crop, e.g. wheat on the Vaalhartz irrigation scheme, be reduced with minimal yield loss and reduced financial results?

(b) How does the profitability of different irrigation strategies for wheat on the Ramah irrigation scheme compare on soils with different profile available water capacities and considering yield variability as well as the farmers' attitude towards risk?

For the selection of risk efficient irrigation scheduling strategies for wheat, account was taken of the dynamic and uncertain environment in which irrigation takes place and the central role of the goals and preferences of the decision-maker.

In summary it can be stated that solutions have been presented which can improve the crop production decisions of irrigation farmers by means of economic analysis: Firstly, due consideration is given to the dynamic and uncertain environment in which irrigation occurs, through the use of crop growth models. Secondly, a strong point of departure in the economic approach is that explicit recognition must be given to the importance of the decision-maker.

In spite of the mentioned research contributions, much more applied research needs to be done on the economics of crop production. Most of this work is in respect of the validation of crop growth models. Multi-disciplinary team work needs to be promoted because this research is time consuming and expensive.

Accurate determination of yields for different cultivars of the same crop under conditions of sufficient water as well as water shortages during the growing season is required for different climatic conditions and soils over a number of years. For the purpose of economic analysis the experimental design must make provision for a large number of treatments even if the number of replications must be reduced and statistical elegance is thereby lost (Dillon & Hardaker, 1980: 114-115). These experiments and crop models are needed for a spectrum of commercially important field, horticultural and pasture crops and must be validated for schemes at different geographic locations. Apart from cultivar selection and plant density, cultivation practices, fertilization, weed and pest control must be incorporated. Irrigation strategies and profitability analysis for annual and perennial crops under climatic extremes such as droughts and floods need to be conducted.

The irrigation scheduling strategy of one crop must be integrated with the production and scheduling of successive crops. In comparison with other countries no studies have been done in which optimum crop combinations are determined while at the same time considering crop water requirements, variable yield and water limitations (Groenewald & Van Zyl, 1986: 42-48). Research on irrigation scheduling will there-

fore provide beneficial solutions if scheduling decisions can be analysed on a whole-farm basis. In this regard proposals have been made to investigate the economically efficient use of water and energy at a farming level within the dynamic environment of irrigation and the risk attitudes of decision-makers (Botes, 1991).

Economics of resource allocation

Natural, capital and human resources are the means of production in irrigation. Apart from the efficient use of resources, solutions must be provided for the problems of optimal allocation of scarce resources. Decisions must be taken e.g. to allocate a large volume of water to a small area of land or vice versa; to invest in capital intensive irrigation equipment versus labour intensive irrigation methods; and to apply management skills on a small scheduled area with intensive irrigation or a large area with extensive irrigation (in terms of both capital and water per unit of land).

Again, the interaction between resource use and resource allocation, as well as relationships between resources is of importance. To illustrate this argument, consider a change from labour intensive flood irrigation to capital intensive centre-pivot irrigation. This will probably only be economically justified if efficiency of crop production (output-input ratios) increases and managerial ability is of a high standard. In each case the opportunity cost (net income foregone in the best alternative use) together with resource cost must be calculated before deciding on a re-allocation of resources. This can only be done if knowledge exists of, e.g., substitution ratios and management requirements (see e.g. Backeberg & Bronkhorst, 1990: 7-12 and 20, for an application of these principles and methods in a hypothetical case study of sprinkler versus drip irrigation of cotton).

Soil and water relations were discussed in the previous section and therefore capital, labour and management will briefly be reviewed here, while it is accepted that land resources (in contrast to soil) are thereby somewhat neglected.

Capital and labour resources

The most recently available information indicates that sprinkler irrigation is the most important method of irrigation on 55 per cent of the irrigated area, followed by flood irrigation on 33 per cent and micro irrigation on 12 per cent of the area of 1 230 844 hectare irrigated (Department of Agricultural Development, 1990: 19). Within each broad category different types of equipment are used which differ in terms of capital and labour requirements.

Technological developments also continuously take place in respect of water storage, water distribution and equipment for irrigation. The most important developments include low energy precision application (LEPA) irrigation; low pressure centre-pivot irrigation; reduction of operating pressures on sprinkler irrigation; corner irrigation; drip irrigation; travelling linear trickle irrigation; and laser levelling of fields for flood irrigation. In the engineering field, research has been done to increase the technical efficiency and optimize the design of mechanized irrigation equipment such as centre-pivots (Reinders, 1989; Ottermann, 1988; Van der Ryst, 1990). These results must be evaluated economically because of the relative scarcity of capital in relation to the relative surplus of labour in a developing country such as South Africa.

A study of the economic evaluation of irrigation equipment has recently been completed. Crop growth models for a typical crop rotation and soils with different water-holding capacities on the Ramah scheme were used. Procedures were developed to determine the financial and economic feasibility of a long-term investment in centre-pivot irrigation equipment. Yield and price risks as well as the risk attitude of producers were also taken in account (Meiring, 1989). The method used for calculating costs is also applicable, with only minor adaptations, for other types of equipment. The conclusions are that feasibility depends on the defined soil characteristics, type of crop and degree of double cropping, irrigation application capacity and pumping heights. Financial and economic feasibility was particularly sensitive to the costs of the equipment and variation of product prices.

No research has thus far been done on labour productivity on irrigation farms. A major research challenge is to determine the present level of labour management and requirements for a labour management development programme, which must be designed and carefully monitored. The labour management audit technique which has already been developed to measure the attitude of labourers as a determinant of productivity and to quantify labour management (Oosthuizen & Radley, 1991: 18-28) can be applied for this purpose. At the same time the minimum cost design of flood, sprinkler, side-roll, travelling gun, rotating boom, linear and centre-pivot, micro and drip-irrigation must be quantified. Not only knowledge of capital and operating costs is needed, but also accurate labour requirements for each type of equipment. The substitution of labour for capital for irrigation of different crop combinations and crop yields must be deduced from this information. This will enable the choice of the appropriate technology under specific circumstances of subsistence farming, emerging commercial farming and commercial farming.

Management resource

Management as human resource must be distinguished from other resources because management is not only the means of production, but also an end of production

(Van der Post, 1937: 260). Numerous commission reports have documented that the quality or level of managerial ability is decisive for successful irrigation development (Commission of Enquiry on Agriculture, 1970: 63). It is consequently of major interest to know if management can be measured for the purpose of e.g. selection of applicants for irrigation settlements. But also and maybe more important is that discovery of managerial processes will enable training of existing and prospective managers (Nielson, 1961: 1250 - 1261).

Research has been done to investigate the characteristics of successful irrigators on the Vaalhartz scheme and a questionnaire for selection of applicants was designed (Van Zyl, 1965). The decision process of table grape farmers in the Hexriver Valley has also been studied (De Swardt, 1965). In the early seventies a management aptitude scale was developed, tested and applied (Burger, 1967; Jansen, Swanepoel & Groenewald, 1972). Later the emphasis was placed on the output of the manager in relation to managerial aptitude (Hill, 1974).

Conscious efforts have been made to select potential buyers of irrigation farms on government water schemes. The concept of management quality and successful selection of the best managers for settlement in the Great Fish River Valley has been evaluated (Backeberg, 1984: 113-126). On the basis of the findings of this research, the actual objectives of farmers are now determined and included in models for the planning of commercial farms on irrigation schemes (Backeberg, 1984: 141-154; 1989). Similar research work for subsistence and emerging commercial farmers has been done (Fenyés, Vink & Van Rooyen, 1980).

The challenge remains to fully understand the decision process of managers in both subsistence and commercial farming (Andison, 1989; King, 1989). For this purpose research is needed of the organisation structure of irrigation farms, the expected utility function, composition of goals and risk preferences of managers (e.g. Meiring, 1990). Research of the management factor must be output orientated with the emphasis on developing profiles of successful managers and relating these to a set of variables associated with successful irrigation enterprises. Inter- or multi-disciplinary co-operation with psychological and sociological disciplines is therefore required.

Economics of irrigation farming

The entrepreneur is the driving force in agriculture and for that matter in all sectors of the economy (Kirzner, 1973: 8); investments will be made if economically viable opportunities exist. This is largely determined by the market, prices and output in relation to the quality and cost of inputs and it is therefore important to study the natural, economic and social environment in which decisions are made. The decision-making unit is the farming system in which resources are combined and utilized by crop and livestock activities to satisfy and/or optimize a multi-criterion utility function of the manager. This implies that the managerial attitude and behaviour of the farmer should also receive attention. Success in terms of achieving the objective depends on correct interpretation of external environmental variables as well as the standard of internal management variables.

Whether data pertaining to a specific farm or to a survey of a group of farms are analysed and budgets are drawn up, or a model is constructed for a representative farm as an aid in decision-making, the essential elements of farming systems are the following:

1. Limited resources
2. Alternative activities
3. Multi-criterion objective functions

Various approaches can be followed and different methods can be used in model building.

Experimental farm results on the Hartbeespoort scheme and static as well as parametric linear programming (LP) as tools were employed to analy effects of limitations set by water, labour and operating capital on optimum organisation and profitability (Hancke & Groenewald, 1972: 9-16); Van Rooyen, 1979: 9-17). Information gained from group discussions was applied in parametric LP of case studies in sub-regions of the Crocodile River in Eastern Transvaal. Land and quotas for factory tomatoes were found to be limiting in this particular area, but not water (Brotherton & Groenewald, 1982: 22-30). Stratified sample surveys of farms on the Pongola scheme were done to determine the minimum cost combination of labour and capital and limitations set by water and cane quotas with the help of LP (Olivier & Behrmann, 1969: 19-26). The results obtained in these separate but isolated studies provide useful insights for management and policy advice in the planning of other irrigation schemes.

The development of any irrigation scheme proceeds in phases and involves a process of decision-making (Bergmann & Boussard, 1976). Detailed plans of irrigation farming systems are required to determine the financial feasibility of the proposed development. As early as the Convention: Water for the Future, Kassier & De Swardt (1970: 3-5) recommended that parametric and dynamic programming models be compiled for this purpose. Only comparatively recently has research in South Africa illustrated the practical applicability of dynamic linear programming (DLP) as an instrument to provide optimal investment and production plans based on data collected by stratified surveys and verified by group discussions (Backeberg, 1984: 127-203). The time value concept is incorporated in these models and the optimum growth path in farming is specified. The solution can be subjected to sensitivity analysis of e.g. production

and price levels. Experiments with alternative resource limitations and combination of activities can also be performed.

Since then guidelines have been formulated (Backeberg, 1988a) and DLP has been operationally applied in multi-disciplinary analysis and planning of various irrigation schemes (Department of Agriculture and Water Supply, 1989: 55-56).

The relative advantages of dynamic as compared to static modelling of irrigation farm systems have been illustrated and discussed by Backeberg (1985). The challenge remains to demonstrate the application of dynamic-stochastic methods of planning. These models definitely have large potential merits because they also incorporate risk in addition to time as a variable. A major obstacle appears to be availability of data to adequately describe and quantify probability distributions of decision variables. Research proposals to develop and apply a decision support system and evaluate risk management have recently been made (Meiring, 1990). Risk analysis of irrigation farming following the systems approach is also receiving attention in the research programme of the Directorate of Agricultural Economics (1991).

According to Johnson (1987: 101-102), "problem-solving models necessarily contain a maximizing component to convert positive knowledge (not about values or goodness and badness) and normative knowledge (about values or goodness and badness) into prescriptive statements about what "ought to be done in order to solve the problem under investigation". In order to achieve this, it will in future be important to interact with decision-makers (investors and policy advisors) in building and testing models. When used specifically for policy analyses, scenarios can be generated out of computational models for long-term planning of farming systems under uncertainty. This will entail "prediction of the conditions under which a system or policy that is to be analysed, designed or evaluated is assumed to perform" (Quade, 1982: 191-193). Scenario writing can enhance communication between experts constructing models and decision-makers using these models.

Economics of regional development

For the purpose of this paper a regional system includes a socio-technical grouping of a number of private farms and irrigation schemes in one or more river basins within a defined homogeneous area. Farming inputs may be required from adjacent regions and outputs are delivered to other regions in different stages of processing. Depending on the quality and stability of natural resources as well as (and most important) the accessibility of markets, water storage and irrigation farming can potentially contribute to regional development. An important component of development is the level of economic activity and economic growth brought about by re-allocation of resources and increased productivity. The major issues are whether irrigation development itself has been successful and what impact, if any, irrigated agriculture has made on regional development.

In spite of the large amounts of capital from public and private sources invested in irrigation and the significant contribution to agricultural production, relatively few studies have been done to describe and evaluate the success of irrigation development. This is particularly disturbing since evaluation is an integral part of the development process (Bergmann & Boussard, 1976). A systematic analysis of the elements of success and failure is therefore necessary to correct imbalances and gain knowledge in order to improve on the planning of new schemes (Gittinger, 1982: 25).

Research results which have been reported include an evaluation of development in the Great Fish River Valley (Backeberg, 1984: 10-111); the Vaalhartz government water scheme (Viljoen, Van der Merwe & Oosthuizen, 1989: 11-18); the Qamata and Tyefu irrigation schemes respectively in Transkei and Ciskei (Bembridge, 1986: 600 618).

Relative little attention has similarly been given to the description and measurement of the economic impact of irrigation development. Pioneering research has recently been done to determine the contribution of irrigated agriculture to the regional economy in terms of output, income, distribution of income and employment for irrigation areas including the Ramah scheme in the south-western Orange Free State (Kirsten, 1989; Kirsten & Van Zyl, 1990: 162-170). Regional input-output tables were derived to quantify multipliers and calculate the total economic impact. The results clearly show the backward and forward linkages and provide evidence of the contribution to regional economic development. In the only other study available in South Africa, the socio-economic impact of the Vaalhartz scheme has been identified and described (Viljoen, *et al.*, 1989). Use has been made of mainly the economic base theory and comparison between areas, together with e.g. the phase theory of regional development, location theory and central place theory. This research also confirms the dominant role of intensive irrigation farming for the development of surrounding districts.

Convincing evidence and arguments have been put forward for the assertion that little is known of actual performance and too few adequate accounts of irrigation schemes exist. It must be concluded that there is an important research need for independent project evaluation and retrospective studies of established schemes (Bembridge, 1986). This knowledge of comparative economic advantages and disadvantages of different schemes or regions is required before decisions are taken to develop new schemes, or for the transfer of water to schemes of different river basins, or to rehabilitate a specific scheme in favour of another.

In conjunction with the evaluation of schemes, the marketing potential of irrigation crops must be studied with reference to e.g. the infrastructure, population growth, projected supply and demand and development policies in different regions (cf. Kassier, Harrison, Tarr & Rhodes, 1988).

Further challenges must be accepted to quantify the economic impact of irrigated agriculture. This is especially applicable in regions where local processing of agricultural products is undertaken and forward linkages are expected. The supposition is that the economic impact will be greater and development of existing or new schemes must be stimulated in these regions. Apart from the economic impact, aspects such as the demographic, social, fiscal, public service and environmental impact must receive separate or concurrent attention (Leistritz & Murdock, 1981: 3).

Except for the complementary relationships between soil and water, there are also detrimental effects such as rising water tables, salinisation and soil erosion. Public debate is increasingly focusing on the subject of water quality and environmental conservation. The economic effect of pollution on agriculture and maintenance of the productive capacity of natural resources but also irrigation as a source of polluted water for e.g. human consumption must be researched. While care must be taken not to treat symptoms, the economic feasibility of artificial drainage must be evaluated and one remedy may be to internalize externalities (Timmons, 1983: 191-192 and 197). This will mean that individual firms who cause the high water table etc. because of over-irrigation, must bear the cost of drainage or pay penalties in the form of effluent charges (Ciriacy-Wantrup, 1985: 117-126). This will vary from one region to another and must therefore be approached from a perspective of regional economic development.

Regional production functions indicating the relationships between agricultural output and water input are presently not available. These aggregate functions must be fitted for a scheme or a number of irrigation farms and schemes within specific regional boundaries. From the production function the demand schedule for water and price elasticities of demand can be derived. In view of the evident scarcity of water, this knowledge is essential to determine the function that prices can fulfil in the optimal allocation of water between competing uses.

Economics of water policy

In the field of water resource economics it is critical to distinguish between the economics of water policy and the economics of resource development (Ciriacy-Wantrup, 1985: 61-62 and 67-71). According to Ciriacy-Wantrup (1985) "water policy may be regarded as a set of decision rules in a multistage decision process" within a three level hierarchy involving operational, institutional and policy decisions (see Backeberg & Groenewald (1991) for further details).

In the study of water policy it is necessary to identify the characteristics of the national water resource system. This consists of mixed groundwater-surface water systems with private and public investments for water utilization. On the operational level decisions by households, private firms and public utilities in different regions and all sectors of the economy are most significant. In the case of agriculture, farming enterprises are operated on private, irrigation board and government water schemes which occupy 59 per cent, 22 per cent and 19 per cent of the irrigated land respectively (Department of Water Affairs, 1986: 2.4) but are related to each other as a part of an integrated system. Determination of the financial and economic feasibility of irrigation farming systems, in other words maximizing a specified objective function, is of foremost importance (see section 4.3).

As indicated, "one particular class of water resource system" (is) the public, multi-purpose development of surface water through storage dams, canals and other large engineering structures" (Ciriacy-Wantrup, 1985). Although of less importance in South Africa in terms of the area under irrigation, government water schemes attract attention because projects of this nature are usually undertaken on a large scale with the use of public funds. Consequently the development of irrigation schemes must be justified on the basis of improving the welfare of society. This involves a process of allocating priorities for the optimal allocation of capital to alternative investments (e.g. comparing the construction of dams with construction of roads, schools, hospitals etc.) and the optimal scale of development (e.g. size of the dam and area irrigated) by means of benefit-cost analysis. In terms of the phases of development referred to earlier, benefit-cost analysis in the final process before investment decisions are taken and a project is implemented.

The major objective in economic benefit-cost analysis is to determine whether resource development will maximize or at least increase the national income of society as a whole. Other objectives such as distribution of income, level of savings, creation of employment opportunities, upgrading the level of education and rural health, etc. can be accommodated in the process of project selection. Benefit-cost analysis briefly involves identifying relevant direct project costs and benefits, secondary costs and benefits as well as intangible costs and benefits. Project costs and benefits must be valued starting with market prices and making adjustments for direct transfer payments and then adjusting price distortions by shadow pricing based on the principle of opportunity costs. Project costs and benefits must finally be compared over time by discounting at a chosen interest rate and calculating

various decision criteria such as net benefit-cost ratio, net present value and internal rate of return. That project alternative ought to be chosen which will maximize cash flow relative to capital resources used, therefore at the same time maximizing value added and in turn maximizing the contribution of capital to national income (Gittinger, 1982).

In the past water resources (in South Africa) have been developed largely on an *ad hoc* basis ... but (were) inadequate from the point of view of cost-benefit analysis (Department of Water Affairs, 1986: 1.31). Irrigation development has been undertaken mainly in terms of physical measures and economic considerations were of subsidiary importance (Kassier & De Swardt, 1970: 2). Theoretical considerations and the advantages of the application of benefit-cost analysis for rational decision-making for public investment and government action have been discussed (Döckel, 1972: 17-24; Spies, 1975: 221-232). The methodology of benefit-cost analysis for river basin development has been implemented on the Orange River Project (specifically the Orange, Fish and Sundays rivers) treating investments in dams and canals as a sunk cost. Project and associated costs as well as primary benefits were quantified and the conclusion was that development of the area is economically feasible using different decision criteria (De Swardt, 1969). Comprehensive research results of theoretical principles and methods of social benefit-cost analysis with practical application in the case of the Makatini Flats have also been presented (Van Rooyen, 1983). Amongst others a paradigm for agricultural development planning was expounded; economic considerations for planning large-scale irrigation schemes were specified with reference to the project cycle. Linear programming was combined with benefit-cost analysis to determine the financial and economic basis and pre-requisites for small-farmer participation.

In contrast with earlier imperfections, benefit-cost analysis has been put into practice in both developed agriculture (Department of Agriculture and Water Supply, 1985) and developing agriculture (Van Rooyen, 1986: 650-666). Furthermore the standardization of benefit-cost analysis has been promoted by the publication of a manual by the Central Economic Advisory Service (1989). The most recent application is a benefit-cost and macro-economic impact study of the Pongola water scheme (Department of Water Affairs in co-operation with Department of Agricultural Development, 1990).

The challenge which must be faced is to continue with the implementation and improvement of the methodology of benefit-cost analysis for all new irrigation projects. Even in the case of existing schemes which have not developed to full potential or which must be rehabilitated, benefit-cost analysis will provide valuable knowledge. The combination of operation research models with social benefit-cost analysis in order to allocate water from a multi-purpose scheme to different sectors of the economy warrants further attention (Pansegrouw & Groenewald, 1987). The pre-requisite is a multidisciplinary approach and involvement of agricultural economists from the point of project conceptualisation and identification.

The water system in South Africa is characterized by extreme occurrences of floods and drought. For the purpose of assessing flood damage, demand and supply relationships and economic requirements for optimal water use have been discussed. Fundamental concepts of flood control and guidelines for the determination of the cost of floods are explained. The principles are applied to the Orange, Vaal and tributary rivers with specific reference to damage of farms, towns and involvement of public agencies (Viljoen, 1979). On the other extreme, the socio-economic consequences of water restrictions have been described and quantified. Tangible and intangible effects on agriculture were analysed. It was found that the largest negative effect was a reduction or loss of crop production but the consequences for agriculture are small in comparison to other sectors of the economy (Van Zyl & Viljoen, 1986). Because of the frequency of water surpluses and shortages, further research is required to understand the competitive advantages or disadvantages irrigation farming experiences under these circumstances in different regions. With regular water shortages, supplemental irrigation and diversified farming may e.g. be economically advisable. This has far reaching consequences for restructuring of farms and schemes which were initially planned for intensive irrigation.

The probabilistic forecasting of floods and insurance against flood damage in irrigation farming is also a research area which warrants further attention (see e.g. Van Zyl & Groenewald, 1988).

Increasing scarcity of water is already a problem but the difference between water and other resources is that there are no known substitutes for water in satisfying demand (Timmons, 1983: 189). A study of the Report on the Management of Water Resources in South Africa (Department of Water Affairs, 1986) reveals a number of contradictions in terms as far as policies to overcome this problem are concerned. It is stated that in the past capital and operating expenses on irrigation schemes have been highly subsidized. These artificially low administered "prices" have not contributed to efficient water use. Since agriculture is the largest single consumer of water, savings must be accomplished to allocate water to other competing users. This must be achieved by reducing water distribution losses, improved irrigation techniques and methods as well as training of farmers.

In the discussion of expected refinements in the tariff policy it appears that the emphasis is on deter-

mination and adjustment of water tariffs by discretion of Departmental officials. Mention is made of a search for "fair tariffs" to avoid conflicts in the allocation of water. Although it is "realized that the allocation of water as an increasingly scarce resource would be more effective if market forces were allowed to play a dominant role in determining the price of water" (Department of Water Affairs, 1986: 6.30), water pricing is based solely on cost recovery. No recognition is given to the market process and interactions of supply and demand to achieve a balance between competing (and therefore necessarily conflicting) uses of water.

According to Timmons (1983: 195) "studies are needed on water allocation alternatives, varying from competitive market pricing to institutional allocations that would facilitate water use on a basis of its productivity". A proposal has been made and research on water pricing is presently receiving attention (Backeberg, 1988b). Given the scarcity problem and existing supply and demand relationships, it is hypothesised that the market process will ensure optimal allocation and use of water. The objective is to formulate a theoretically sound but practically applicable pricing mechanism, based on the theory of the new resource economics (Anderson, 1983: 3).

Research priorities

The South African agricultural economy has a dualistic characteristic with a developed commercial agriculture existing alongside underdeveloped subsistence agriculture (Groenewald, 1970: 168-172; Du Preez, 1975: 7-12). Although more a problem of general economic and agricultural policy research than specifically of water policy research, the effect has also been the creation of somewhat artificial boundaries. With the present reform and debate e.g. on the White Paper on Land Reform, these will disappear but a conscious effort must be made in the thinking process of applied research to overcome divisions of the past.

Within each system and sub-system there are linkages between subsistence, emerging and commercial farming which must be clearly understood. Further research on lifting barriers in water management, the land tenure system and marketing function (Vink, 1984: 439-449) and the small farmer approach within agricultural development models (Van Rooyen, Vink & Christodoulou, 1987: 207-223) is therefore urgently required.

Research priorities have been spelt out on a number of previous occasions: a workshop was e.g. held on economic, sociological and ecological aspects of irrigation development. The recommendations and research requirements are well documented and published (C.C.I.R., 1986; Groenewald, 1986). They have been influential in the formulation of research which has recently been completed or is presently receiving attention (cf. Virag, 1988; Kirsten, 1989; Meiring, 1989; C.E.A.S., 1989; Botes, 1990, Oosthuizen, 1990). Apart from some priorities listed below, corresponding research challenges vary diversely, with whole-farm modelling of crop production with changing levels of water availability, irrigation scheduling and variable yield on the one side. On the other spectrum but directly related are investigations of market potentials, projections of demand and supply and prices for irrigated crops. Specific priorities which include improvement in the usefulness and reliability of data in all fields of research and improved communication between various disciplines involved in applied research and formal interaction with decision-makers, must be re-emphasised.

Two broad areas of research have been identified for the purpose of a national water management strategy (Department of Water Affairs, 1986: 7.5-7.7). These are the need for the expansion of irrigation and the socio-economic impact of irrigation development, which are a problem of respectively the economics of water policy and regional growth. However, it is clear that economic theory and method must also be applied to specific priorities such as more efficient water utilization, deterioration in water quality, drought management, increasing the availability of water and the influence of water resource development on the environment (Department of Water Affairs, 1986: 7.12-7.15).

In assessing the potential contributions of economists in water resources research, several problems and major research needs have been discussed (Timmons, 1983: 187-199). Amongst these, studies of institutional alternatives for the creation of a market for water and competitive pricing must be specially mentioned. The reason is that directly or indirectly, pricing policies also influence decision-making on efficient water use by e.g. guiding the choice between intensive and supplemental irrigation and minimizing the detrimental effect of water caused by over-irrigation.

Accepting the need for a reorientation in the research of water economics together with the above perspectives of research requirements, the following applied research priorities which must receive simultaneous attention are specified, based on the reasoning in this paper.

Solutions to the problem of non-existent knowledge

- Crop simulation for economic optimal water and energy use on a whole-farm basis.
- Analysis of decision processes, utility profiles and risk preferences of irrigation farm managers.
- Dynamic and stochastic modelling of irrigation farming systems.
- Quantifying the social, fiscal and economic impact of irrigation development.
- Deriving regional production functions and the

demand for irrigation water.

Solutions to the problem of deviation from a relevant optimum

- Analysis of the appropriate technology for subsistence, emerging and commercial farming.
- Retrospective evaluation of the success of irrigation schemes.
- Managing water quality through internalizing of externalities.
- Social benefit-cost analysis for rehabilitation of existing or development of new schemes.
- Studies of the market for water rights and pricing of irrigation water.

Conclusion

The basic premise in this paper is firstly that effective and efficient irrigation can best be analysed by means of economic theory because of the supply and demand relationships of water (Timmons, 1983: 186-187). Secondly a useful principle framework is provided by systems theory for the analysis and synthesis of the complex water system with inherently dynamic and uncertain interactions.

A discussion of future applied research challenges requires an outline of the content and present state of knowledge of the economics of irrigation. Because the subject covers a wide field from the micro-economic to the macro-economic level, this paper inevitably cannot give a detailed account of all research work. In fact each of the sub-systems within the water system would justify a separate overview as is the case with the technical subjects discussed during this session.

Available research results and references quoted show that solutions have been provided for the problem of choice for optimal allocation and use of relative scarce human, capital and water resources. Although progress has been made, the results are certainly not conclusive and several research priorities have been identified. Efforts must continue but expenditures for research can only be justified if solutions contribute to maximizing individual utility and welfare of society as a whole. The central role of the decision-maker on both the irrigation farming level and water policy level must consequently be emphasised.

A prerequisite for useful research results to solve practical problems is of course the availability of agricultural economic researchers. Firstly this necessitates a certain degree of specialisation and continuous involvement in the research of e.g. the economics of water resources (Groenewald, 1973; Backeberg, 1988c). Secondly agricultural economists must themselves be effective by choosing that field of research according to real and immediate problems in life; and be efficient by verifying data and validating models (Groenewald, 1990: 245-246).

This can be achieved, in spite of a proportionately small group of agricultural economists who are active in research, through multidisciplinary research, team work and co-operation between different organizations. Examples are multidisciplinary project teams of the Department of Agricultural Development, the Unit for Agricultural Water Management of the University of the Orange Free State and combined research by the Directorate of Agricultural Economics and various universities.

Awareness of the problems and needs of the farming community must be created by formulating a correct research strategy. Formal communication channels and decision rules must therefore be established between research organisations and individual farmers or their elected farmer associations and unions. This will ensure timeous identification of problems and opportunities, provision of relevant solutions and promotion of pre-active applied research.

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SOME CONCERNS INVOLVING ECONOMICS OF IRRIGATION FARMING

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Abstract
Economic concerns regarding irrigation farming include both macro and micro aspects, and involve both efficiency and equity considerations. Ethical and equity considerations arise because benefits from irrigation are not evenly distributed; there are gainers and losers. It is difficult to find a common denominator to weigh up totals of "goods" and "bads". Equity or ethical questions involve, *inter alia*, the rights of underprivileged or present non irrigating groups to water demanded by efficient irrigators. Payment for water is also involved. Water project development has historically been regarded as a solution for insufficient or variable supply, distribution situations and quality problems. Water has generally been underpriced and users have treated it as an abundant resource. Urban water needs grow rapidly; this will create relative shortages for agriculture. Opportunity costs of water will increase. Adjustment will be needed; the historical institutional structure may impede this adjustment. A market in which water rights may be traded or leased may the most effective allocative mechanism from both equity and efficiency viewpoints. It can be effective particularly in times of water shortages. Pollution creates problems of efficiency and equitability; polluters' actions damage interests of others, but polluters tend to persevere unless compensated or stopped. Regulation is needed. Quantification of effects is difficult. No single control system can in itself solve the problem. The ethical question arises again: who should foot the bill for pollution control expenses; those upstream, or those downstream? In irrigation project planning, crop selection and water allocation should be optimized simultaneously. Shadow prices should be used with large scale projects. Production function analysis is used to determine profit maximizing water input and crop yield levels. Although the techniques are well known, too few field experiments include enough relevant variables. Stochastic studies and time frames are useful to determine optimum water use strategies when water is scarce. These range from abandoning some fields to changed crop combinations to optimisation of water application between growth stages of crops. Optimal irrigation technology is a function of costs and returns. Variability in water supplies sometimes increases the viability of more expensive systems which reduce water losses.

Introduction

Economic concerns regarding irrigation farming involve many facets. These facets include micro concerns, aimed at the individual irrigator, or macro concerns involving groups. Groups may involve communities of irrigators on established irrigation milieus or those in a stage of conversion: from non-irrigation farming to irrigation, or from lower level to higher level technologies. Group considerations also involve the interface between different groups of irrigators or between irrigators and other water users.

Another important interface concerns efficiency and equity. Whereas the former involves economic returns in a micro or macro sense, the latter involves distribution of benefits between groups or between individuals.

These factors cannot all be dealt with in depth in one single paper. Since all these considerations are however of vital importance in irrigation planning, irrigation policy and ultimately the practice of irrigation, an effort will nevertheless be made to include a wide variety of these in this paper.

Ethical considerations

Irrigation farming bestows benefits on some people and/or groups. But not all receive the same benefits; some may loose in a relative sense in that others gain more than they do. Others may loose in an absolute sense: their access to water may be reduced quantitatively or qualitatively, or their revenues may decline because of market effects. Water pollution, as caused by the transfer of agricultural chemicals to water by irrigation farming, has become a well known phenomenon. As well known is pollution by other users of water intended for irrigation. It is no wonder that access to water and pollution thereof have been the source of much litigation between persons, groups and even governments (e.g. Arizona vs California). It has also at times been an important political issue, nationally and internationally.

Longrun allocations and environmental impacts confer goods to some people and bads on others. The nature of these goods and bads is disparate, and this renders it extremely difficult to find a common denominator among them to subtract the total of the bads from the total of the goods. There are four prerequisites for optimizing prescriptions as solutions to environmental problems (Johnson, 1983):

(a) a common denominator for all bads and goods involved,
(b) interpersonal validity of the common denominator,
(c) existence of a maximum in the net difference between goods and bads, and
(d) an agreed-upon decision rule.

In such considerations, the methods of allocative efficiency - traditionally the domain of agricultural

economists - do not quite foot the bill. Equity considerations are not addressed adequately. Value judgements are needed, and this creates an impasse. We do not yet have the tools to generate value judgements, but these value judgements are necessary (Burness, Gorman & Landford, 1983). Benefit-cost analysis is usually consistent with a limited set of ethical criteria. What appears to be "best" with one set, may be rejected with another set of ethical criteria (Burness *et al*,. 1983). The same phenomenon occurs with different economic criteria (Pansegrouw & Groenewald, 1987).

Some ethical questions may, for example, revolve around the consideration as to whether water should exclusively or mainly go to those who use it most efficiently, or not. Then, arising from this, should a group who have been underprivileged and who are at an earlier stage of technology development and capital accumulation cede some or all of their water rights to a more advanced group? Should they be compensated, and how? Or should the disadvantaged group receive protection in the form of preferential treatment? How much protection should they receive, and what should be the nature of such protection? Who should foot the bill? One should also bear in mind that the mere quantification of water rights to some group will not yet necessarily address equity sufficiently; these water rights, once quantified, usually depend on funding for projects necessary to make water delivery available.

Another ethical question involves whether decisions should take into account only past performance, or whether scarce water should be preserved for groups who have not utilized their water rights. Is the principle of chronological seniority - "first in time, first in right" - invalid, or valid, and if so, to what degree? These questions are particularly relevant in societies where a racial or ethnic label is attached to the concept of underprivileged groups and existing user groups - such as South Africa - and particularly where legal systems have for long discriminated against the underprivileged groups.

The ethical question can be extended to that of payment for water. It is economically sound to demand that the user of water or any other resource pay, but how much, and for what? Should it sometimes substitute for welfare payments - in other words, where, when and to whose benefit is subsidisation feasible and desirable? This question also involves the ability to pay and also induced effects concerning linkages to the rest of the community. The latter, although readily quantifiable (Kirsten & Van Zyl, 1990), still has to be viewed within the ambit of societal norms and goals.

Many water development decisions will eventually be made by politicians, whose set of values is often determined by their will to govern. But they do need the necessary information from the agricultural brotherhood. Much of it boils down to the price of water.

If water is subsidized, there are once again groups of winners and losers. Irrigation water projects offer a selective subsidy, providing an inexpensive resource to geographically concentrated farmers. It may however mean loss in total welfare. Increased output by irrigators may result in lower product prices, which in their turn affect incomes of other farmers negatively. Consumers gain by lower prices, but at the same time lose by having to foot the irrigation project costs through increased taxation and/or inflation (Foster, Calvin, Johns & Rottschaefer, 1986). Lower income consumer groups may gain, while higher bracket taxpayers may lose.

The market for water becomes important for efficiency, ethical and equity considerations.

The water market

Few studies have yet been made on the distributional effect of different water pricing and water subsidy effects on gainer and loser groups. It has however been shown that the effects can be considerable (Foster *et al.*, 1986).

Historically, increases in the relative scarcity of water associated with population growth and economic growth have been ameliorated by developing additional supplies.

New development has been seen as a solution for the following problems (Dõckel, 1971):

(a) supply, when regional demand exceeds long-term supply,
(b) variability, when fluctuations cause short-term shortages,
(c) distribution, where there are distances between points of supply and use, and
(d) quality, if available water does not satisfy quality requirements.

In practice, water - even in areas of limited supply - has often or almost invariably been priced at levels below marginal cost or its marginal value product; water has thus been treated as if it was relatively abundant (Dõckel, 1971; Vauz, 1986).

In pure economic terms the cost of using water for a specific purpose is its opportunity cost; that is, the benefits foregone by not using it for the most advantageous alternative. Underpricing results in diseconomies, especially between users and in intensity of specific uses.

The major determinants of water demand have been population growth, economic development and also, as result of the first two, demand for preservation of the environment.

South Africa is in a process of rapid urbanisation, and urban water needs may very well double over the next decade. This will create relative shortages of water for agriculture. Elasticities of demand for water for domestic, industrial and commercial use are generally low. They have been estimated to vary

between -0.62 and -0.84 in South Africa (Dõckel, 1973); these elasticities correspond with estimates in the USA (Howe & Linaweawer, 1967; Turnovsky, 1969; Vaux, 1986). A 10 per cent increase in urban water prices can therefore be expected to have the effect of reducing urban demand by only approximately 7 per cent. The demand for water for agricultural purposes has not, as far as can be determined, been estimated. It will be a function of crop prices, and current trends suggest that on a costing basis there will be little growth in demand unless unexpected changes occur in world markets for food and fibre (Vauz, 1986).

Trends in increasing supply costs and growing urban demand suggest future increased opportunity water costs in virtually all sectors. In an economic sense, differences in demand growth would indicate shifts in water allocation if maximisation of social welfare is the predominant goal. The historical institutional structure will impede adjustment; past policies have placed a heavy emphasis on security of water rights (Vaux, 1986) and in South Africa, institutional rationing has been the main tool of allocation (Dõckel, 1971). Water management has traditionally been viewed as a technical or engineering problem. This view has substantially contributed to misallocation (Young, 1986).

The best alternative could be a water market where water rights are transferable among individuals or groups in the form of either the leasing or selling of rights. From an economic point of view, marginal cost pricing is the best alternative for pricing between water supplier and user groups. Assuming marginal value productivity to be higher, the transaction price of water will also be higher, and water transactions will enhance the economic returns to both parties involved in a contract. Two parties may be two farmers, or they may also be industry and agriculture.

Transferability of water rights implies a need for a new approach in terms of statutory irrigation water allocation. Rather than doing it on a "list area" basis, efficiency will be enhanced by basing it purely on water usage, and making this transferable. The tie to area increases transaction costs, since water rights become capitalised in property value.

Transferability may in particular ameliorate problems in times of weather-induced water shortages. Under those conditions, returns are optimised if water use is temporarily shifted to uses with the highest marginal value product to water. In irrigation farming, this often implies shift between crops grown by irrigators (Hancke & Groenewald, 1972; Van Rooyen, 1979; Groenewald & Van Zyl, 1986). But this principle goes further than this. Efficiency and returns to both parties may also be enhanced if some irrigators will under such conditions sell their water allotment for a specific year to other users, who may or may not be irrigators.

Under these conditions, returns may be maximised if industry will under such conditions buy farmers' water rights for a period of time. It has been shown in Idaho (Hamilton, Whittlesea & Haverson, 1989) that economic returns to both irrigators and industry can thus be substantially enhanced in droughty periods; expected industrial output created by such an interruptible water market should far exceed expected costs to agriculture. Long-term contracts are needed for such a purpose. The most likely form of compensation appears to be a combination of annual payments (in the form of an option) and lump sum payments in years of water interruption (Hamilton *et al.*, 1989).

Resource degradation

Irrigation farming has been blamed for resource degradation, which takes on various forms. Much literature has been devoted to the effect of salts and other chemicals which pollute streams through discharges by drainage and to soil salinisation. Groundwater pollution is another case. Industrial effluent have also contaminated water in likewise fashion.

Both economic and ethical considerations get involved. The pollutor's actions damage the interest of other parties, i.e. downstream water users or users of groundwater.

Action to prevent or materially reduce pollution costs money, and in an unregulated situation, the pollutor will be unwilling to incur those costs un he is compensated by the other users (Dõckel, 1971). Ethically, it can be considered to be unfair to other users, particularly those who had previously had access to better quality water. Some type of regulation is therefore needed.

Management strategies for this purpose can be evaluated in various ways, but a major problem is the uncertainty or variability in estimates of the outcomes used to rank alternatives (Spofford, Krupnick & Wood, 1986). There is a need for quantification of health risks and economic losses.

Farmers must receive an inducement to reduce drainage volumes and pay for their safe disposal. Some such strategies have been evaluated in California (Dinar, Kapp & Letey, 1989). A direct charge on drainage water equal to disposal costs appears to be impractical because of high costs associated with monitoring - even though it could induce efficiency in water application. Other approaches could be through pricing of irrigation water which could, on the one hand, increase irrigation efficiency, and on the other hand, provide funds for pollution control. Tiered water pricing is one possible alternative. These possibilities need further investigation.

In such research, the relative costs of, and returns to alternative on-farm irrigation practices for reduced salt loading must first be determined. A holistic

approach, which will simultaneously also include optimal crop selection and stochastic elements, is needed for both upstream and downstream water users (Gardner & Young, 1989).

No single system of control seems to be able to solve the question in itself. These have to examined for their possible contributions in a whole systems complex. The major possibilities appear to be (Milon, 1986):

(a) deterrence, involving application standards (including labelling) targeted to specific chemicals and specific hydrological areas,
(b) land-use management (zoning, acquisition and easement) targeted to areas of critical concern,
(c) fiscal incentives (taxes, subsidies, tradeable permits),
(d) remedial action (compensation), and
(e) tort rules (including prosecution).

Ethical, legal and equity considerations once again become important: who have the largest rights - those upstream, or those downstream? If downstream users held all the rights, then the upstream users should be liable in proportion to their pollutant discharge; if the upstream irrigators held all the rights, downstream users would have to pay program costs (Gardner & Young, 1988). If rights were shared, both groups would have to contribute. The question of allocating shares is clearly at least partially one of an ethical nature.

Crop selection and water use - macro considerations

On the macro level, planning of an irrigation scheme should consider allocation of water and crop selection simultaneously; these two are interdependent. Crop selection is neither a pure economic nor a pure technical consideration. Neither can it be divorced from technology of water application or from soil and water quality.

A procedure followed in the development of irrigation water resources in South Africa has often been to postulate some crop combinations based upon technical data and static budgeting of gross or net margins, computation of project costs, and water allocation based upon incremental cost-benefit analysis. Decisions based on such modelling have been evaluated in the case of the Fish River (Backeberg, 1984) and the Theewaterskloof Scheme (Pansegrouw, Groenewald, 1987). Both evaluations have found such a procedure to yield suboptimal results. In the Fish River case, the cropping pattern adopted by farmers differed radically from the hypothesised pattern, and corresponded fairly closely with an optimum derived by dynamic linear programming (Backeberg, 1984). In the Theewaterskloof case, the crop/water allocation results achieved by simultaneous optimisation of water allocation and crop selection, differed radically from those obtained with the method of incremental cost-benefit analysis and predetermined cropping patterns; the simultaneous optimisation approach yielded net economic results in excess of 250 per cent of that of the other approach (Pansegrouw & Groenewald, 1987).

There has often - perhaps invariably - also been a lack of specification of project goals. The first question becomes one of what should be optimised; economic logic dictates that the best results are achieved if economic gains relative to the scarcest resource is maximised. But more contemplation, in a more holistic sense, is needed to decide which factor is, in effect the scarcest - irrigable land, irrigation water, capital or managerial aptitude. Yet, each of these criteria will yield different answers. It has been shown that criteria of net economic benefit and the benefit/coast ratio both yield radically different results if expressed per m^3 of water or per R1 000 of capital (Pansegrouw & Groenewald, 1987). The relative measure of scarcity may differ substantially from region to region.

These considerations also amply illustrate the eventual futility of the goal of some planners who advocate the adoption of a goal of maximum physical crop yield per m^3 of water. Elementary production theory indicates that even if it was generally agreed - and no such general agreement exists - that irrigation water is the scarcest resource, this criterion will yield maximum economic benefit if, and only if all resources are free, which they are not.

Even economic benefit can be defined in different terms. In the Pansegrow-Groenewald analysis mentioned above, it was defined in terms of financial benefit to irrigation farmers - i.e. management and ownership of assets. Different criteria - eg. direct or indirect manpower employment - could most certainly yield different results. There may be a real case for inclusion of equity considerations in objective functions. Different solutions will also be obtained to the extent that indirect and/or sociological benefits are added to primary benefits. The use of cost-benefit studies for decision-making concerning irrigation projects has virtually become standard practice. There has, however, often been an important omission - the distinction between price takers and projects of sufficient size to influence market prices of farm products. In the latter case, it is often misleading to use single market prices in these cost-benefit analyses. There is also a difference between pure financial and economic benefits. If, in the case of a large scheme, benefits are quantified for purposes of economic analysis, shadow pricing should be employed. Exportable products should be credited according to prospective export earnings. Analytical methods exist for this, and even for combining these considerations with technology (Van Rooyen, 1983).

Crop selection and water use - micro considerations

Economically optimal water application and crop yield

are determined where marginal revenue equals marginal cost. Marginal analysis, employing production function analysis, is useful for this. A prerequisite is, however, that crop experiments are planned and executed in such a way that the results can be used for this type of analysis. Selection of only two levels of a variable does not foot the bill, since these implicitly assume the type of linear response which occurs only under rather special conditions in laboratories.

Water and soil quality, drainage and fertilization are all relevant variables. Cost and complexity often preclude experiments that involve introduction of all variables. Since soil salinity is often simultaneously an intertemporal result of irrigation practice, some researchers appear to shy away from including those in repetitions of field trails. It has, however, been shown that, even if it is not a predetermined variable, it can successfully be incorporated in production function analysis. Drainage volumes and salt concentration of drainage water associated with the relevant variables can also be analysed in the same framework (Dinar, Rhoades, Nash & Waggoner, 1991).

Water supply can vary considerably inter-temporarily. The effect is changes in optimal use of water on crops and in optimal crop selection (Groenewald & Van Zyl 1986; Anderson, 1968; Hancke & Groenewald, 1972; Van Rooyen, 1979). In years with critical water shortage, the optimal behaviour does in some cases include abandoning some planted crops and using water in such a way as to maximize its average value product (Zusman & Amiad, 1965). The mere existence of only limited predictability renders the use of stochastic, rather than deterministic, analyses desirable.

Various studies have been done on crop modelling with the purpose of achieving optimum results in drought periods. The irrigator's choice is complicated thereby that water allocation must be optimised over time. Dynamic linear programming, separable programming and stochastic dominance have been used for this purpose (Bosch, Eidman & Oosthuizen, 1987), as has been sequential marginal analysis (Virag, 1988). Sequential marginal analysis as well as stochastic dominance have both shown that optimal strategies include allocation of water among growth stages in such a way that gross margin can be maximised (Virag, 1988; Harris & Mapp, 1986). Stochastic dominance has the advantage that it can make provision for the individual irrigator's risk preference - i.e. is he a risk seeker, or a risk avoider? (Pandey, 1990; Botes & Oosthuizen, 1990).

Irrigation scheduling is not important only in times with severe moisture stress. It is always important. The optimal schedule will depend on a host of factors including soil type and condition, plant factors, weather, crop prices and prices of inputs, including irrigation water. Many of these factors have a stochastic character. Economic optimization has been attained with the use of random time frames. It consists of a dynamic programming model of irrigation scheduling which incorporates stochastic weather conditions, provides simple irrigation decision rules and can be operated on micro-computers (Mc Guckin, Maple, Landsford & Sammis, 1987). In a situation of high level technology, this model of optimisation has been illustrated to result in considerable enhancements of financial returns.

Technology

Under any set of conditions, the choice of irrigation technology ought to be based on costs and returns.

The relevant variables are (Berthelot & Robertson, 1990):

(a) investment costs, which assume an incremental value if the system is changed,
(b) running costs involved with using the system,
(c) associated variable costs brought about because of the system - e.g. increased harvesting costs, and
(d) additional benefits accruing from irrigation.

The benefits can accrue in the form of higher physical yields and/or product price increases induced by better quality of product.

These differences are specific to systems, soils, growth conditions, crops and market conditions. Since some irrigation systems are more capital intensive than others, farmers' financial situations are also important. Farmers with capital shortages or high indebtedness will be at more financial risk if they adopt capital-intensive schemes than those in sounder financial situations. Indebtedness has, for example, been identified as the most important determining factor regarding financial feasibility of centre pivot irrigation at Vaalhartz (Strauss, 1991).

The more unstable and variable the water supply, the more attractive become systems that increase gross margins per m^3 of water. It has for instance been shown that deterministic analysis may indicate a less efficient system (in terms of water delivery) such as flood irrigation to be the optimal, or close to optimal, irrigation system. However, if stochastic variables are employed and protracted periods of water deficiencies occur randomly, then it becomes profitable to inv larger amounts of money in systems which will, through higher water deliverance efficiency, enhance production values during drought (Strauss, 1991).

Optimum technology is, besides the factors already mentioned, also a factor of managerial ability. Higher level, more sophisticated technology may be well be optimal where high managerial levels, involving *inter alia* high technical skills, prevail. The same technology is often not optimal to managers with fewer

technical and other skills; it increases risk to these groups who are moreover usually financially poorer as well. This applies to irrigation systems. It certainly also applies to biological technology, including selection of crops or cultivars of the same crop (Van Zyl, Groenewald & Geerthsen, 1985).

It appears that broad generalisations advocating or condemning a certain technology mix are likely to be misleading and dangerous; technology choice has to be specific to local conditions.

Conclusion

Problems concerned with irrigation farming and water use are many faceted and varied. Tools to analyse many of these problems are available; improvement in all these tools is possible. There are other problems where these tools will be really useful only when better technical data become available. There are, however, also problems inherent with equity and ethical considerations. In this field, the armoury of the agricultural economist is weak. Yet, he cannot shy away from these problems. The solution of micro or technical irrigation problems will ultimately not have any meaning if the ethical ones are not resolved.

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A MARKET DIRECTED APPROACH FOR THE EFFICIENT AND EQUITABLE REHABILITATION OF GOVERNMENT WATER SCHEMES

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Abstract
Government water schemes in South Africa were constructed as an insurance against drought and as settlements to establish new owner-operators. The technical productive life of these schemes is over and decisions regarding rehabilitation are anticipated. Within the water system, decisions on the policy, institutional and operational level are identified. A framework for the economics of water policy is discussed whereby the interactions between decision levels in a multistage decision process can be analysed. Given the present mature phase of development, arguments in favour of rehabilitation instead of new developments are presented. This will require a change in policy objectives to include both efficiency and equity considerations. Efficiency can be achieved through market pricing of water resources. This in turn will necessitate reform of institutions away from control towards influencing of decisions through the establishment of a market for water rights. These principles can be applied partially, despite present control measures of the water system. In addition to water tariffs for recovery of variable costs, equitable allocation of fixed costs amongst beneficiaries is attainable through water right charges. Deregulation is however essential to promote creation of new wealth by entrepreneurs. Changes in decision rules and improvement in decision-making through a learning process is advisable. Continuation of research to design new policy, institutional and operational systems is emphasized.

"The market for any good or service will operate more or less efficiently depending on the structural characteristics of the market, the adequacy of the definition of the property rights being exchanged, the availability of information, and the cost of bargaining and reaching agreements among interested parties. Water, despite frequent allegations that it is somehow wholly unlike all other goods, is no exception" *(Timothy D Tregarthen, 1977)*

Introduction

In South Africa a social objective was pursued in the development of government water schemes. The government took the initiative in the construction of engineering works to store and supply water. This was used as an insurance against drought and for food production; to create settlements, and establish owner-operators in agriculture; and to provide employment opportunities (Van der Post, 1937: 217-218). Capital expenditure was subsidized fully and operating expenditure partially (Department of Water Affairs, 1986: 1.32-1.33).

A number of schemes were constructed in the period from the depression and drought of the thirties to the second world war. From a technical point of view, the productive life of these schemes is over and questions of replacement or rehabilitation arise. Furthermore, settlements like the Vaalhartz, Riet River, Pongola and Loskop irrigation schemes are not isolated cases, but schemes are scattered across the country in different river basins with varying but significant areas under irrigation (Department of Water Affairs, 1971).

The irrigation schemes are part of a national water system which interacts with the agricultural and broader economic, social and political system. It is anticipated that policy decisions regarding the future development of existing schemes will be required. Economic analysis can guide the formulation of alternative strategies in this complex environment (Randall, 1981: 197).

The purpose with this paper is to indicate a realistic approach that can be followed for the rehabilitation of government irrigation schemes, but not to provide definitive answers.

A framework for the economics of water policy

Within the context of systems theory, "water policy may be regarded as a set of decision rules in a multistage decision process" (Ciriacy-Wantrup, 1985: 67). Decisions are taken over time and space and the first requirement is to identify the characteristics of the water resource system with which policy is concerned and for which decisions are necessary.

This system is a mixed groundwater-surface water system and it is the integration of the two that is important for water policy. In South Africa approximately 1.231 million hectare are under irrigation of which nearly 78 per cent is permanent irrigation (Department Agricultural Development, 1990: 18) probably using mostly surface water sources. For groundwater no accurate figures are available. Based on the adjusted estimates of the Department of Water Affairs (1986: 3.19) corresponding irrigation from groundwater sources comprises approximately 31.5 per cent of the area under irrigation. From this it can be concluded that groundwater is used mostly for supplemental irrigation. More important is that irrigation depends on

integrated groundwater and surface water resources and the Sanddrift government irrigation scheme in the Hexriver valley and the Olifantsnek irrigation board scheme near Rustenburg are cases in point.

Groundwater is developed largely by private enterprise. Surface water development is undertaken by both private and public agents. Of the total area under irrigation, 59 per cent are private schemes, 22 per cent irrigation board schemes and 19 per cent government water schemes (Department of Water Affairs, 1986: 2.4). On a hectare basis, private development is therefore most important.

Secondly, for the purpose of finding decision rules for the integrated water system in terms of water sources and public and private investment, a hierarchy of decisions on three levels can be distinguished (Ciriacy-Wantrup, 1985: 68-71). This involves operational, institutional and policy decisions. On each level, decision rules must be sought in order to make the best decision on that level.

On the lowest operational level decision-making refers to planning and control of physical and financial inputs and outputs which change over time and are uncertain. As already mentioned, the decisions are taken by individuals in the private and public sectors. These are households, private firms and public utilities in different regions and all sectors of the economy. The generally accepted rule is to maximize or at least improve a specified objective function which may be individual utility or profit.

On the middle institutional level, decision-making influences the decision process on the operational level. Institutions include water law which influences water development, water allocation and water quality. It is important to note that the purpose of decisions on the institutional level is not to directly control decisions on the operational level. "Rather, the purpose is to maintain and increase welfare by continuously influencing decision-making on the lower level under continuously changing conditions..." (Ciriacy-Wantrup, 1985: 70).

Institutional influences are different from e.g. resource availability or technological conditions. For individual private decisions institutions are external constraints, but in the social environment, institutions are considered to be independent or dependent variables. Institutional systems may be modified by government and therefore the "performance of such decision-making system can be appraised only by viewing the system as it functions over time under various economic conditions" (Ciriacy-Wantrup, 1985: 70).

On the policy level, decisions of the institutional level are of concern. The constitution of a country sets the framework for policy level decisions. Consequently water policy is determined by decisions in the political process, which are also subject to continuous adjustment over time. Finally, the objectives of water policy cannot be studied in isolation or separately from agricultural and economic policy objectives.

Decision processes clearly differ from level to level but are interrelated and interact with each other. This means that the effect of a decision on one level can be traced to all levels. When observing the effects on the water resource system, decision-making on each level can be improved by a learning process. This "is the essence of the multi-stage decision process" (Ciriacy-Wantrup, 1985: 69). In studying the decision-making process, emphasis must be placed on its structure, functioning and performance.

Rehabilitation versus new development of water resources

The development of water resources occurs in phases over time. These phases can be classified into an expansionary phase and a mature phase, which are two segments of a continuum (Randall, 1981: 195-196). During the expansionary phase, social costs are low and new projects are developed. Expensive repairs and delayed impacts such as rising water tables and salinisation are not yet apparent. The false impression exists that water is cheap. If society chooses, water use can be subsidised at moderate cost to satisfy increasing demands. Project evaluation based on benefit-cost analysis is of major concern to justify economically efficient development.

During the mature phase, the incremental cost of water supply is rising sharply. More direct and intensive competition is experienced between different users and the interdependence among water users increases drastically. Benefit-cost analysis remains important and actually becomes more challenging because of the complexities of the water system. However, the emphasis shifts to questions such as the allocation of water between competing uses, the high social costs of development, the role of pricing and rehabilitation as an alternative to new developments. (Consult Table 1 for more detail).

Twenty five years ago, at the time of the last National Irrigation Symposium, developments were still in the expansionary phase and water was not very scarce. There was sufficient water to satisfy the demands for irrigation, mining, industrial and domestic uses in for example the Vaal river catchment area (Siertsema, 1968: 13-14). Some years later, analyses showed strong growth rates in the non-agricultural consumption of water on the Witwatersrand. Because irrigation schemes already were residual recipients of water, increased shortages of water for irrigation purposes were projected (Dõckel, 1973: 17-22). Based on the information contained in the Report on the Management of Water Resources of South Africa (Department of Water Affairs, 1986) there is overwhelming evidence to support the conclusion that the mature phase has been reached. Although expensive new development opportunities are present,

Table 1 Characteristies of expansionary and mature phases of water resource development

Item	Expansionary phase	Mature phase
1. Long-run supply of impounded water	Elastic	Inelastic
2. Demand for delivered water	Low, but growing; eleastic at low prices, inelastic at high prices	High and growing; eleastic at low prices, inelastic at high prices
3. Physical condition of impoundment and delivery systems	Most is fairly new and in good condition	A substantial proportion is aging and in need of expensive repair and renovation
4. Competition for water among agricultural, industrial and urban uses, and instream flow maintenance	Minimal	Intense
5. Externality, etc., problems	Minimal	Pressing: rising water tables, land salinisation, saline return flows, groundwater salinistion, water pollution, etc.
6. Social cost of subsidising increased water use	Fairly low	High, and rising

proposals to rehabilitate and ameliorate adverse effects of existing schemes become pressing during this phase (Randall, 1981). Apart from water, capital for investment in water resource development is also scarce. For economic growth, optimal resource allocation between competing uses for new development versus rehabilitation is required.

Rehabilitation of existing schemes is more economical than the construction of new schemes. Firstly higher returns will be achieved on investment for replacement than on new investment. The reason is that fixed investments have already been incurred for existing water supply structures. Secondly, capital requirements for development of suitable damsites of new schemes are high because of design requirements and high unit costs (Van Nieuwkoop, 1989: 10-13; Department of Water Affairs, 1986: 3.13).

This implies that analysis of possible policy changes is warranted.

Policy level decisions

Although a strong case exists for investment in rehabilitation, it does not neccessarily imply that capital must again be allocated by public decision-makers. It is also debatable whether further subsidies are required since subsidies are transfer payments and not conducive to efficiency. The alternative is private investment decisions and/or capital recovery from beneficiaries. Therefore it is necessary to explain not only (a) previous direct involvement of government in the construction of irrigation schemes and subsidisation with public funds to achieve social objectives; but also (b) why there is government control of water resources through legislation.

The justification is largely based on the argument that water is a free collective good; a common property resource; occurring in a state of natural monopoly; with external economies and diseconomies. These characteristics may lead to market failure and inefficiencies because of non-exclusiveness and non-rivalry in consumption (Randall, 1981: 197-198). The reasoning then continues that this situation requires government intervention. Control measures are implemented in the form of regulations which include legislation regarding the ownership of resources; allocation of quotas; and which facilitate payment of subsidies. These provisions are included in the Water Act 54 of 1956 in South Africa (Department of Water Affairs, 1986).

The economics of public choice postulates that incentive structures and individual action within government based on self-interest, lead to government failure (Anderson, 1983: 5-6; Gwartney, Stroup & Studenmund, 1990: 743-751). Reasons can be given "why governmental action has failed to achieve efficient resource allocation" (Anderson, 1983): First, voter ignorance and imperfect information; Second, special-interest effects; Third, short-sightedness effects; Fourth, little entrepreneurial incentive for internal efficiency; and last, imprecise reflection of consumer preferences and the bundle purchase effect.

Examples can be given which may lead to government failure. These are, for instance, (a) applications by irrigation board schemes to write off loans obtained for investment in waterworks; and (b) discretion in the "adjustment of water tariffs by apportioning capital costs" (Department of Water Affairs, 1986: 6.34) for government irrigation schemes, which are set out in White Papers and are subject to approval by Parliament. Although written

submissions are made, published for comment and also publicly debated, it is uncertain whether the general public is aware of these uses of public funds.

Promotion of efficiency through policy level decisions can be achieved by reducing central control of the water system. An environment must be created which encourages private initiative, profit incentives and individual accountability. With reference to the rehabilitation of government irrigation schemes, there is a need that policy objectives which guide decisions must consciously and explicitly shift the emphasis from a purely social objective to both efficiency and equity considerations. Although it is controversial, the contention is that efficiency can be achieved through markets and equity through taxation (Samuelson & Nordhaus, 1985: 395).

Indications are that some movements are being made in this direction. The development of new government irrigation schemes has been curtailed; efforts are made being to transfer the management of government schemes to irrigation board schemes; and further development of private schemes is being supported (Department of Water Affairs, 1986: 6.31 and 7.7). However, care must be taken that these changes are a matter of principle and not only brought about by temporary shortages of public funds.

It can be expected that established interest groups in agriculture will continue to press for subsidies. Further subsidies, however, are counterproductive and ways must be found to recover capital.

There is general agreement that these funds will have to come from beneficiaries themselves (Van Nieuwkoop, 1989). It is not unreasonable that irrigators pay for the service provided to them. A necessary pre-condition for this to succeed is an improvement in the quality of services. If water supplies are unevenly distributed or unreliable, irrigators will obviously not be prepared to pay. Rehabilitation therefore also implies modernisation of existing schemes. The aim should be to improve the overall technical and organizational infrastructure and management capabilities. A partial approach which concentrates on repairs of technical deficiencies only is not acceptable.

In order to achieve efficiency with rehabilitation, attention in the process of formulating policy strategies must focus on the role of markets and prices with respect to the following (Randall, 1981: 197):

(a) ability to generate revenues;
(b) managing growth in the quantity of water demanded;
(c) directing the reallocation of water between competing users.

Consequently it is necessary to study theoretical considerations in the provision of water to irrigation schemes for use in farming.

Efficiency through market pricing

For the purpose of this paper, a thorough discussion of the theory of costs and competitive supply and the theory of production and marginal products is not opportune (see Samuelson & Nordhaus, 1985, Chapters 21, 22 and 26). However, static equilibrium theory assists in the clarification of the underlying relationships for the determination of factor market prices by supply and demand. With the simplifying assumptions of perfect competition, certainty and profit seeking, the following conclusions can be drawn:

(i) For a specific size of an irrigation scheme along the long-run average cost curve, the short-run marginal cost (MC) curve is the supply function of water. This MC curve is specified by the total costs (fixed and variable costs) of supplying varying quantities of water to a scheme. The breakeven price for water where the total costs can be recovered is at the intersection of the MC and average total costs (ATC) curves (see Figure 1) (Samuelson & Nordhaus, 1985:479).

(ii) The farm firms' demand for water inputs or water as a factor of production is derived from the consumer demand for final products. For a given factor price, cost minimizing firms allocate variable inputs according to their marginal value product (MVP) function, which is the derived demand function for water. Market demand will be obtained by aggregating the individual demand for each farming enterprise (see Figure 2) (Samuelson & Nordhaus, 1985: 601-02).

In principle it is therefore possible to supply water and recover costs from beneficiaries according to the quantifiable short-run MC function. Similarly water inputs can be purchased according to the quantifiable MVP function (Watson & Rose, 1980: 15).

For rehabilitation of existing irrigation schemes, these supply and demand relationships in the market for water, give clear direction to actions which must be taken to enable efficient utilization of water. The requirements (or Pareto-optimal conditions) which must be met include the absence of artificial restrictions; homogeneity of water resources; perfect information; and mobility of resources (Watson & Rose, 1980: 16-18 quoting Graaff, 1957). Attention must also be given to considerations of the theory of second-best (Randall, 1981: 198). Further complications arise because of the "intertemporal nature of water storage and delivery; the stochastic nature of precipitation, water inflow and water demands" (Randall, 1981: 200); and cyclical properties which make water a renewable resource (Watson & Rose, 1980: 18-19). Although the practical application of theoretical principles is not a simple task, the problems

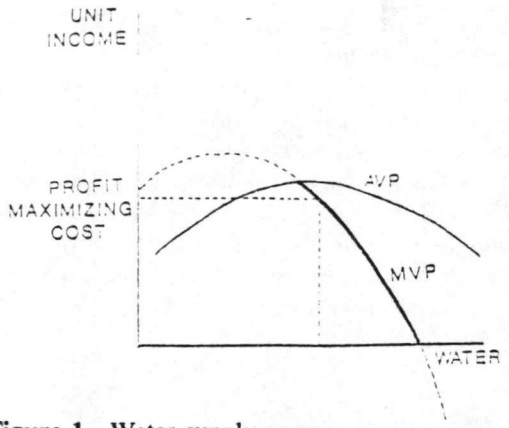


Figure 1 Water supply curve.

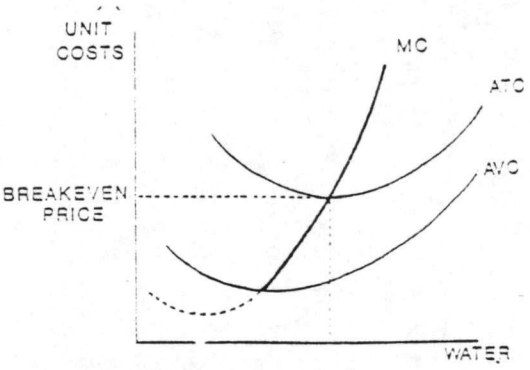


Figure 2 Water demand curve.

are not insurmountable. Attention must shift from defensive objections based on the "water-is-different" philosophy (Watson & Rose, 1980: 19-20) to the institutions which control water.

Institutional level decisions

A major leap away from an administratively controlled and a politicised market for water, to a completely free market is not realistic. However a move away from institutional control towards institutional influencing is not only desireable but essential.

"Institutions are sets of ordered relationships among people which define their rights, exposure to the rights of others, privileges and responsibilities" (Schmid, 1972: 893; see also the previous paragraph on a framework for the economics of water policy). Based on this definition, examples of institutions in the water system of South Africa are the Water Act 54 of 1956 which largely regulates government irrigation schemes; and the statutes of irrigation board schemes which also reside under the Water Act. According to the Water Act, the government has sweeping powers of control over public and private water (Vos, 1978: 85). It follows logically that changes to the Water Act are necessary. The economics of property rights indicate what changes are appropriate.

According to Anderson (1983: 4) individuals make decisions and not groups or societies, but decision-making occurs in an institutional framework. The property rights paradigm facilitates an understanding of how individuals interact in the market process. Essentially decisions will be affected by the benefits and costs resulting from decisions. These in turn depend on the definition, enforcement and transferability of property rights. These elements are therefore critical for a well functioning market, since:

(a) Defining property rights enables individuals to know what is being traded and what actions they can take regarding resources. For the allocation of water through markets, the unit of measurement and superiority of rights must be unambiguously specified. If rights are not defined, there would be little or no incentive to economize or to make full productive use of water (Tregarthen, 1977: 139).

(b) Enforcement of property rights determines the likelihood that an owner of rights can earn the benefits which are attached to it. In cases where there is a low probability to gain benefit from a specific use, there is a smaller chance that water will be diverted to that use.

(c) Transferability of property rights allows owners to fully realize the opportunity costs in alternative higher valued uses. Therefore "restrictions on transferability are restrictions on efficiency" (Anderson, 1983).

Definition, enforcement and transferability of water rights will allow individuals to evaluate the costs and benefits of irrigation (Tregarthen, 1977: 139-140). In practice the use of productive irrigation techniques and methods to save water; adaptation to intensive or supplemental irrigation according to the availability and reliability of water supply on a particular scheme; and water allocation to the best alternative use within or outside of agriculture, will all be achieved simultaneously. The important point is that these decisions will be taken by affected producers themselves and not enforced in accordance with clauses and regulations based on still-to-be-constructed complicated models as envisaged by the Department of Water Affairs (1986: 6.33).

Because property rights guide decisions in the market process, this will contribute towards the establishment of a market for water rights, a movement towards an equilibrium price between the marginal cost of water supply, productive value of utilized water and the opportunity cost of water to achieve efficiency. By implication, if these requirements are fulfilled, market failure will be avoided.

The last two of the above elements of security (the assured rights to water in the future as a precondition for capital investment in irrigation development) and flexibility (the ability to legally transfer water rights and thereby reallocate water between competing demands) are criteria to evaluate institutional

performance (Ciriacy-Wantrup, 1985: 62 and 94-98). Water misallocations are therefore "largely a function of inefficient institutions or the absence of needed institutions" (Timmons, 1983: 193). Consequently there is a need to "search for institutions capable of expanding the supply whenever it is technologically and economically feasible ... since the conventional laws, regulations and agencies are not solving the water crisis and are often making it worse" (Anderson, 1983: 3).

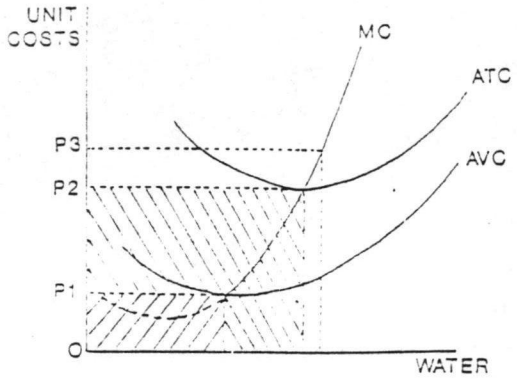
Institutional reform or changes to the Water Act that are required to make efficient rehabilitation possible, are therefore those that regulate water rights: "The Act makes provision only for the right of use of public water and not for the right of ownership" (Department of Water Affairs, 1986: 8.10); "water rights attach to riparian land and the transfer of the land transfers the rights, unless otherwise agreed" (Vos, 1978: 46). The relations between water economics, policy and law in South Africa are subject to more in-depth research (Backeberg, 1988b). However, a cautious statement can be made that the following aspects of water law which are regulated by the Water Act must be scrutinised. The nature of public water; rights to public water with specific reference to rights and use of normal flow and surplus water; relationships between water users; existing rights and transfer of rights, again with specific reference to acquisition of rights and alienation of rights (Vos, 1978: 12, 27, 29, 31, 33 40, 46 and 49). Various issues regarding secure expectations of right holders and obligations of water authorities must be resolved to achieve efficiency in markets (Randall, 1981: 201-202). It is also evident that further discussions and exchange of ideas are necessary because these proposals are in conflict with suggested refinements of water law. These are (a) intensification of control over the abstraction of public water as pressure on the available water resources increases and (b) promotion of optimal use of public water by ultimately suspending water rights not exercised beneficially and issuing directives aimed at achieving the most productive use of water, as advocated by the Department of Water Affairs (1986: 8.15).

Nevertheless, with the present restrictions, it is obvious that no real market transactions of water rights can take place and this is detrimental to efficiency. In the process of gradually changing the institutions to influence rather than control operational decisions, possibilities do exist to promote efficiency and at the same time attain equitable rehabilitation of irrigation schemes.

Equity through user and benefit taxation

There is no immediate pressure to apply the concepts of efficiency pricing to water in all streams, rivers, irrigation board and government water schemes. As a starting point, attention can however be directed towards the decisions to rehabilitate government irrigation schemes.

Based on MC pricing and assuming operation at full (minimum cost) capacity, price P1 in Figure 3 must be levied to recover variable (operation and maintenance) costs. This will ensure short-run provision of services. Price P2 must be levied to recover total costs. This will in turn allow breaking even or balancing the budget over the long-run. If this price level cannot be maintained, a loss will be made or subsidies will be necessary.



Key: /// Water tariff to cover variable cost
\\\ Water right charges and general taxes to cover fixed costs

Figure 3 Water pricing for cost recovery.

A water tariff or user tax such as price P3 will imply profits (for a private developer) or a budget surplus (for a public agency).

In the case of existing government irrigation schemes, the following equity considerations need attention (Gittinger, 1982: 215-217 and 222-225). It is desirable to determine how costs must be allocated amongst various groups who benefit. Irrespective of private or public investment, the primary issue is whether an irrigation scheme will generate sufficient income to reimburse the developer for resources allocated to rehabilitation. Development projects such as an irrigation scheme give rise to increased use of intermediate inputs as well as increased production of agricultural products and raw materials for further processing and final consumption or export. In this process are associated increased revenue from direct and indirect taxes. Therefore the goal is not solely that beneficiaries must pay capital and operating costs. The fiscal effects must be traced to make a conscious decision about water prices and cost recovery.

Some recovery of cost will definitely come from existing general taxes in the economic system. Any measure to recover costs and benefits in addition to water pricing and existing taxes should be selective and affect only the beneficiaries on an irrigation

scheme. These measures are called benefit taxes and are usually assessed against land, varying according to income potential, development costs, etc. (cf. Goedhart, 1975: 126; Randall, 1981: 214). However, it is important to maintain a delicate balance between incentives for producers to participate in a development project and recovery of costs to provide an efficient and reliable service.

Established producers on irrigation schemes have in some real sense paid for subsidies on previous capital investments (Randall, 1981: 213) which are in any case sunk costs. It is also important to remember that the majority of irrigation schemes were initially justified for social and political reasons (Van der Post, 1937: 257-258). Although past performance must be judged against this background, arguments have been presented which support a new approach. Decisions to rehabilitate must therefore focus attention on recovery of incremental capital costs and current operating and maintenance costs.

Rehabilitation in practice

The concepts of efficiency and equity are not only of theoretical interest but have tremendous practical relevance.

The present low, subsidized tariffs give a price signal that water is a near free commodity. Producers who strive for maximum physical production and not maximum economic production per mm water, therefore act perfectly rationally in order to maximize profits (Backeberg, 1986b). Water costs are a small percentage (more or less 5 per cent) of total farming costs, and tariff increases on their own will not lead to negative cash flow or insolvency. Income from water tariffs (user taxes) must cover only variable (operating and maintenance) costs. Tariff increases to this level is the first step for efficient water use and operation of an irrigation scheme, and this is already accepted policy (Department of Water Affairs, 1986: 6.32). In this process the interaction between supply and demand and response of irrigators can be tested and monitored.

The opportunity cost principle to determine water tariffs can be applied by estimating the productive value of water in alternative uses. In this form of institutional allocation water is priced through a synthetic market of shadow prices (Timmons, 1983: 195-196). The precondition for this approach to succeed is that the present strict controls regarding water rights must be relaxed.

The second step is to recover incremental fixed (capital and interest) costs through the valuation and allocation of additional water rights but which are lawfully attached to the land. This practice is also accepted policy (Department of Water Affairs, 1986: 1.34) and is based on the valid argument that irrigation development can lead to increases in land prices. However the misconception must be disposed of that increases in land prices are due to the capital investment in irrigation works (see Van der Post, 1937: 272-273 for an illuminating explanation). Water right charges (benefit taxes) must in principle be based on the expected increases in net income, and income capitalization is one appropriate method to follow (Backeberg, 1986a; Saliba & Bush, 1987: 202-227). Incentives for farmers to undertake development are accommodated by, amongst others, basing the value of water rights on the incremental productive capacity of land. In a sense this approach is also market directed because calculations are based on projected prices, yields and costs, but certain limitations must be attended to (see discussion below).

As has been explained, a 100 per cent cost recovery is not necessary and care must be taken not to double charge. Research results have clearly shown that the economic impact of irrigation development can be quantified (Kirsten, 1989). From this must be deduced that the fiscal impact can also be quantified, although it is not disputed that difficulties regarding accurate and reliable data must be overcome. The issue is even more complicated because the analysis must be done with and without rehabilitation.

Nevertheless, even if not precise but only indicative computations are done (Gittinger, 1982: 223), taxes as a source of income can be quantified and deducted from the incremental capital expenditure for rehabilitation. In the case of private development, a part of the capital costs which will be recovered through future taxes can be discounted and paid out as a lump sum. For both public and private development, only the remaining balance must be recovered by allocating water rights.

The principles explained here are equally applicable to horizontal and vertical expansion of irrigation and have partially been put into practice in e.g. the Hex and Sundays river valleys respectively (cf. Directorate Agricultural Production Economics, 1985; 1986). Again it is necessary to emphasise that the prerequisite for allocating and charging for water rights is that rehabilitation is accompanied by modernisation which will allow producers to operate more efficiently.

Further improvements in the valuation of water rights have been recommended (Backeberg, 1988a): *Firstly*, to involve producers in the process of valuing water rights instead of only agricultural economists of the Department. The argument is that individual producers "can and do make decisions which they assume will make them better off .. (and) that these individuals are the best judges of what is best for each of them" (Tregarthen, 1977: 141). In this way information will be generated which will be of benefit to each individual but for which each individual must also bear the cost (Randall, 1981: 202). *Secondly*, to enable bargaining over the value of water rights between the Department of Water Affairs and irrigators; and (in addition) between the Department of

Water Affairs and private developers to prevent a monopoly in e.g. rehabilitation of irrigation schemes. From the point of view of economic efficiency, this is an adequate way to initiate a market in rights for water.

Although not nearly complying with the requirements for market exchanges of water rights, the proposals are apparently controversial and therefore still under discussion.

In summary, for the efficient and equitable recovery of incremental fixed and variable costs incurred for rehabilitation, it is important to understand the functioning of the economic system; to apply the principles of the market process; to involve irrigators and private developers; and to promote individual initiative.

These principles can be expanded and are also relevant for new resource development (Randall, 1981: 214-217) but will not be discussed here.

Operational level decisions

Markets are not perfect and public intervention may be required (Tregarthen, 1977: 151). Institutions must however influence and not control investment in rehabilitation of irrigation schemes and agricultural production. This must preferably be done through market directed water tariffs and water right charges rather than participation in economic activity. Investment decisions for reallocation and use of resources must be taken through private initiative. Attention must therefore be given to the role of the entrepreneur (Anderson, 1983: 6).

The entrepreneurial element in decision-making and individual action is an "alertness to possibly newly worthwhile goals and to possibly newly available resources" (Kirzner, 1973: 35). The function of the entrepreneur is therefore to discover unused opportunities, to locate new ideas and to put them into practice (Baumol, 1968: 64-71). Entrepreneurial activity necessarily takes place with incomplete knowledge and information and therefore involves uncertainties and the acceptance of risk. The incentive in striving towards a better use of resources is the possibility of increased profitability (Kirzner, 1973: 48) or the attainment of any other multi-criterion objective.

Water is a scarce resource and increasing competition for the use of water resources is already present. The concepts of entrepreneurship and competition are inseparable. With free choice in the market process, entrepreneurs will aim to utilise or create opportunities which will put them in a more attractive position. Every entrepreneur with better ideas and more willingness to create opportunities must be able to do so. Competition is potentially present, so long as there are no barriers to entering the market or access to resources (Kirzner, 1973: 11-12).

As has been explained, a system of property rights is a pre-requisite for well functioning markets. When competition is also present, entrepreneurs can fulfil their role and react to price signals which indicate where opportunities exist. The potential of realizing an economic rent or (in other words) a return on resources over and above opportunity costs, will lead to productive activity or rent creation. It comprises the introduction of cost saving or yield increasing technology or a reallocation of resources from lower to higher valued uses. In this way the entrepreneur is the driving force for economic growth (Buchanan, 1980: 3-7; Anderson, 1983).

Regulations in one form or another limit competition and suppress productive entrepreneurial activity. It can lead to another type of entrepreneurial decision which results in transfer activity or rent seeking. Regulations very often cause arbitrary or artificial scarcity and entrepreneurs will attempt to obtain "initial assignments of rights or replacement assignments as other initial holders (lose their) priveleged positions" (Buchanan, 1980: 7-9). Entrepreneurs will use time and make an effort to influence government decisions. Under these circumstances rents can be obtained through subsidies or by controlling competitors and in either case valuable resources are wasted (Anderson, 1983: 7).

Regulations of water use by means of the Water Act in South Africa make rent seeking possible. Examples are requests to increase water quotas; continued pressure to maintain low water tariffs and high capital subsidies; and delegations with submissions to decrease the valuation of water right charges.

For economic growth there is a need to promote rent creation and avoid rent seeking. This can be done by the accepted policy of deregulation and commercialization, which is therefore also applicable to the Water Act. Finally, it illustrates that policy level decisions in the water system influence institutional level decisions which can encourage productive activity through operational level decisions.

Conclusion

In the present mature phase of the water economy in South Africa, attention must be given to the rehabilitation of existing irrigation schemes. Capital requirements as well as operating and maintenance costs for this purpose, must be recovered from beneficiaries. Subsidies, which distort market forces, must be avoided. Within the present regulations which control the water system, water tariffs must be levied to recover current operating and maintenance costs. After compensating for income from general taxes, water right charges must be determined to recover the balance of fixed costs. Thereby a degree of effic t and equitable rehabilitation will be achieved.

However, a gradual change of the decision rules on the three levels of the decision hierarchy is advisable. The effects of these changes on the water system can

be observed within the framework of the multi-stage decision process. Knowledge gained in the learning process can be used to improve decision-making. Specific emphasis must be placed on a review of objectives on the policy level; a shift away from control to influencing on the institutional level; and a promotion of productive activity by entrepreneurs on the operational level.

Much can also be learnt from the writings of eminent economists and agricultural economists on the theory of the economics of public choice, property rights and the role of the entrepreneur. Proposals for reform and the practical application of theory in countries such as the U S A and Australia must be studied. Research presently being undertaken at the Directorate of Agricultural Economics together with the University of Pretoria (Backeberg, 1988b) must continue to design new policy systems, institutional systems and operational systems for the creation of a market for water rights in South Africa.

Note: The interpretation of facts and opinions expressed in this paper do not necessarily agree with or reflect those of the management of the Department of Agricultural Development.

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AN ECONOMIC EVALUATION OF A DEFICIT IRRIGATION SCHEDULING STRATEGY FOR WHEAT IN THE LOWER P.K. LE ROUX DAM AREA

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Abstract

The purpose of this article was to compare the profitability of a deficit irrigation scheduling strategy with four typical irrigation scheduling strategies for wheat in the lower P.K. le Roux Dam area. The procedure involved the description of the five irrigation scheduling strategies and the simulation of the wheat yields by means of the PUTU model on soils with a profile-available water capacity (PAWC) of 45, 100 and 160 mm. The relevant cost items were estimated for two 60-ha centre pivot systems with a gross application capacity of 12 mm per day and a static pumping height of 10 metres. An important factor when applying a deficit irrigation scheduling strategy is a high profile-available capacity of the soil. A net income increase of R295 per hectare was realised when the deficit scheduling strategy was used on soils with a PAWC of 160 mm instead of 45 mm. The net opportunity cost of less sophisticated irrigation scheduling strategies are relative high (83 c/mm per ha) in comparison to the price of water (16.5 c/mm).

Introduction

Irrigation water has a scarcity value for the irrigation farmers in the lower P.K. le Roux Dam area as a water quota of 11 000 m^3 per hectare per year is allocated at 1.65 c/m^3. In the long term an irrigation farmer must therefore decide with which crop rotation system he can best utilize the scarce capital, irrigation water and soil. In the short term he must decide how the water quota, given the available land area, should be allocated during a specific season.

The equal marginal income or opportunity cost principle provides a criterion how to allocate a limited quantity of irrigation water between alternative application possibilities during a particular period of the growth season (Boehlje & Eidman, 1984: 191). For the purpose of this article the opportunity cost of irrigation water is defined as the income obtained by using the most profitable irrigation scheduling strategy for wheat (Boehlje & Eidman, 1984: 192). The allocation of the water quota by means of the equal marginal return principle has an opportunity cost that is less than or equal to the return expected for the marginal unit of water.

A need exists to analyse the profitability of a deficit irrigation scheduling strategy in the lower P.K. le Roux Dam area because of the relative scarcity of irrigation water. At high pumping heights irrigation variable cost constitutes a large part (approximately 60 percent) of the total irrigation cost (ownership cost of the centre pivot and machinery equipment, production cost, irrigation and yield variable costs), and consequently the profitability of irrigation can be expected to be increased if deficit irrigation is applied.

The purpose of this article is to compare the profitability of a deficit irrigation scheduling strategy with four typical irrigation scheduling strategies for wheat in the area of study by applying the opportunity cost principle.

The following hypotheses are made:

1. An important factor for the successful application of a deficit irrigation scheduling strategy is a high profile-available water capacity (PAWC) of the soil.
2. If a deficit irrigation scheduling strategy for wheat is introduced on soils with a high PAWC, the profitability of irrigation can be increased.
3. If farmers used the opportunity cost of irrigation water as decision-making criterion, they could be encouraged to apply more sophisticated irrigation scheduling strategies.
4. Farmers do not use sophisticated irrigation scheduling strategies for wheat because the economic decision-making variables in irrigation are not understood well.

Literature study

Definition of deficit irrigation

Irrigation scheduling strategies that apply controlled under-irrigation with a view either to increase the profitability of irrigation farming or to save water, are generally known as deficit irrigation (Martin & Van Brocklin, 1985: 1). Profit maximization is accomplished by maximizing the economic yield of a farmer's total resource combination: long, medium and short term capital, soil, water, labour and management. This happens if, and only if, the yield on the most scarce, most limiting resources available to management is a maximum (Groenewald & Van Zyl, 1986: 43). According to many authors the principle of equal marginal return should be the guiding principle in all water allocation decisions. If it is accepted that water is the most limiting resource, profit is maximized if the marginal income from the application of the last usable unit of water is the same for all crops or usages (Groenewald & Van Zyl, 1986: 42).

Irrigation levels at which profits are maximized change as a result of many factors. According to Stockle & James (1989: 86) the most important factors are physical soils properties, pumping height, uniformity of application and the ratio of commodity prices to production cost. In order to apply a deficit

irrigation scheduling strategy, water use should therefore be brought into relation with crop yield. Water can be saved if the timeliness and the irrigation quantity can be managed very accurately. Such precise management can only be carried out effectively if information is available on yield reactions at various irrigation levels and the timeliness of water application (Vaux & Pruitt, 1983: 64). However, this type of information is difficult to obtain.

The advantage of water use efficiency ratios

Water use efficiency ratios can be expressed in both physical and financial terms (Barnard & Nix, 1981). Bennie (1989) discuss three water use efficiency ratios that are widely used. The water use efficiency ratio used by Bennie *et al.* (1988) is the ratio between crop yield (kg/ha) and net irrigation quantity (mm/ha). If the net irrigation water quantity is processed to a gross figure, the water use efficiency varies between 7 and 11 kg/mm per ha. According to Barnard & Nix (1981: 198) this physical criterion should also be expressed in financial terms, for example water cost per R100 of product income, because the cost of water application and prices of products can vary.

Water ruse efficiency ratios could imply that the lower the quantity of water applied in relation to the yield realized, the more efficient the irrigation scheduling strategy. The advantage of water use efficiency ratios is to be found therein that increased efficiency usually leads to higher profitability. A further advantage is that water use efficiency ratios can be calculated relatively easily.

Unfortunately water ruse efficiency ratios cannot be used to determine the optimum irrigation level. because the economic optimum varies with the degree of flexibility in time and output and depends on whether production is continuous or intermittent (Barnard & Nix, 1981: 198). Water use efficiency ratios therefore do not give reliable guidelines for determining optimum economic irrigation levels.

Crop-water production functions

The use of crop-water production functions is one of the methods whereby the optimum irrigation level can be determined. A production function provides information about yield responses at various irrigation levels.

A disadvantage of the use of crop-water production functions is that the functions are very region-specific and do not take the timeliness of water application into account. Therefore these functions are not suitable for an irrigation farmer who wants to increase irrigation efficiency (Bosch, Eidman & Oosthuizen, 1987: 233). In addition, experiments to determine these functions require a great deal of time and money (Stockle & James, 1989).

Crop growth simulation models

Schulze & George (1987) showed that a crop growth simulation model can be used successfully to help irrigation planners to determine to what extent the maximum irrigation water applications can be decreased before excessive stress has a detrimental effect on profitability. By using the ACRU model, Schulze & George (1987) determined that maximum profit for irrigated maize in Namibia is realized at a deficit irrigation scheduling strategy which applied 5 mm per day instead of the generally recognized norm of 12 mm per day.

In an attempt to move closer to the point of water use efficiency, De Jager *et al.* (1987) used the PUTU crop growth simulation model to schedule irrigation water in such a way the eighty percent of the crop water requirements of wheat were met. Crop water requirements associated with this strategy were used to plan scheduling. The variable that was monitored was the hydraulic crop factor (Fh). Fh is a sensitive indicator of moisture stress and is calculated on a daily basis by the model from weather, plant and soil parameters. When the value of Fh becomes less than one, the crop experiences stress. If the value of Fh is less than 0.5 the crop is in a severe state of stress (De Jager *et al.*, 1982). De Jager *et al.* (1987) estimated a crop-water production function for wheat in the Vaalharts area by using a simulation model. This function was used to determine thew rational phase of wheat production in order to theoretically plan irrigation scheduling strategies which would maximize either yield or water ruse efficiency. Maximum production and water use efficiency are realized at 620 and 460 mm, respectively. Total-farm profit is maximized if between 10 and 14 irrigations of 45 mm are applied.

Irrigation frequency

English & Nakamura (1985) investigated the question of a link between crop yield and the irrigation frequency when deficit irrigation is applied. The effect of frequency and irrigation quantity on crop yields has not been studied sufficiently. The studies that have bee done produced contradictory answers. Frequency, irrigation quantity and yield are three related variables. These three variables are largely affected by soil properties such as the water holding capacity, matrix potential and soil depth. The above statement is particularly important under low frequency irrigation. Soil properties, on the other hand, are less important when high frequency irrigation or full irrigation is applied. Under these conditions the soil water as well as the matrix potential remains high and consequently water moves through the soil easily. The availability of water is therefore determined by the infiltration rate rather than the amount of water in the soil at that stage.

The opportunity cost of water

English *et al.* (1985) showed that savings can be made on two types of costs if deficit irrigation is applied. The first is a saving in fixed cost, which can be made if the farmer saves on capital by deliberately installing a low capacity irrigation system. The second cost is variable cost. This cost is related to the quantity of water applied, as well as the yields realized. Another cost component that should be taken into account according to English (*et al.* (1985) is opportunity cost. English *et al.* (1985) showed that a deficit irrigation scheduling strategy decreased water applications by 35 percent. However, it was important that the 35 percent saving in irrigation water resulted in a 54 percent increase in planted land area.

Two general approaches for typifying costs exists. The first approach is to use accounting costs, which represent all costs for which records can be kept. The second approach is to determine the opportunity cost of the resource.

Boehlje & Eidman (1984: 192) defined opportunity cost as the return that can be achieved for the use of a resource in its most profitable alternative use. According to Groenewald & Van Zyl (186) a scarce resource is applied in the most profitable alternative if the yield of the scarce resource is a maximum. Stated differently, the return from a scarce resource is maximized when the input is allocated to its most profitable use and the value added by the last unit of the resource is the same in each of its alternative uses (Boehlje & Eidman, 1984: 191). Consequently, if the resource is applied in its most profitable alternative according to the equal marginal return principle, the opportunity cost of irrigation water will always be equal to or less than the marginal income of the water. If the resource is applied sub-optimally, the opportunity cost will be greater than the marginal income.

Barnard & Nix (1981: 225) defined the term net opportunity cost as the difference between what the farmer could possibly earn if he followed the best alternative and what he actually earns at that moment.

The price of water

According to Moncur & Pollock (1988) it is important to take the scarcity value of water into account when determining a water price. By ignoring the scarcity value of water the impression is created that water is cheap. This situation results in the excessive withdrawal and use of water.

In the long term the efficiency of water use can be increased by pricing water according to the equal marginal cost principle. According to Moncur & Pollock (1988) the price of water consists firstly of the marginal cost of withdrawing water and secondly of a scarcity value if the available water supply is depleted. This means that the water price at any point in time represents the marginal opportunity cost of storing water for future usages, as well as present application. According to Seagraves & Easter (182) the low value of an additional unit of water, erratic flow of river sand the government's commitment to keep food prices low, are reasons for ignoring the scarcity value of water.

Implications from literature review

Preference is given to crop growth simulation models rather than production function methods to estimate the water yield ratios under deficit irrigation conditions, because the former takes into account more factors that affect the water yield ratios.

The deficit irrigation scheduling strategy used by De Jager *et al.* (1987) to subject wheat systematically to stress conditions should be analysed economically as a separate scheduling strategy.

The profile-available water capacity of soils must be taken into account in an economic analysis of a deficit irrigation scheduling strategy.

Irrigation frequency and soil properties play an important role in respect of yield realization under deficit irrigation conditions. The irrigation frequency depends to a large extent on the quantity of water applied during each irrigation.

When calculating the opportunity cost of water it is firstly very important to specify the planning period. If opportunity cost is calculated for the short term it implies that the farmer is already committed to irrigation and therefore already has an irrigation system with a certain application capacity. The water price and all input prices, as well as the output price, are therefore given. No attempt will be made to determine a price for irrigation water according to the marginal cost principle as discussed by Seagraves & Easter (1982) and Moncur & Pollock (1988).

The opportunity cost approach is generally used by economists because this approach explicitly takes into account the scarcity of a resource. This cost also represents the only true cost of a scarce resource. The differences between the alternative scheduling strategies can be compared on a net opportunity cost basis.

Procedure

The comparison of the profitability of a deficit irrigation scheduling strategy to four typical irrigation scheduling strategies in the lower P.K. le Roux Dam area firstly comprises a description of the irrigation scheduling strategies and the simulation of the wheat yields by means of the PUTU model on soils with profile-available water capacities (PAWC) of 45, 100 and 160 mm. Secondly the relevant cost items are estimated for two 60-ha centre pivot systems with a gross application capacity of 12 mm per day and a static pumping height of 10 m. Thirdly the opportunity cost and net opportunity cost of the different irrigation scheduling strategies are calculated.

The full irrigation scheduling strategies

Four irrigation scheduling strategies for wheat in the lower P.K. le Roux Dam area were formulated by means of the Delphi technique for soils with a high (160 mm), average (100 mm) and low (45 mm) profile-available water capacity. All the irrigation scheduling strategies maintain maximum plant growth conditions, but differ in respect of the levels and types of information used. Strategy 1 is a highly sophisticated irrigation scheduling strategy which uses full soil, plant and meteorological information. Strategy 2 is reasonably sophisticated because scheduling decisions are based on full soil information, but the plant and meteorological information is of a more general nature. Strategy 3 is slightly sophisticated because the irrigation scheduling strategy uses relatively little soil, plant and meteorological information. Strategy 4 is an unsophisticated irrigation scheduling strategy that uses no soil, plant or meteorological information.

The deficit irrigation scheduling strategy

In contrast to strategies 1 to 4, controlled under-irrigation is applied with the deficit irrigation scheduling strategy. For this purpose the hydraulic crop factor (Fh) is monitored on a daily basis by means of the PUTU model. When the Fh reaches a value of 0.8 on a certain day, an irrigation of 30 mm is applied on the next day. For the purposes of the study it was found that 30 mm per irrigation ensures a suitable irrigation frequency. The PUTU programme is activated again until the Fh drops to 0.8. This process is repeated until the wheat reaches the ripening growth phase.

Simulation of yields and water quantities.

The PUTU crop growth simulation model was selected and calibrated to estimate yields and the corresponding water quantities for the five irrigation scheduling strategies on the three soils in the area of study.

The three soils selected were taken to field water capacity before planting time. Wheat yields, as well as the net irrigation water quantities were simulated for all five scheduling strategies on the the three soils. After the season the soil profile was returned to field water capacity. The simulations were executed with the meteorological data of the lower P.K. le Roux Dam for the years 1978 to 1988. The yield levels, as well as the sum totals of the soil-water shortages and irrigation water were documented. The net irrigation water quantities were adjusted by an application efficiency factor of 85 percent for centre pivots to obtain gross figures.

Irrigation system

The irrigation cost of the scheduling strategies was based on two irrigation systems. Both were 60-ha irrigation systems with a gross application capacity of 12 mm per day and the water was pumped at a static height of 10 m. The one system was used on soils with a PAWC of 100 mm and 160 mm (sandy soils) under a low pumping pressure of 53 m. The other system, with a higher pumping pressure of 70 m was used on the soil with a high clay content (PAWC of 45 mm).

Estimation of cost

An adjusted model of Bosch & Eidman (1987) was used as basis for the estimation of cost. The computerized irrigation cost programme as described by Meiring (1989) was used to estimate the ownership and irrigation variable cost. The ownership cost of the irrigation system on the clay and sandy soil amounted to R245 and R240 per hectare respectively. The irrigation variable cost on the clay soil amounted to 79 c/mm per ha for the first 66 mm and 59 c/mm per ha thereafter. However, the irrigation variable cost on the sandy soil was calculated as 63 c/mm per ha for the first 98 mm, whereafter it dropped to 50 c/mm per ha. The irrigation variable cost for each of the eleven years on the soils with PAWC of 45, 100 and 160 mm was estimated by means of the above cost figures.

It was assumed that the farmer did not lower his input levels when he applied deficit irrigation. The production cost for all five irrigation scheduling strategies was R954 per hectare, while the ownership cost of the machinery equipment amounted to R75 per hectare. The yield variable cost was calculated at the harvesting tariff of R30 per ton and a transport cost of 33 c/ton per km over a distance of 50 km.

By subtracting the ownership cost, production cost, irrigation variable and yield variable cost from the gross income of wheat, the pre-tax net income on soils with a PAWC of 45, 100 and 160 mm for the years 1978 to 1988 was obtained. The comparison of the profitability of the deficit irrigation scheduling strategy to the four scheduling strategies generally used in the lower P.K. le Roux Dam area was based on average pre-tax incomes.

Opportunity cost

The opportunity cost and net opportunity cost of water were not calculated for each year for which yields were simulated, but were based on the average results for each soil. Because all the irrigation scheduling strategies do not apply the same quantity of water, the profitability of the alternative irrigation scheduling strategies was expressed in terms of average income per millimetre of water per hectare.

The average income per millimetre of water was obtained by dividing the average pre-tax net income over eleven years by the average gross irrigation water quantity. The opportunity cost in Rand per millimetre of water per hectare was calculated, whereafter the net opportunity cost for each scheduling strategy on soils with a PAWC of 45, 100 and 160 mm was calculated.

The net opportunity cost was obtained by calculating the difference between the opportunity cost and the actual income that was realized.

Results and discussion

Importance of a high profile-available water capacity of soils

A summary of the average yields and gross irrigation applications of each irrigation scheduling strategy on soils with a PAWC of 45, 100 and 160 mm is given in Table 1. Together with this the average percentage decrease in yields and gross irrigation water quantity which the deficit irrigation scheduling strategy (5) showed in relation to the highly sophisticated irrigation scheduling strategy (1), are given.

Although scheduling strategy 5 applied approximately the same quantity of water on the soils with a PAWC of 45, 100 and 160 mm, it is significant that the average yield obtained from the soil with a PAWC of 45 mm was considerably lower than that from the soils with a PAWC of 100 and 160 mm.

Scheduling strategy 5 applied 29, 24 and 24 percent less water than strategy 1 on the soils with a PAWC of 45, 100 and 160 mm. The percentage saving in gross irrigation water applied to the various soils was therefore approximately 25 percent. In contrast to this, the percentage decreases in yield for the three soils were 14, 9 and 3 percent, respectively. With more or less the same percentage decrease in applied water, the soil with a PAWC of 45 mm showed the biggest percentage decrease in yield, followed by the soils with a PAWC of 100 and 160 mm, respectively. The difference in percentage decrease in yields occurred because wheat experiences plant water stress sooner on soils with a lower PAWC than on soils with a higher PAWC. Reasons for this could be that the soil with a lower PAWC stored less water in reserve and that the irrigation frequency on the soils with a lower PAWC may be too low.

Furthermore it is clear that the soil with a PAWC of 45 mm is much closer to the point of highest water use efficiency than soils with a PAWC of 100 and 160 mm, because the ratio of percentage decrease in yield to percentage decrease in gross irrigation water is much greater on the PAWC soil of 100 and 160 mm. The point of highest water use efficiency differs from soil to soil. With reference to the results in Table 1 it is clear that a saving in irrigation water, and consequently also the application of a deficit irrigation scheduling strategy, must take into account the profile-available water capacity of soils. This result agrees with results obtained by Stockel & James (1989: 85) who stated: "Large soil water holding capacity, high soil water contents at planting and deep root exploration were found important for successful implementation of deficit irrigation".

Water use efficiency

The average water use figures corresponding to the five irrigation scheduling strategies expressed in physical and financial terms for wheat on soils with a PAWC of 45, 100 and 160 mm are given in Table 2.

The deficit scheduling (strategy 5) is physically the most efficient irrigation scheduling strategy on all three of the soils. The highest physical water use efficiencies of 13, 13 and 16 kg/ha per mm respectively were realized with irrigation scheduling strategy 5 on the soils with a PAWC of 45, 100 and 160 mm. The physical strategy 5 to strategies 1,2,3 and 4. Both scheduling strategies 5 and 1 are highly sophisticated. In general the efficiency of the scheduling strategies decreased as the sophistication of irrigation scheduling strategies decreased.

The difference in water application cost between the sandy soils (PAWC of 100 and 160 mm) and the clay (PAWC) of 45 mm) can be seen if the financial water use efficiency of, for example, strategy 1 on the soils of PAWC 45 and 100 mm is studied. Although the physical efficiency of strategy 1 on both these soils was 11 kg/ha per mm, the higher irrigation variable cost for the clay caused the efficiency ratio to weaken from R14 per R100 of product income on the soil of

Table 1 A comparison of the average yields and gross applied irrigation water of the five scheduling strategies for wheat on soils with a profile-available water capacity of 45, 100 and 160 mm in the lower P.K. le Roux Dam area.

Strategy	Soil with a PAWC of 45 mm		Soil with a PAWC of 100 mm		Soil with a PAWC of 160 mm	
	Yield (kg/ha)	Amount of water (mm/ha)	Yield (kg/ha)	Amount of water (mm/ha)	Yield (kg/ha)	Amount of water (mm/ha)
Strategy 1	6692	615	6696	613	6700	523
Strategy 2	6703	741	6701	745	6705	737
Strategy 3	6702	735	6701	752	6706	751
Strategy 4	6704	922	6702	926	6706	927
Strategy 5	5731	435	6104	465	6523	400
% Decrease[1]	14	29	9	24	3	24

(1) The percentage decrease in yield and gross irrigation quantities which indicates the deficit scheduling strategy (strategy 5) in relation to the highly sophisticated scheduling strategy (strategy 1)

Table 2 The average water use efficiency of five irrigation scheduling strategies on soils with a profile-available water capacity of 45, 100 and 160 mm in the lower P.K. le Roux Dam area.

	WATER USE EFFICIENCY RATIOS					
STRATEGY	SOIL WITH A PAWC OF 45 mm		SOIL WITH A PAWC OF 100 mm		SOIL WITH A PAWC OF 160 mm	
	Physical[1] (kg/ha/mm)	Financial[2] (R/R100)	Physical (kg/ha/mm)	Financial (R/R100)	Physical (kg/ha/mm)	Financial (R/R100)
Strategy 1	11	17	11	14	13	12
Strategy 2	9	20	9	17	9	17
Strategy 3	9	20	9	17	9	17
Strategy 4	6	25	7	21	7	21
Strategy 5	13	14	13	12	16	10

(1) Average physical water use efficiency expressed as yields (kg) per gross irrigation water quantity (mm) per hectare
(2) Average financial water use efficiency expressed in irrigation variable cost (R) per hectare per R100 product income per hectare

PAWC 100 mm to R17 per R100 of product income on the soil of PAWC 45 mm.

Although increased efficiency ratios unfortunately do not offer reliable guidelines for determining optimum economic irrigation levels.

Profitability

The average net incomes, variation in incomes and coefficient of variation of five irrigation scheduling strategies on soils with a PAWC of 45, 100 and 160 mm in the lower P.K. le Roux Dam area are given in Table 3.

The deficit irrigation scheduling strategy (5) was the most profitable scheduling strategy on the soil with a PAWC of 160 mm. The average pre-tax net income of strategy 5 was R425 per hectare in comparison to the R415, R310, R304 and R214 per hectare for scheduling strategies 1 to 4 respectively.

Irrigation scheduling strategy 1 was most profitable on soils with a PAWC of 45 and 100 mm. Although irrigation scheduling strategy 5 had the highest efficiency of all five irrigation scheduling strategies throughout (Table 2), strategy 5 was not the most profitable on the soils with a PAWC of 45 and 100 mm. It is clear that the efficiency ratios are not a reliable criterion for determining profitability (Barnard & Nix, 1981: 199). However, the reliability will increase as the cost of water application increases. Another reason for the decrease in profitability on the soils with a PAWC of 45 and 100 mm was excessive stress because of a too low PAWC or too low irrigation frequency.

The variation in net incomes of scheduling strategy 5 is much bigger throughout than scheduling strategies 1, 2, 3 and 4, regardless of the PAWC of the soil. The coefficient of variation on the soil with a PAWC of 45 mm, for example, was 59 percent in comparison to the 8, 8, 5 and 3 percent for scheduling strategies 1, 2, 3 and 4 respectively. The coefficient of variation of scheduling strategy 5 decreased appreciably as the PAWC of the soil increased, because such soil stores more water in reserve which can be used in times of water shortages.

The risk attached to the application of a deficit irrigation scheduling strategy is therefore considerably higher on all the soils, notwithstanding the fact that this scheduling strategy was the most profitable scheduling strategy on the soil with a PAWC of

Table 3 The average pre-tax net income (R/ha), standard deviation (R/ha) and coefficient of variation of all five the alternative irrigation scheudling strategies on soils with a PAWC of 45, 100 and 160 mm.

STRATEGY	SOIL WITH A PAWC OF 45 mm			SOIL WITH A PAWC OF 100 mm			SOIL WITH A PAWC OF 160 mm		
	Average net income (R/ha)	STD[1] (R/ha)	KV[2] (%)	Average net income (R/ha)	STD[1] (R/ha)	KV[2] (%)	Average net income (R/ha)	STD[1] (R/ha)	KV[2] (%)
Strategy 1	306	24	8	370	20	6	415	22	5
Strategy 2	234	19	8	305	20	7	310	18	6
Strategy 3	238	12	5	302	12	4	304	12	4
Strategy 4	126	4	3	213	4	2	214	4	2
Strategy 5	130	77	59	270	72	27	425	43	10

(1) Standard deviation
(2) Coefficient of variation

160 mm. The choice between the deficit irrigation scheduling strategy and the full irrigation scheduling strategies is therefore made more difficult by the differences in risk between the scheduling strategies.

If the water and electricity costs rise, the deficit irrigation scheduling strategy becomes more profitable relative to the full irrigation scheduling strategies. In a situation of rising energy costs, research on the profitability of deficit irrigation scheduling strategies become increasingly important.

Importance of irrigation scheduling with limited water

In Table 4 a summary is given of the opportunity cost and net opportunity cost of water (R/mm per ha) for five irrigation scheduling strategies on soils with a PAWC of 45, 100 and 160 mm.

The most profitable irrigation scheduling strategies on the soils with a PAWC of 45, 100 and 160 mm realized R0.50; R0.60; and R1.06 per millimetre of water per hectare. The opportunity cost of applying the less profitable scheduling strategies on the costs of applying the less profitable scheduling strategies on the soils with a PAWC of 45, 100 and 160 mm are therefore respectively R0.50; R0.60; and R1.06 per millimetre of water per hectare.

The net opportunity costs of scheduling strategies 1 to 5 on the soil with a PAWC of 45 mm are therefore R0; R0.18; R0.17; R0.36; and R0.20 per millimetre water per hectare. With the application of irrigation scheduling strategy 5 on 45 mm PAWC soil, a potential income of R0.50 per millimetre of water per hectare is sacrificed, while R0.30 per millimetre of water per hectare is earned. The net opportunity cost is therefore R0.20 per millimetre water per hectare. The net opportunity cost increases as the sophistication of the scheduling strategies decreases (strategies 1 to 4). This implies that farmers sacrifice an increasingly larger potential income if they move further away from more sophisticated irrigation scheduling strategies. If farmers used the opportunity cost of irrigation water as decision-making criterion, they could be encouraged to apply the more sophisticated irrigation scheduling strategies.

A comparison between the net opportunity cost of scheduling strategy 2 and 5 on the soil with a PAWC of 160 mm is given in Table 5.

The difference in net income between scheduling strategies 2 and 5 on the soil with a 160 mm PAWC was R115 per hectare. The net opportunity cost of scheduling strategy 2 on the same soil where an average of 737 mm was applied, was R472 per hectare (737 mm/ha x R0.64 per mm/ha). The difference of R357 per hectare was the additional income earned if the 337 mm per hectare (737 mm/ha - 400 mm/ha) was regarded as applied and not merely as lost. The differences in average net incomes underestimates the actual costs of a specific scheduling strategy. A deficit irrigation scheduling strategy decreased water

Table 4 Opportunity cost and net opportunity cost of irrigation water (R/mm/ha) for five irrigation scheudling strategies on soils with a PAWC of 45, 100 and 160 mm.

	Average pre-tax net income (R/mm/ha)	Opportunity cost (R/mm/ha)	Net opportunity cost (R/mm/ha)
STRATEGY		SOIL WITH A PAWC OF 45 mm	
Strategy 1	0.50	0.50	0.00
Strategy 2	0.32	0.50	0.18
Strategy 3	0.32	0.50	0.18
Strategy 4	0.14	0.50	0.36
Strategy 5	0.30	0.50	0.20
STRATEGY		SOIL WITH A PAWC OF 100 mm	
Strategy 1	0.60	0.60	0.00
Strategy 2	0.41	0.60	0.19
Strategy 3	0.40	0.60	0.20
Strategy 4	0.23	0.60	0.37
Strategy 5	0.58	0.60	0.02
STRATEGY		SOIL WITH A PAWC OF 160 mm	
Strategy 1	0.79	1.06	0.27
Strategy 2	0.42	1.06	0.64
Strategy 3	0.40	1.06	0.66
Strategy 4	0.23	1.06	0.83
Strategy 5	1.06	1.06	0.00

Table 5 A comparison between the net opportunity cost of scheduling strategy 2 and 5 on the soil with a PAWC of 160 mm.

	STRATEGY 2	STRATEGY 5
Water (mm/ha)	737	400
Income (R/ha)	310	425
Income (R/mm/ha)	0.42	1.06
Opportunity cost (R/mm/ha)	1.06	1.06
Net opportunity cost (R/mm/ha)	0.64	0.00

applications by 45 percent. The 45 percent saving in irrigation water resulted in a 40 percent increase in net income. However, it is important to note that the 45 percent saving in irrigation water could increase planted land area by 85 percent.

Conclusions

An important factor that affects the successful application of a deficit irrigation scheduling strategy, is the PAWC of the soil. The average pre-tax net income decreases by approximately R295 per hectare if the PAWC of the soil decreases from 160 mm to 45 mm. The PAWC of the soil is therefore also a very important variable which affects the economics of irrigation.

A deficit irrigation scheduling strategy can increase the profitability of irrigation on soils with a high PAWC. The profitability of irrigation on the soil with a PAWC of 160 mm increases from approximately R415 per hectare to R425 per hectare if a deficit irrigation scheduling strategy is applied.

The profitability differences between the scheduling strategies do not reflect the true cost of the scheduling strategies. The net opportunity cost of less sophisticated irrigation scheduling strategies is relatively high compared to the price of water. For each millimetre of water per hectare applied by means of the unsophisticated scheduling strategy, a potential income of R0.83 per hectare is lost. However, this millimetre of water costs the farmer only 16.5 cents. If farmers use the opportunity cost of irrigation water as the decision-making criterion, therefore, they could be encouraged to use more sophisticated irrigation scheduling strategies. The relatively cheap water is a counterproductive force which hampers the application of more effective irrigation scheduling strategies. Other decision-making variables that farmers must understand better are the profit maximizing principle, deficit irrigation scheduling strategies and the PAWC of soils.

Research implications

The risk sensitivity of decision-makers must be taken into account explicitly when the economics of irrigation is analysed.

More research will have to be done on the effect of PAWC of soils and other conditions that have to apply if a deficit irrigation scheduling strategy is to be used successfully. The PAWC of soils should be taken into account where water savings in certain growth stages of the plant are planned. Secondly, a so-called search method can be used where the most efficient yield point for a fixed quantity of water can be determined with the aid of repeated simulations. These yield reference points can be used to calculate the percentage decrease in yield as a result of a percentage decrease in water application.

The profitability of a deficit irrigation scheduling strategy should be analysed on a whole-farm level.

More research should be done to evaluate the economic implications of deficit irrigation scheduling strategies under various climatic, soil and management conditions. At the same time the effect of frequency and quantity of irrigation on yield should be analysed. These analyses become important as irrigation variable cost rise.

The opportunity cost of water should be determined over the long term where the price of water is not accepted as fixed.

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AN ECONOMIC PROFITABILITY ANALYSIS OF ALTERNATIVE IRRIGATION SCHEDULING STRATEGIES FOR WHEAT

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Abstract

The main purpose of the article is to propose and apply a procedure for analysing the profitability of alternative irrigation scheduling strategies in the area below the P.K. le Roux Dam. Four irrigation scheduling strategies for wheat were formulated by means of the Delphi technique for soils with a high (160 mm), average (100 mm) and low (45 mm) profile available water capacity (PAWC). The PUTU9-87 crop growth simulation model was used with weather data to simulate wheat yields and the corresponding total net irrigation applications for 11 years. The annual fixed and variable irrigation costs of a 60-hectare centre pivot with a gross application capacity of 12 mm per day was estimated by means of a computer programme. A satisfactory procedure for analysing the profitability of alternative irrigation strategies was developed and illustrated. On all three soils the most sophisticated irrigation scheduling strategy was the most profitable. An increased return of at least R157 per hectare resulted from the application of a highly sophisticated scheduling strategy instead of a naive irrigation scheduling strategy when the pumping height was 10 m. The difference in net incomes between the highly sophisticated and naive irrigation scheduling strategies increased to approximately R300 per hectare at a pumping height of 100m. The seasonal plan or strategy according to which a farmer schedules irrigation water is therefore one of the major variables that influence the economics of irrigation.

Introduction

Four different irrigation scheduling strategies for wheat in the area below the P.K. le Roux Dam were formulated with a view to assessing the benefits of more scientific irrigation scheduling methods. The application of the various irrigation scheduling strategies would have cost implications since they differ in respect of the degree of sophistication of the required input information. A profitability analysis is an important first step in the economic analysis procedure of alternative irrigation scheduling strategies.

The main purpose of the article is to propose and apply a procedure for analysing the profitability of alternative irrigation scheduling strategies in the area below the P.K. le Roux Dam. The hypotheses to be tested are the following:

1. The four typical irrigation scheduling strategies used in the area below the P.K. le Roux Dam differ mainly in respect of the quantity of water applied, while the yield levels are approximately the same.
2. If the irrigation scheduling strategies are such that applied water fully satisfies the crop water requirements, the profile available water capacities are not utilised economically.
3. If more sophisticated irrigation scheduling strategies for wheat are applied, the profitability of wheat under centre pivot irrigation would increase because less water would be applied.
4. If the pumping height and/or the price of water increase(s), the economic importance of more sophisticated irrigation scheduling strategies would increase.
5. The seasonal plan or strategy whereby a farmer schedules irrigation water is one of the main variables that influences the economics of irrigation.

Literature Study

Methods for the evaluation of economic efficiency

According to Bosch, Eidman & Oosthuizen (1987: 232), three methods can be used to study the efficiency of irrigation water use. The first method involves the use of basic crop-water production functions. In the second method computerised crop growth models are used. Finally, reference is made to models which in the efficiency analysis not only explicitly take into account environmental risks, but also the risk sensitivity of irrigation farmers.

Hexem & Heady (1978) used crop-water production functions to determine the irrigation levels at which profits are maximised. However, production functions are very area-specific. In addition, the timing of water applications can be as important as the quantity of water applied, because it is the daily availability of soil water to the plant rather than the total quantity of water applied, that determines crop yield (Bosch, Eidman & Oosthuizen, 1985: 5). These factors determine the usefulness of basic production models as decision-making instruments at farm level.

Computerised crop growth models, on the other hand, have the potential of simulating crop responses over a wide range of irrigation scheduling strategies for the variety of weather conditions which occur over a period of many years. By using crop models, alternative irrigation scheduling strategies can therefore be analysed economically. The only crop growth simulation models adapted for single crops in South African conditions, are the models of De Jager *et al.* (1987) and Schulze (1984).

If computerised crop-growth models are to simulate crop response over a wide range of irrigation scheduling strategies for a variety of weather conditions, crop simulations for each irrigation scheduling strategy have to be repeated with the weather data of a number of years. For the profitability and risk efficiency analyses of alternative irrigation scheduling strategies, use must be made of a probability distribution of yields rather than of single yields.

The choice of the most profitable probability distribution is made difficult by the different risks attached to the various irrigation scheduling strategies. According to Bosch *et al.* (1987), a method of determining the risk sensitivity of irrigation farmers is required, whereafter evaluation of the alternative irrigation scheduling strategies is possible. A suitable risk-efficient decision-making criterion should therefore be used. The third method discussed by Bosch *et al.* (1987) complies with this requirement. Stochastic dominance with respect to a function is a method which, given differences in risk sensitivity, could be used to economically evaluate alternative irrigation scheduling strategies.

Implications from the literature study

The literature study indicates that an economic analysis of alternative irrigation scheduling strategies could best be carried out by means of a computerised crop growth simulation model. Although many such models exist, a crop growth simulation model which has been adapted for the climate, cultivars and planting dates in the specific area should be selected. The PUTU and ACRU models have been used as the crop growth models in various local studies. However, the PUTU model is the only crop growth simulation model specifically adapted to simulate wheat yields under irrigation conditions in the lower P.K. le Roux Dam area.

According to Nielson (1982) price risk need not be taken into account in the profitability analysis of alternative irrigation scheduling strategies, because it is assumed that any one of the outcomes in the probability distribution has an equal chance of occurring in a specific year.

The break-even budgeting technique and sensitivity index can be used to determine the importance of assumptions about certain parameter variables.

Procedure

The procedure whereby scheduling strategies for wheat under centre pivot irrigation are analysed economically, requires, on the one hand, the estimation of relevant cost items and, on the other, the simulation of wheat yields, repeated for alternative years with different weather conditions and also for various irrigation scheduling strategies on soils with different profile available water capacities (PAWC), by means of the PUTU9-87 model. Soils with a low PAWC of 45 mm, average PAWC of 100 mm and a high PAWC of 160 mm were selected in the study area, in conjunction with a soil scientist.

Cost estimation

An adjusted model of Bosch & Eidman (1987) was used as the basis for cost estimation. Bosch & Eidman (1987) divided all costs into overheads, production cost, irrigation variable cost and yield variable cost. A computerised procedure developed by Meiring (1989), was used to estimate both the irrigation variable cost and the ownership cost of the centre pivot irrigation system. In estimating the pre-tax net income, constant prices were used. The prices of all the income and cost components were determined as on 23 March 1989.

Irrigation system: For this study two of the eighteen representative centre pivot systems listed by Meiring (1989) for the lower P.K. le Roux Dam area were selected to estimate the irrigation cost. The selected centre pivots both had 60 ha under irrigation, a gross application capacity of 12 mm per day, and the water was pumped to a static height of 10 m.

The first irrigation system was selected to irrigate the soils with a PAWC of 100 and 160 mm. These two soils contained 8 and 10 percent clay respectively. The system on these soils operated at a pumping pressure of 53 m giving a wetted band width of 19 m. Two 30 kW motors were used. The total purchase price of the system was R240 378.

The second irrigation system was adjusted for the soil with a PAWC of 45 mm. This soil had a much higher clay percentage, namely 29 percent. Consequently, the irrigation system was adjusted to operate at a pressure of 78 m and gave a wetted band width of 41 m. Two 45 kW motors were used. The total purchase price of this irrigation system was R246 119.

Irrigation cost: The annual fixed cost of the two centre pivot irrigation systems on the sandy soil (PAWC of 100 and 160 mm) and the clay soil (PAWC of 45 mm) at a static height of 10 m amounted to R21 556 and R22 086 per year respectively. The ownership cost of the irrigation system per hectare was obtained by assuming a 150 percent irrigation area utilisation.

When determining the irrigation variable cost, the cost of water and electricity must be specified. The cost of water was 1.65c/m^3 and the cost of electricity was 15.59c for the first 1 000 kWh per month and 9.02c/kWh thereafter. The irrigation variable cost on the soils with a PAWC of 100 and 160 mm was calculated by applying the first 88 mm at 63c/mm.ha and then the rest of the full amount of water at 50c/mm.ha. On the clay soil (PAWC of 45 mm) the irrigation variable cost was calculated as 79c/mm.ha for the first 66 m and then the cost was reduced to

59c/mm.ha.

Production cost: An enterprise budget was drawn up for wheat under centre pivot irrigation in the study area. The group discussion technique was used to collect relevant information and the cost was calculated with the Apland (1986) budget generator. The ownership cost of the implements was R75 per hectare. The variable production cost of wheat amounted to R954 per hectare.

Yield variable cost: The yield variable cost included harvesting and transport costs and was determined by the yields that were realised. The nearest grain silo was approximately 50 km away. The transport cost was calculated at 33c/ton.km. Harvesting cost was R30 per ton. The yield variable costs for the different irrigation scheduling strategies were more or less the same (R312) because yields did not differ much.

Irrigation scheduling strategies

Four irrigation scheduling strategies for wheat in the lower P.K. le Roux Dam area were formulated by means of the Delphi technique for soils with a high (160 mm), average (100 mm) and low (45 mm) PAWC. The Delphi technique is an appropriate approach to the complex problem of formulating irrigation scheduling alternatives for purposes of economic analyses, since the technical aspects of irrigation can be fully taken into account. All these irrigation scheduling strategies maintained conditions of maximum plant growth, but differed in respect of the levels and types of input information used. Strategy 1 was a highly sophisticated irrigation scheduling strategy which used a comprehensive set of soil, plant and meteorological information. Strategy 2 was reasonably sophisticated because scheduling decisions were based on the same soil information, although the plant and meteorological information used was of a more general nature. Strategy 3 was slightly sophisticated because the irrigation scheduling strategy used relatively little soil, plant and meteorological information. Strategy 4 was an unsophisticated irrigation scheduling strategy that used no soil, plant or meteorological information.

Sensitivity analysis

The effect of pumping height and the price of water on the profitability of irrigation water was investigated by means of sensitivity analyses. The price of water was increased from 1.645c/m^3 by 10, 20 and 30 percent to 1.815; 1.98 and 2.145c/m^3, respectively. The pumping height was increased by 30 m intervals from 10 m to 40, 70 and 100 m.

The sensitivity analysis was carried out on the soil with a PAWC of 100 mm only. For this purpose the irrigation system had to be adjusted to continue applying 12 mm per day at the higher static heights. This was done by adjusting pumping pressures to 83, 113 and 143 m heads, respectively.

When the irrigation and yield variable costs for each pumping height were calculated it was assumed that the yield realised remained unchanged because the irrigation system capacities remained unchanged and the same irrigation water quantities were therefore applied at the different pumping heights. The production cost and yield variable cost remained unchanged at R954 and approximately R312 per hectare, regardless of an increase in pumping height.

The average pre-tax net income of the four irrigation scheduling strategies was determined at the different pumping heights and water prices. The average pre-tax net income figures were used in a sensitivity index to determine the direction and extent of change in the pre-tax net income as a result of a change in pumping height and water price. A break-even pumping height was then determined for each irrigation scheduling strategy.

Sensitivity index: The sensitivity index as formulated by Gill (1984) was used. The parameter values used for the sensitivity index were pumping height and price of water. Pumping heights of 10, 40, 70 and 100 m were used, and the water price was taken as 1.645; 1.815; 1.98 and 2.145c/m^3.

Break-even analysis: A break-even pumping height was determined for each irrigation scheduling strategy on soils with a PAWC of 100 mm. The break-even pumping height was determined by plotting the average pre-tax net incomes of the four scheduling strategies, with the different water prices, against the different pumping heights. Assuming that the income between the specified pumping heights decreased linearly, the break-even pumping height could be read off where the net income was zero.

Yield simulations

After the PUTU crop growth simulation model was calibrated, wheat yields, as well as the total net quantity of irrigation water, were simulated on soils with a PAWC of 45, 100 and 160 mm for the four irrigation scheduling strategies which varied in sophistication. The simulations were repeated with the meteorological data for the lower P.K. le Roux Dam for the years 1978 to 1988. The total net irrigation water quantity for each soil and scheduling strategy combination was obtained by summing the soil water shortage and the quantity of water applied throughout the growing season. An application efficiency of 85 percent was assumed to determine the gross irrigation water quantities to be used in calculating irrigation variable cost.

The net income was determined by multiplying the simulated yields with a wheat price of R339, whereafter the ownership cost of the centre pivot and implements, production cost, irrigation and yield variable cost were deducted.

Results and discussion

Yield levels and irrigation quantities on soils with a PAWC of 45, 100 and 160 mm

The estimated average wheat yield levels as well as the average gross water applications for four irrigation scheduling strategies and three soil types over the period 1978 to 1988 in the lower P.K. le Roux Dam area are given in Table 1.

The wheat yields for the four irrigation scheduling strategies on the three different soils were the same for all practical purposes. The average wheat yields varied from 6 692 to 6 706 kg/ha. These results can be ascribed to the fact that the scheduling strategies generally used in the lower P.K. le Roux Dam area maintained maximum plant growth conditions. Assuming that yields were only affected by the timeliness and quantity of applied water, it is understandable that yields for the different scheduling strategies and over years were approximately the same. Consequently, there were no significant income differences between the four selected irrigation scheduling strategies for wheat.

However, the irrigation quantities on each of the three soils showed considerable differences. As the sophistication of the irrigation scheduling strategies decreased (from strategy 1 to strategy 4), the irrigation water applications increased. The average irrigation water quantities varied from 523 mm for irrigation scheduling strategy 1 to 927 mm for irrigation scheduling strategy 4.

It can also be seen in Table 1 that irrigation scheduling strategies 2, 3 and 4 led to approximately the same irrigation quantities being applied to the soils with different profile available water capacities. The only exception was the highly sophisticated scheduling strategy (1) on the soil with a PAWC of 160 mm. In this case, less water was applied than on the soils with a PAWC of 45 and 100 mm, because the strategy took the storage capacity of the soil into account to a greater extent, and consequently rainfall was utilised more effectively. Those irrigation scheduling strategies which regularly satisfied the potential water requirements of the crop did not exploit the possible cost-reducing effects of a large soil PAWC.

Net income

The average pre-tax net incomes of the four alternative irrigation scheduling strategies over the period from 1978 to 1988 for soils with a PAWC of 45, 100 and 160 mm were calculated and are given in Table 2. The net incomes of the different irrigation scheduling strategies differed as the sophistication of the strategies changed. The highest net income of R415 per hectare was realised on the soil with a PAWC of 160 mm with the highly sophisticated irrigation scheduling strategy (1). The lowest net income of R126 per hectare, on the other hand, was realised on the soil with a PAWC of 45 mm with the naive irrigation scheduling strategy (4).

More specifically, it can be seen that, on the soil with a PAWC of 100 mm, average net incomes of R213, R302, R305 and R370 per hectare were realised for the naive (4) to the highly sophisticated (1) irrigation scheduling strategies. This represents an increase of R157 per hectare if strategies 4 and 1 are compared. The 313 mm/ha water that was saved (Table 1) caused this difference. If 60 ha of wheat were grown, the farmer could increase his pre-tax net income per season by R9 420. It can therefore be concluded that if farmers used more sophisticated scheduling strategies for wheat, the profitability of wheat under centre pivot irrigation would increase because less water is applied.

It is also clear that the profitability of irrigation on the sandy soils (PAWC of 100 and 160 mm) was higher than that of the clay soil (PAWC of 45 mm). However, the largest part of the increase in net income cannot be ascribed to a saving of water or an increase in yield above the other soils (Table 2), but to the fact that it was more expensive to apply the same amount of water on the clay soils (PAWC of 45 mm).

Table 1 Average yields and gross applied irrigation water for wheat on soils with a PAWC of 45 mm, 100 mm and 160 mm respectively in the lower P.K. le Roux Dam area.

STRATEGY	SOIL WITH A PAWC OF 45 mm		SOIL WITH A PAWC OF 100 mm		SOIL WITH A PAWC OF 160 mm	
	Yield (kg/ha)	Quantity water (mm/ha)	Yield (kg/ha)	Quantity water (mm/ha)	Yield (kg/ha)	Quantity water (mm/ha)
Strategy 1	669	2615	6696	613	6700	523
Strategy 2	670	3741	6701	745	6705	737
Strategy 3	670	2735	6701	752	6706	751
Strategy 4	670	4922	6702	926	6706	927

Table 2 The average pre-tax net income (R/ha) for four alternative irrigation scheduling strategies for wheat on soils with a PAWC of 45, 100 and 160 mm in the lower P.K. le Roux Dam area.

STRATEGY	SOIL WITH A PAWC OF 45 mm	SOIL WITH A PAWC OF 100 mm	SOIL WITH A PAWC OF 160 mm
	Net income (R/ha)	Net income (R/ha)	Net income (R/ha)
Strategy 1	305	370	415
Strategy 2	234	305	310
Strategy 3	238	302	304
Strategy 4	126	213	214

The effect of pumping height and water price on the profitability of the irrigation scheduling strategies

The average pre-tax net income for all four formulated irrigation scheduling strategies on the soils with a PAWC of 100 mm at pumping heights of 10, 40, 70 and 100 m and water prices of 1.645, 1.815, 1.98 and 2.145c/m^3 is shown in Table 3.

In the first place it is clear from Table 3 that the economic advantages of using more sophisticated scheduling strategies increased as pumping height and water price increased. The difference in average net income between scheduling strategies 4 and 1 at a pumping height of 10 m and a water cost of 1.645c/m^3 was R157 per hectare. This difference in average net income increased to R334 per hectare at a pumping height of 100 m and water price of 2.145c/m^3. At high pumping heights and water prices it is therefore increasingly important to use more sophisticated irrigation scheduling strategies, because under these conditions over-irrigation will bring about high costs for the irrigation farmer.

Secondly, it can be seen that the average net income of, for example, scheduling strategy 2, dropped from R305 per hectare at a pumping height of 10 m and a water price of 1.645c/m^3 to -R122 if the pumping height was increased and the water price remained unchanged. This represents a difference of R427 per hectare in net income. For a sixty hectare irrigation system this means that a farmer who irrigates at a pumping height of 100 m would earn R25 620 less per wheat season than the farmer who has to pump only 10 m.

An increase in the water price from 1.645 to 2.145c/m^3, on the other hand, meant that the average pre-tax net income of scheduling strategy 2 at a pumping height of 40 m dropped from R174 to R138 per hectare. This represented a decrease of R2 160 per 60 ha irrigation area.

Sensitivity index: The sensitivity of the pre-tax net income with respect to changes in pumping height and water prices for four irrigation scheduling strategies on soil with a PAWC of 100 mm is shown in Table 4. The negative values of the sensitivity index are indicative of the fact that as the pumping height and water price increased, the pre-tax net income for all four irrigation scheduling strategies decreased.

Table 3 The average pre-tax net income (R/ha) for four alternative scheduling strategies for wheat on soil with a PAWC of 100 mm in the area below the P.K. le Roux Dam if the water price and pumping height increase.

	PRICE OF WATER IN CENTS PER CUBIC METER			
	1.645	1.815	1.98	2.145
PUMPING HEIGHT OF 10 METER				
Strategy 1	370	360	350	340
Strategy 2	305	292	280	267
Strategy 3	302	288	276	263
Strategy 4	213	197	181	166
PUMPING HEIGHT OF 40 METER				
Strategy 1	259	249	239	229
Strategy 2	174	162	150	138
Strategy 3	170	157	145	132
Strategy 4	54	38	23	8
PUMPING HEIGHT OF 70 METER				
Strategy 1	177	167	157	147
Strategy 2	76	64	52	40
Strategy 3	71	58	46	33
Strategy 4	-67	-82	-98	-113
PUMPING HEIGHT OF 100 METER				
Strategy 1	10	0	-10	-21
Strategy 2	-122	-134	-146	-159
Strategy 3	-129	-141	-154	-166
Strategy 4	-309	-324	-339	-355

At low pumping heights the net incomes of all four scheduling strategies were relatively insensitive to an increase in pumping heights, because a unit increase in the pumping height caused a less than proportional decrease in the average pre-tax net income. The net income sensitivity for a pumping height change increased, however, as the sophistication of the scheduling strategies decreased. At the higher pumping heights, the net income sensitivity of all four scheduling strategies was much higher, because a unit increase in pumping height resulted in a more than proportional decrease in the average net income. It is also clear that at large pumping heights the difference in net income sensitivity between the four scheduling strategies was much greater than at smaller pumping heights.

Table 4 Sensitivity index of the pre-tax net income in respect of a change in the pumping height and water price of the four irrigation scheduling strategies in the area below the P.K. le Roux Dam on the soil with a PAWC of 100 mm.

	STRATEGY 1	STRATEGY 2	STRATEGY 3	STRATEGY 4
Pumping height (m)				
10	-0.10	-0.14	-0.15	- 0.25
40	-0.42	-0.75	-0.78	- 3.00
70	-2.20	-6.05	-6.59	-13.06
Water price (c/m³)				
1.645	-0.25	-0.41	-0.42	-0.72
1.815	-0.31	-0.46	-0.47	-0.86
1. 98	-0.31	-0.48	-0.49	-0.93

The net income differences between the alternative irrigation scheduling strategies therefore increased as pumping height increased.

The same trends observed in the sensitivity index of pumping height were present in the sensitivity index of a water price change. However, it was significant that a unit change in the price of water regardless of the scheduling strategy resulted in a less than proportional decrease in the average pre-tax net income. The pre-tax net income was therefore more sensitive to a unit increase (meter) in pumping height than to a unit increase (c/m³) in the price of water.

Break-even pumping height for each irrigation scheduling strategy: The break-even height of the four irrigation scheduling strategies at a water price of 1.645c/m³ on the soil with a PAWC of 100 mm is shown graphically in Figure 1. The break-even height of scheduling strategy 1 at a water price of 1.645c/m³ was approximately 103 m. The break-even pumping height of scheduling strategies 2 and 3 at the same water price dropped by 20 m to approximately 83 and 81 m respectively. The break-even pumping height of scheduling strategy 4 dropped a further 30 m to a pumping height of approximately 53 m.

If the water price increased from 1.645 to 2.145c/m³, the break-even pumping height of all four irrigation scheduling strategies dropped by approximately 5 m. The break-even pumping height analysis clearly showed that a water price increase had relatively small implications for profitable pumping heights. Secondly, farmers who have large pumping heights should use highly sophisticated irrigation scheduling strategies, as substantial income losses were realised with the naive irrigation scheduling strategies at large pumping heights.

Conclusion

A satisfactory procedure was developed and illustrated

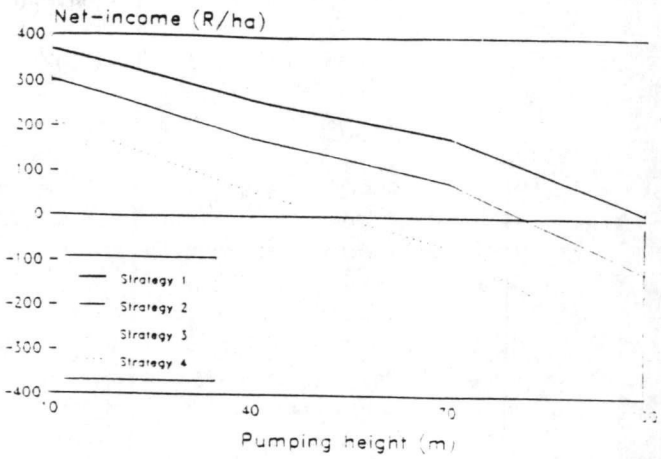


Figure 1 The break-even pumping height of four irrigation scheduling strategies at a water price of 1.654c/m³ on the soil with a PAWC of 100 mm.

to analyse the profitability of alternative irrigation scheduling strategies economically.

Simulated yields for the various scheduling strategies varied from 6 692 to 6 706 kg/ha. Gross irrigation water quantities, on the other hand, varied from 523 to 927 mm. A considerable measure of confirmation was therefore found for the first hypothesis. The four typical irrigation scheduling strategies in the area below the P.K. le Roux Dam differed in respect of the quantity of irrigation water, whereas the realised yield levels under each irrigation scheduling strategy were approximately the same.

When the same irrigation scheduling strategy was applied to the three different soils, no significant irrigation water utilisation differences were found. The gross irrigation water quantities of strategy 2, for example varied from 737 to 741 mm/ha in the soils with PAWC of 45, 100 and 160 mm. The hypothesis that if an irrigation scheduling strategy regularly satisfies the crop water requirements completely, the profile available water capacity of the soil is not utilised economically, was substantially confirmed by the results.

An increase of at least R157 per hectare with a corresponding increase in profitability was realised when the highly sophisticated strategy was applied instead of the naive irrigation scheduling strategy. The reason is that less water is applied with the more sophisticated irrigation scheduling strategies. A considerable degree of confirmation was therefore found for the initially stated hypotheses.

The implications of the above-mentioned hypotheses are more pronounced at larger pumping heights (e.g. farmers on the Cape side of the Orange River) where the difference in net incomes between the highly sophisticated and naive irrigation scheduling strategies increased to approximately R299 per hectare. The increase in pumping height had a

large effect on the profitability of irrigation. The drop in profitability was mainly caused by the increase in irrigation variable cost as well as a relatively smaller increase in ownership cost of the irrigation system. At large pumping heights and high water prices the economic importance of more sophisticated scheduling strategies increased, because the saving in irrigation water (as a result of more sophisticated scheduling strategies) caused greater savings in cost than at low pumping heights.

From the economic analysis it can be concluded that the seasonal plan or strategy according to which a farmer schedules irrigation water, is one of the major variables affecting the economics of irrigation.

Because of the high cost of applying water, farmers can no longer follow a scheduling strategy that wastes water. The irrigation farmer already has to contend with input costs which have recently increased to extremely high levels. These cost increases must be incorporated anew into decision making by the irrigation farmer concerning production levels which are most profitable. In this respect, a more sophisticated irrigation scheduling strategy could make a valuable contribution towards increasing the profitability of irrigation.

Research implications

In order to analyse the effect of the PAWC of soils on the economy of irrigation, a deficit irrigation scheduling strategy should be included in the analysis.

If the opportunity cost (actual cost) of water is brought into account in the analysis, the profitability of the more sophisticated irrigation scheduling strategies can be increased further. Irrigation water is scarce and should be allocated to the best alternative application.

The profitability analysis of alternative irrigation scheduling strategies should in future be carried out on a whole farm basis. The crop growth simulation model should therefore be calibrated to enable inclusion of the most important other rotational crops such as cotton, late maize, peanuts, soyabeans, potatoes, peas, beans and lucerne in the analysis.

The profitability of more sophisticated irrigation scheduling strategies should also be analysed in humid irrigation areas, because the importance of scheduling increases as a result of the higher probability of rain.

Finally the risk efficiency of irrigation scheduling strategies should also be analysed. The risk sensitivity of the decision-maker should be taken into account explicitly in the analysis.

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ANALYSIS OF THE ECONOMIC PROFITABILITY OF TYPICAL CENTRE PIVOT SYSTEMS TAKING INTO ACCOUNT PRODUCTION AND PRICE RISK

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Abstract

The purpose of this paper is to determine the economic profitability of eighteen typical centre pivot systems using the net present value method. The procedure involves the choice of a crop rotation system, the estimation of production and irrigation costs and the choice of product prices and yields. All the irrigation systems had positive net present values, implying that all were economically profitable. The economic profitability of irrigation investment strategies is greatly influenced by the size and capacity of the system and the static height at which water is pumped. Irrigation on sandy soils is consistently more profitable than on clay soils because of the lower irrigation costs. Production and price risk cause substantial variation in the profitability of centre pivot irrigation systems and should therefore be considered in economic analysis.

Introduction

Investment decisions, including the purchasing of expensive assets such as land, buildings and machinery, are among the most important decisions that a manager can make (Boehlje & Eidman, 1984:315). The investment decision comprises the evaluation of planned investments and the allocation of capital among competing investments (Stevens, 1979:1). The evaluation of alternative investments and their influence on profitability and cash flow are critical tasks in farm planning and can only be carried out by drawing up capital budgets and financial analysis.

The capital-intensive nature of mechanised irrigation systems requires that the profitability of these investments be evaluated. Robertson, Musser & Tew (1982) showed that the profitability of irrigation investments can be determined by calculating the net present value of such investments. Boggess & Amerling (1983) determined the risk and yield of irrigation investments with a bio-economic simulation model. The profitability of typical irrigation systems in the irrigation of various soil types was also determined by Wilson & Eidman (1981). Irrigation investment decisions in Central Minnesota were evaluated by Gill (1984) using the net present value technique. Research results on the evaluation of irrigation investments at a micro level in South Africa are rare. In the cases where various systems were considered (Backeberg, 1988), the purpose of the work had not been to compare alternative systems. The economic profitability of alternative centre pivot systems has not yet been determined locally.

The current weak financial position of many irrigation farmers (Free State Agricultural Union, 1989), emphasises the importance of thorough evaluation of the economic profitability and financial feasibility of centre pivot systems. The purpose of an economic profitability analysis is to determine whether a project contributes to the long-term profitability of a firm (Boehlje & Eidman, 1984:316).

The purpose of this article is to determine the economic profitability of typical centre pivots, as identified by Meiring (1989), by applying the net present value technique. Price risks are taken into account in the analysis.

Given a feasible crop rotation system and a reasonably optimal irrigation scheduling strategy, the following objectives are pursued:

- To determine how the size, capacity and static height of centre pivot irrigation systems affect the economic profitability of the relevant irrigation investment strategies.
- To determine whether centre pivot irrigation systems on sandy soil are more profitable than similar systems on clay soil.
- To account for the effect of production and price risks of a typical crop rotation system in the Southern Free State sub-region when determining the economic profitability of each centre pivot irrigation system.

Literature Review

Boehlje & Eidman (1984:315) described four steps for the evaluation of investment alternatives:

- Identify possible profitable investment alternatives.
- Analyse the economic profitability and financial feasibility of the alternatives.
- Re-evaluate the decision using different price and yield assumptions.
- Make a choice on the basis of the results of the above-mentioned steps as well as other available information.

Casler, Anderson & Aplin (1984:1) also considered that investment decisions are among the most important management decisions that can be made, and should therefore rest on reliable procedures.

The net present value technique

Rules that are used when making investment decisions are normally called capital budgeting techniques. According to Bierman & Smidt (1988:6), a capital

budgeting technique is characterised by costs and benefits that are spread over periods of time.

Capital budgeting techniques must comply with four requirements (Copeland & Weston, 1983:26):

- All cash flows must be taken into account.
- Cash flows must be discounted against the opportunity cost of funds.
- In the case of mutually exclusive investment alternatives the one that maximises the owner's welfare should be selected.
- A manager must be able to consider each investment independently from the other.

Four capital budgeting techniques are generally used, namely the accounting return rate, repayment period, internal return rate and net present value methods. The first two methods do not take all relevant cash flows and the time value of money into account. Copeland & Weston (1983:31) compared the net present value method and the internal return rate method on the basis of their stated requirements and found that the internal return rate does not meet the last three requirements. The net present value method was used in several studies to determine the profitability of irrigation investments (Robertson *et al.*, 1982, Boggess & Amerling, 1983; Gill, 1984; Bosch, Taylor & Ross, 1988; Lazarus & Scott, 1981).

According to Boehlje & Eidman (1984:318) the net present value technique is preferable to other capital budgeting techniques because this technique takes the opportunity cost and time value of money into account. Bierman & Smidt (1988:6) regarded the discounted cash flow or net present value framework as the best method for analysing the cash flow of investments, provided the technique is used correctly. The excellence of this method has already been clearly illustrated, according to Casler *et al.* (1984:ix).

The net present value of an investment is the maximum amount that a firm can pay for an opportunity to make the investment without being financially weaker (Lambrechts, Reynders & Scheurkogel, 1986:151; Bierman & Smidt, 1988:45).

The simplest equation for calculating the net present value N is as follows (Boehlje & Eidman, 1984:321):

$$N=\sum_{n=1}^{k}\frac{I_n}{(1+d)^n}-O \qquad (1)$$

where n = period,
k = last term of flow,
I = net cash flow in period n,
d = discounting rate and
O = cash investment.

The financing method of the capital investment does not affect the value of the investment. The capital sources (debt or own capital) and the deductibility of interest for tax purposes was already taken into account when the discount rate was calculated (Boehlje & Eidman, 1984:324). For the same reason, interest on debt for financing the asset is not included as an annual cash expense. Depreciation is not included in the annual cash flow, but affects the cash flow indirectly by tax reduction (Boehlje & Eidman, 1984:324). Tax savings are equivalent to a cash inflow (Fuller & Nordquist, 1978:3).

In spite of various advantages of the present value technique, the method also has its weak points. Investments can only be compared if they have the same useful life (Casler *et al.*, 1984:30). According to Lambrechts *et al.* (1986:152) it is assumed when using this method that all interim financing takes place at the same rate. Projects with positive net present values cannot be ranked because it is an absolute and not a relative criterion (Gittinger, 1982:329).

Net benefit: investment ratio

A suitable criterion for placing independent projects in order of priority is the net benefit:investment ratio which is reliable in most cases (Gittinger, 1982:347). It is a form of benefit: cost ratio which divides the present value of the net benefit by the present value of the investment.

The decision-making criterion that applies here is that all projects with a net benefit: investment ratio greater than one are accepted when the benefit and cost of any project are discounted against its opportunity cost. The investment with the biggest ratio is made first. By selecting the independent investments in order of decreasing net benefit: investment ratios, the yield on each rand invested is maximised. Consequently the maximum net present value and therefore also the maximum income flow of a group of investments is obtained.

Production and price risk

The climate has a significant influence on crop yields and eventual profit realised by farmers. The yield per hectare and the product price are two of the most critical variables that determine the profitability of a specific crop (Oosthuizen, 1983:66). Although irrigation decreases the risk of low yields, the weather still has an effect on yields, and factors such as extreme temperatures can still have a detrimental effect on yields. In the case of products that are mainly grown on dry land, and the price of which is determined by the total national yield, irrigation does not decrease the risk of realising lower prices at all. Production and price risk should therefore be taken into account in economic analysis.

In many local studies that deal with the economics of irrigation, average long-term yields are assumed and prices are kept constant or are adjusted by the general inflation rate (Janse van Rensburg, 1983; Backeberg, 1984; Kirsten & Backeberg, 1988). Although sensitivity analyses are made for changes in yield levels and prices, the important results of yields

and prices that vary annually are not taken into account over the planning period. The results of an analysis, using an average price or yield, can appear much more favourable than an analysis which is done with varying prices and yields.

Procedure

The procedure for the economic evaluation of alternative centre pivot investments includes the choice of investment alternatives, a crop rotation system, estimation of costs and income, yield simulation and the calculation of the net present value of the investments.

Alternative centre pivot investments

The annual fixed and variable costs of eighteen typical centre pivots in the Southern Free State sub-region were calculated by Meiring (1989). These systems are described in Table 1.

Table 1 Description of typical centre pivot systems in the Southern Free State sub-region, 1989.

Pivot number	Size (ha)	Capacity[1] (mm/day) (m)	Static height	Soil type
1	60	8	-15	sandy
2	60	8	-15	clay
3	60	8	+10	sandy
4	60	8	+10	clay
5	60	10	-15	sandy
6	60	10	-15	clay
7	60	10	+10	sandy
8	60	10	+10	clay
9	60	12	-15	sandy
10	60	12	-15	clay
11	60	12	+10	sandy
12	60	12	+10	clay
13	30	8	-15	sandy
14	30	8	-15	clay
15	30	10	-15	sandy
16	30	10	-15	clay
17	30	12	-15	sandy
18	30	12	-15	clay

1 Gross application per day

Crop choice

In the economics of irrigation the point of departure is to select a crop rotation system that is representative for the area. The crops included in this study are wheat, maize and cotton in a crop rotation system. The length of the growing season of the crops limits soil utilisation to 150% of the area per year, of which each crop constitutes 50%, while the other 50% lies fallow.

The BEWAB-computer program (Bennie, Coetzee, Van Antwerpen, Van Rensburg & Burger, 1988) was used to determine scheduling strategies for wheat, maize and cotton. When applying the schedule, rainfall is taken into account, so that the cost implications of different irrigation requirements resulting from annual variations of rainfall are included. In each case the type of soil and the capacity of the irrigation system are also taken into account.

Estimation of costs

The costs involved in the economic evaluation of centre pivot investments can be divided into production and irrigation costs. Production cost estimates were obtained from crop budgets drawn up for wheat, maize and cotton in the Southern Free State (Meiring, 1989). Irrigation costs are made up of variable and fixed costs and are influenced by the relevant system that is used. As the costs are estimated to calculate the net present value of each investment, interest and depreciation costs are not taken into account. Two other fixed cost items are relevant, namely the annual insurance of the system and the fixed electricity levy per month. The fixed costs and irrigation variable costs estimated for each of the systems (Meiring, 1989) were used for the profitability analysis. The variable cost is expressed as a cost of applying a millimetre of water per hectare.

Production prices

The profitability of irrigation investments is very sensitive to the product prices that are used (Boggess & Amerling, 1983:90; Bosch *et al.*, 1988:178). Apart from the price levels, the price risk associated with each crop is also important. The cultivation of cotton does not have a big price risk for the producer at present because a fixed price is paid to the farmers by the cotton-ginneries and the local demand for cotton exceeds the supply. The producer price of R1,00/kg for machine-picked seed cotton is therefore used. The cultivation of maize and wheat has definite price risks for the producer since there has been a move away from the one-channel fixed price scheme. The various marketing boards announce price scenario's for both crops before the start of the planting season. A procedure whereby price risk can be taken into account (Meiring, 1989) was used in the study. The procedure uses the suggested price scenario's and the historic harvest yields. The prices used for the two crops are shown in Table 2.

Yield simulation

Production risk is taken into account by using crop growth models to simulate yields under variable environmental conditions. Two simulation models developed by De Jager, Mottram & Singels (1986) and De Jager, Van Zyl, Kelbe & Singels (1987) were used to simulate wheat, maize and cotton yields.

Simulated wheat yields for the different irrigation

systems are shown in Table 3. The variation in the yields was relatively small between years, and between the different irrigation applications of the 8 mm, 10 mm and 12 mm systems. The reason for this is that the soil profiles were at field-water capacity during planting. In spite of lower water applications with the 8 mm and 10 mm systems, the plant met its water requirements by using available water in the profile. The utilisation of the profile-available water capacity is proved by the shortages in the profile after the wheat was harvested. In the case of wheat, the lower-capacity centre pivot systems therefore did not cause lower yields.

The standard deviations show that yield variations on the clay soil increased noticeably relative to the sandy soil as the water application dropped. This result can be explained by assumptions in the model concerning water retention properties of the two different soils.

The simulated maize yields shown in Table 4 displayed much more variation than the simulated wheat yields. As the water application levels increased, invariably higher yields resulted. This result indicates that the application capacity of the

Table 2 Adjusted national wheat and maize production and the corresponding expected producer prices for the period 1956 to 1988.

	Wheat		Maize	
Year	Adjusted production (ton)	Producer price (R/ton)	Adjusted production (ton)	Producer price (R/ton)
1956	3 205 748	345	7 187 912	237
1957	3 042 763	358	7 637 482	223
1958	2 575 367	373	6 885 925	237
1959	2 725 948	373	7 280 525	237
1960	2 712 421	373	7 998 748	223
1961	2 846 384	373	8 757 656	212
1962	2 498 149	373	9 537 277	203
1963	2 728 673	373	9 497 741	212
1964	2 816 074	373	7 611 496	223
1965	2 167 982	373	7 673 622	223
1966	1 840 401	373	8 057 480	223
1967	2 571 359	373	12 780 549	203
1968	2 823 948	373	8 277 882	223
1969	2 880 280	358	7 795 848	223
1970	2 911 176	358	8 366 587	223
1971	3 172 285	345	10 574 009	203
1972	3 165 723	345	11 397 334	203
1973	3 216 519	345	5 656 599	250
1974	2 756 031	373	12 567 112	203
1975	2 888 666	358	10 627 499	203
1976	3 330 591	345	8 833 471	212
1977	2 775 502	373	11 019 287	203
1978	2 507 686	373	11 249 132	203
1979	2 863 259	373	9 382 601	212
1980	2 055 486	373	11 757 016	203
1981	2 947 946	358	15 358 799	203
1982	2 957 012	358	9 049 960	212
1983	2 164 851	373	4 642 673	250
1984	2 677 294	373	4 813 673	250
1985	1 913 502	373	8 283 181	223
1986	2 490 791	373	8 183 666	223
1987	3 228 629	345	7 196 549	237
1988	3 387 000	334	7 014 999	237

Table 3 Simulated wheat yields for typical centre pivot systems in the Southern Free State sub-region, based on historic meteorological data for 10 years.

	Wheat yields (kg/ha) for typical systems					
	8 mm systems		10 mm systems		12 mm systems	
Pivot:	1.3.13	2.4.14	5.7.15	6.8.16	9.11.17	10.12.18
Year	Sandy	Clay	Sandy	Clay	Sandy	Clay
1978	6 699	6 539	6 702	6 730	6 703	6 732
1979	6 692	6 679	6 695	6 625	6 696	6 726
1980	6 677	6 691	6 682	6 713	6 683	6 714
1981	6 708	6 728	6 710	6 739	6 711	6 740
1982	6 712	6 730	6 714	6 738	6 715	6 740
1983	6 700	6 725	6 703	6 734	6 704	6 734
1984	6 697	6 707	6 699	6 725	6 700	6 726
1985	6 695	6 719	6 698	6 726	6 699	6 727
1986	6 697	6 703	6 700	6 727	6 700	6 728
1987	6 696	6 721	6 699	6 729	6 699	6 730
Average	6 697	6 694	6 700	6 719	6 701	6 730
Std[2]	9.3	57.0	8.6	33.7	8.6	7.6
Cv[3]	0.1	0.9	0.1	0.5	0.1	0.1

2. Standard deviation
3. Coefficient of variation

Table 4 Simulated maize yields for typical centre pivot systems in the Southern Free State sub-region, based on historic meteorological data for 10 years.

	Maize yields (kg/ha) for typical systems					
	8 mm systems		10 mm systems		12 mm systems	
Pivot:	1.3.13	2.4.14	5.7.15	6.8.16	9.11.17	10.12.18
Year	Sandy	Clay	Sandy	Clay	Sandy	Clay
1978/79	6 811	6 141	7 524	6 782	8 251	7 201
1979/80	7 792	6 748	8 194	7 257	8 860	7 516
1980/81	7 339	6 656	8 018	7 077	8 746	7 433
1981/82	8 107	7 026	8 606	7 567	9 137	7 861
1982/83	6 874	5 956	7 580	6 657	8 177	7 114
1983/84	6 833	5 828	7 410	6 377	7 835	6 677
1984/85	8 763	7 558	9 559	8 284	9 966	8 634
1985/86	7 808	6 786	8 381	7 289	8 939	7 658
1986/87	9 118	7 873	9 869	8 431	10 231	8 729
1987/88	9 575	8 632	9 870	9 057	10 367	9 211
Average	7 902	6 920	8 501	7 478	9 051	7 803
Std[2]	988.2	888.4	955.2	861.2	881.5	808.2
Cv[3]	12.5	12.8	11.2	11.5	9.7	10.4

2. Standard deviation
3. Coefficient of variation

8mm and 10 mm systems was insufficient to prevent stress in maize in spite of a full soil profile during planting time. As crop requirements were not met, the yields on the clay were considerably lower than on the sandy soils. As in the case of wheat yields on clay, the variation in maize yields decreased on sandy and clay soils as water application levels increased.

This large difference in yields should lead to a higher profitability of the 12 mm systems. The simulated yields of cotton (like maize, a summer crop) in Table 5 show the same patterns as that of maize. This result shows that water application by the lower-capacity centre pivots did not meet crop water requirements. The relatively large variation between the yield of each year of maize and cotton in comparison to the yields of wheat is caused by the greater influence of rainfall on the yields. The yield of wheat, which is planted in the dry season, is mostly determined by the irrigation quantities and soil water at planting time. The larger variation in cotton yields for the 10 mm system is difficult to explain. This specific water application could possibly lead to enhancement of simulated vegetative growth, which could make the plant more sensitive to moisture stress later in the season.

The estimated yields for all three crops compare favourably with the results of Bennie *et al.* (1988). In addition, the estimated yields fall within the limits considered realistic by the farmers.

Economic analysis

The economic profitability of each centre pivot was determined by calculating the net present value (NPV) of the investment. The following equation was developed to estimate the NPV of an investment under South African circumstances:

$$NPV = -i + s(1-m) + \sum_{t=1}^{n} \frac{d_t(i)(m)}{(1+v)^{t-1}} + \sum_{t=1}^{n} \frac{ncf_t(1-m)}{(1+v)^{t-1}} + \frac{r(1-m)}{(1+v)^{n-1}} \qquad (2)$$

where i = value of initial investment (R),
s = subsidy on irrigation system (R),
ncf = net cash flow in year t (R),
r = salvage value of system (R)
m = marginal tax rate (%)
d = % depreciation that can be written off for tax purposes in year t,
v = discount rate (%) and
n = economically useful life of investment (years).

Equation 2 was used in a computer program to calculate the NPV of each investment. Values for the investment, subsidy, tax and discount rate were entered and the annual net cash flow was read from previously compiled files. The files containing the net cash flow figures were drawn up by combining the enterprise budgets, the fixed and variable irrigation costs, as well as simulated yields and product prices.

Yields and product prices were selected in such a way that production and price risk were taken into account. The thirty-three prices obtained for maize and wheat by applying the latest price scenarios to the adjusted national production figures, were linked to the ten simulated yields obtained for each scheduling strategy. The assumption regarding the simulated yields was that the historic weather data that were used had an equal chance of occurring again. It was also assumed that the national harvest sizes of the past, after adjusting for trends in area planted and technology, had an equal chance of being realised again. It was assumed that there was no correlation between yields under irrigation and the national harvest size, therefore 330 price-yield combinations were obtained. As price risk is low in cotton cultivation and since only one producer price was used, cotton had ten price-yield combinations.

With a crop rotation system of wheat, maize and cotton, eight wheat and maize harvests and seven cotton harvests could be grown in a period of fifteen years, which is the economically useful life of a centre pivot system. Price-yield combinations were selected randomly for wheat, maize and cotton. T price-yield combinations were used to calculate the gross income for the successive seasons. For each centre pivot system the procedure was repeated twenty times to obtain twenty sets of gross income figures for fifteen successive years.

The cash flow over the period of fifteen years was calculated by using present prices. Therefore real prices were used, which required that the discount rate also had to be in real terms. A real after-tax discount rate of 5% (the result of a nominal rate of 20.75% and an inflation rate of 15%) and a marginal tax rate of 20% were assumed in the analysis.

The initial capital investment of each irrigation system was read into the program. Provision was made for a subsidy for which farmers could qualify when irrigation systems are installed. The subsidy is limited to R7 500 or 33% of the cost of the system, whichever is the smaller amount. In the case of the eighteen systems the subsidy was therefore R7 500, which was taxable. A "50/30/20" accelera depreciation allowance is available for qualifying assets in the tax year in which it is put into commission for the first time and for each of the two following tax years. Therefore 50%, 30% and 20% of the cost can be deducted from the taxable income as depreciation. The resulting decrease in income tax is regarded as a cash inflow. The advantage is calculated assuming that the farmer's marginal tax rate is 20% and that he has taxable income that exceeds the absolute amounts of depreciation. The advantages of

the second and third years are discounted to present money values. Finally, the salvage value of the equipment is discounted using an economically useful life of fifteen years to present value. The salvage value of 15% of the investment cost is taxed because the total asset was written off for tax purposes in the first three years.

The NPV was calculated for the twenty repetitions of the 23 successive yields of the crop rotation system for all eighteen systems. The average and standard deviations of the twenty repetitions were calculated.

The average NPV was expressed over the useful life of the system, per year and per hectare. The net benefit:investment ratio was used as a relative criterion to place the alternative investment strategies in order of decreasing profitability.

Results and discussion

Economic profitability : Net present value

The net present values of the alternative investment strategies are shown in Table 6. The highest, lowest and average net present values of each investment obtained by discounting the results of fifteen years twenty times, and the standard deviations of the repetitions, are provided.

All eighteen irrigation investments are therefore profitable if a positive NPV applies as criterion for profitability. However, the NPV cannot be used as absolute criterion for determining the degree of profitability. The system that produced the largest average NPV over a period of fifteen years was system 9, with a value of R563 238. System 9 is the 60 ha system with a static height of -15 m on sandy soil. System 14, with a 30 ha system on clay, had the smallest average NPV of R72 436.

A positive average NPV indicates that the total present values of the annual net cash flow, the subsidy, tax benefits and the salvage value are bigger than the capital investment, at the chosen discount rate. The fact that the lowest net present value was R11 940 (system 14) means that each repetition indicated a profitable investment. However, if one takes into account that the present value of the tax benefit obtained from writing off the centre pivots varied from R27 228 to R47 605, the NPV will drop considerably if the advantages are omitted. The lowest value of the repetitions for system 14 will be negative in this case.

An investor cannot realise the salvage value of the equipment before the end of the useful life of the system. In addition, the tax benefits are realised only if the farmer has a taxable income. To merely look at economic profitability without taking financial feasibility and risk into account could, however, be misleading.

The risks of the investments are indicated by the standard deviations and the large differences between the lowest and highest net present values calculated for

Table 5 Simulated cotton yields for typical centre pivot systems in the Southern Free State sub-region, based on historic meteorological data for 10 years.

	Cotton yields (kg/ha) for typical systems					
	8 mm systems		10 mm systems		12 mm systems	
Pivot:	1.3.13	2.4.14	5.7.15	6.8.16	9.11.17	10.12.18
Year	Sandy	Clay	Sandy	Clay	Sandy	Clay
1978/79	1 797	1 742	2 477	2 507	2 986	2 825
1979/80	2 439	2 309	3 046	2 809	3 166	3 006
1980/81	2 077	1 949	2 673	2 712	3 085	3 020
1981/82	3 083	2 884	3 756	3 691	4 221	3 999
1982/83	3 377	3 221	4 258	4 114	4 739	4 393
1983/84	3 245	3 019	4 150	3 942	4 611	4 331
1984/85	4 133	3 877	4 684	4 446	4 988	4 692
1985/86	3 998	3 760	4 751	4 537	5 000	4 835
1986/87	3 980	3 694	4 421	4 191	4 710	4 420
1987/88	2 557	2 318	2 945	2 780	3 379	3 073
Average	3 069	2 877	3 716	3 573	4 089	3 859
Std[2]	830.8	772.5	859.9	789.3	837.8	789.3
Cv[3]	27.1	26.9	23.1	22.1	20.5	20.5

2. Standard deviation
3. Coefficient of variation

Table 6 The lowest, highest and average net present values, as well as the standard deviation over the economically useful life of the eigtheen typical centre pivot systems in the Southern Free State sub-region.

System no.	Net present value				
	Lowest (R)	Highest (R)	Average (R)	Standard deviation (R)	Coefficient of variation (%)
1	211 713	454 562	342 119	64 831	19
2	116 682	338 402	238 050	59 594	25
3	147 199	388 145	276 120	64 695	23
4	69 471	290 763	190 393	59 452	31
5	340 842	606 569	483 683	69 011	14
6	229 920	474 798	363 723	64 426	18
7	275 551	539 843	417 319	68 870	17
8	146 609	390 228	280 481	64 837	23
9	409 216	696 845	563 238	71 949	13
10	250 064	506 579	391 469	67 189	17
11	344 853	631 209	498 219	71 912	14
12	176 186	432 761	316 095	66 064	21
13	52 808	173 524	117 451	32 365	28
14	11 940	122 662	72 436	29 734	41
15	128 233	260 796	199 409	34 473	17
16	79 044	201 379	145 930	32 208	22
17	156 310	299 746	233 115	35 953	15
18	109 812	238 060	180 563	33 597	19

each system. Although system 9 produced the largest NPV, its standard deviation was also the largest, namely R71 949. However, the coefficient of variation of system 9 is the lowest, indicating it is relatively the least risky system. The systems with a capacity of 8 mm are characterised by high coefficients of variation (19-41%) which indicate relatively higher risk. In many cases the highest value realised was more than 100% larger than the lowest value, system 14 being the extreme case where the highest value was more than ten times larger than the minimum.

The NPV, expressed per year or hectare, gives a better indication of the value of the investment. The disadvantage is that these are average values which could be misleading and these values are expressed in terms of the present value of money. These values are given in Table 7.

The differences in NPV between the systems are clearly illustrated by the NPV per hectare. The 30ha systems are then comparable to the 60 ha systems. The net present value of system 9 is more than R1 000 per hectare higher than that of system 11 which has the second highest value. The 30 ha system on clay, with a capacity of 8 mm, gave the second lowest NPV of R2 416 per hectare.

The last column in Table 7 gives the annual average NPV per hectare. These values vary from R161 to R626. Between the intervals of R300 to R400 per hectare and R400 and R500 per hectare, five of the eighteen systems can be found. There are three systems in the intervals R200 to R300 per hectare and R500 and R600 per hectare.

The NPV of the investment cannot be used to put the eighteen systems in order of profitability, however, because it is an absolute criterion.

Net benefit:investment ratio

The net benefit investment ratio can be used to select the most profitable investment strategy. Table 8 shows the net benefit:investment ratios for the alternative investment strategies in decreasing order. As in the case of the net present value criterion, all the systems were profitable. System 14 had the lowest ratio of 1.5 which indicates net benefits 1.5 times the investment.

System 9, which also produced the largest NPV, was the most profitable alternative, followed by systems 5, 11 and 7. The four most profitable systems were all 60 ha systems with sandy soils. Systems 9 and 5 both had negative vertical heights of 15 m. System 9 was a 12 mm system, and system 5 was a 10 mm system. Systems 11 and 7 were also 12 mm and 10 mm systems respectively, but had a positive vertical height of 10 mm. These four systems were followed by the first systems on clay, namely systems 10 and 6 with 60 ha under irrigation. These systems were also a 12 mm and a 10 mm respectively,

Table 7 The average net present value of eighteen centre pivot systems in the Southern Free State sub-region over the economically useful life of the systems expressed as an amount per year and per hectare.

System no.	Net present value (R)			
	Average	Per year	Per hectare	Annual/ha
1	342 119	22 808	5 702	380
2	238 050	15 870	3 968	265
3	276 120	18 408	4 602	307
4	190 393	12 693	3 173	212
5	483 683	32 246	8 061	537
6	363 723	24 248	6 062	404
7	417 319	27 821	6 955	464
8	280 481	18 699	4 675	312
9	563 238	37 549	9 387	626
10	391 469	26 098	6 524	435
11	498 219	33 215	8 304	554
12	316 095	21 073	5 268	351
13	117 451	7 830	3 915	261
14	72 485	4 832	2 416	161
15	199 409	13 294	6 647	443
16	145 930	9 729	4 864	324
17	233 115	15 541	7 771	518
18	180 563	12 038	6 019	401

with a vertical height of -15 mm. The 8 mm system which performed best was system 1 which irrigated 60 ha of sandy soil and had a static height of -15 m.

The best 30 ha systems, systems 17 and 15, were eighth and ninth respectively. The systems on sandy soils, with negative heights of 15 m, had capacities of 12 mm and 10 mm respectively.

The 30 ha systems with a capacity of 8 mm had the worst results of all eighteen systems. The system on sandy soils was seventeenth, and the one on clay last. The five systems which performed just better than the 8 mm systems, all had clay soils under irrigation.

Important deductions can be made from the results of the profitability analysis. The combination of sandy soils, a high system capacity of 12 mm an irrigable area of 60 ha and a low vertical height was the most profitable investment.

Systems on sandy soils were much more profitable than similar systems on clay soils. This is illustrated by systems 5, 11 and 7, in spite of lower capacities and higher static heights being more profitable than system 10 which had a capacity of 12 mm and a negative static height of 15 m, but irrigated clay soils. Six of the seven systems that had the worst results irrigated clay soils. The results can be explained by the higher irrigation variable costs of systems that irrigate clay soils, and lower maize and cotton yields on clay than under similar systems on sandy soils.

Secondly, the vertical height has an important effect on profitability. In spite of system 5 being 10 mm system, it was more profitable than system 11 which is a 12 mm system, because the vertical height is 25 m lower than that of system 11.

The 60 ha systems also performed much better than the 30 ha systems. The most profitable 30 ha system, system 17 which is a 12 mm system on sandy soils, follows after seven 60 ha systems. Even system 1, which is a 60 ha 8 mm system on sandy soils, performed better.

As far as capacity is concerned, the 12 mm systems were the most profitable, although the differences between the 10 mm and the 12 mm systems were not large. For example, system 5 which is a 10 mm system, performed better than system 11 which is a 12 mm system, because the vertical height of system 11 is greater than that of system 5. However, the 8 mm systems performed very badly. Four of the five systems that are least profitable are 8 mm systems. The reason for this is the inability of the systems to supply the water requirements of maize and cotton and the resultant yield losses. Higher capacity systems are therefore justified in spite of the higher cost.

Definite differences in profitability are therefore caused by differences in soil type, static height and site factors. The choice of the farmer is however limited to size and capacity of the system. The analysis indicates the best choice to be a 12 mm system that irrigates 60 ha. However, the important effect of soil type and height should be taken into account. As a result of the lower profitability of centre pivot irrigation on clay soils, such development is not economically justifiable in many cases. Increasing vertical heights also reduce profitability and in combination with clay soils profitability drops even further.

Table 8 Initial investment, average net present value (NPV), standard deviation and the net benefit: investment ratio of eighteen typical centre pivots in the Southern Free State sub-region.

System no.	Investment (R)	Average NPV (R)	Standard deviation (R)	Net benefit investment ratio
9	227 997	563 238	71 949	3.47
5	219 536	483 683	69 011	3.20
11	240 378	498 219	71 912	3.07
7	226 149	417 319	68 870	2.85
10	237 553	391 469	67 189	2.65
6	220 929	363 723	64 426	2.65
1	210 071	342 119	64 831	2.63
17	151 443	233 115	35 953	2.54
15	142 562	199 409	34 473	2.40
12	246 119	316 095	66 064	2.28
3	215 746	276 120	64 695	2.28
18	149 432	180 563	33 597	2.21
8	234 105	280 481	64 837	2.20
2	211 484	238 050	59 594	2.13
16	145 439	145 930	32 208	2.00
4	222 674	190 393	59 452	1.86
13	140 766	117 451	32 365	1.83
14	144 573	72 485	29 734	1.50

Conclusion

The economic profitability of irrigation investment strategies is largely influenced by the size of the

system, the capacity of the system and the static height to which the water is pumped. Also, 60 ha systems are more profitable than 30 ha systems. For example, the net benefit: investment ratio of the most profitable 60 ha system is 3.47 as against the 2.54 of the most profitable 30 ha system. Systems with capacities of 12 mm also give better results than 10 mm systems, whereas 8 mm systems are a bad choice. The two systems with the highest net present value are both 60 ha centre pivots with a capacity of 12 mm on sandy soils. The height that the water is pumped also has a large influence on the profitability of the investment. In the case of the above two systems a 25 m increase in static height leads to a decrease of R65 019 in the net present value of the investment.

The four most profitable irrigation systems of these considered are on sandy soils, while six of the seven systems with the lowest profitability are on clay soils. The soil type that is to be irrigated can therefore affect the profitability of centre pivot investment to a large extent.

An important conclusion is that a 60 ha centre pivot with a capacity of 12 mm and a static height of -15 m irrigating sandy soils, is the most profitable alternative of the eighteen investments considered in the Southern Free State sub-region.

Production and price risk of a wheat/maize/cotton crop rotation system cause a large variation in the profitability of a centre pivot irrigation system. The difference between the lowest and the highest net present value obtained with the twenty repetitions, was greater than R200 000 for the 60 ha systems and greater than R100 000 for the 30 ha systems for all cases. A crop rotation system of wheat, maize and cotton under centre pivot irrigation in the Southern Free State sub-region is therefore very risky.

The economic profitability analysis of centre pivot irrigation systems therefore depends to a large extent on the selected crop rotation system; other crop rotation combinations will obviously give different results.

Research implications

- Production and price risks should be taken into account in profitability analysis because of the important effect they have on the results.
- The lack of simulation models for reliable simulating yields for other crops under irrigation limits the scope and value of economic analysis on irrigation. Such models should be developed.
- The typical crop rotation system followed in the Southern Free State sub-region is profitable, but the profitability of alternative crop rotation systems and the economic viability of farming units must be evaluated.
- An increase in static height decreases profitability. Analysis to determine the maximum height that water can be pumped economically should be undertaken.
- Although the selected centre pivot investments are profitable, the financial feasibility (liquidity effects) should be evaluated in a separate step. Debt use adds an additional source of risk, i.e. financial risk of potential equity loss to business risk represented in the NPV model by production and price variability, and should be taken into account in a financial feasibility analysis.
- The profitability analysis of centre pivot irrigation was carried out at the enterprise level. The analysis should be extended to the farm level to determine the economic viability of farming units in the area.

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EFFECT OF INTENSITY AND FREQUENCY OF WATER RESTRICTIONS ON THE LONG-TERM SURVIVAL OF A TYPICAL VAALHARTS FARMER

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Introduction

The main objective of this paper is to show the effect of intensity and frequency of water restrictions on the long-term financial survival of a typical Vaalharts farmer. Specific objectives are to show the effect of water restrictions and availability of working capital on crop rotation, land utilisation, level of water application and cash surplus over a ten-year period of farming.

Methodology

A model of a typical farm at Vaalharts was constructed with the emphasis on balance sheet, cash expenses and crop rotation information. For each crop investigated, a water production function was developed. Based on these water production functions, enterprise budgets were drawn up for each crop for different levels of water application. A dynamic linear programming (DLP) matrix for the typical farm for a ten-year period was then compiled. Water restrictions and availability of working capital were varied parametrically in the running of the model, and the effects on optimal crop rotation, land utilisation, water use per crop and cash surplus were recorded.

Typical farming situation

Various typical farming situations exist at Vaalharts. For the study the focus is on an owner who operates three units with a total farming area of 77 hectares and an irrigation area of 72 hectares (seventy-two of these units exist at Vaalharts.)

The capital investment per farm at 1988 prices is R735 353 (R505 850 in land and fixed improvements and R229 503 in vehicles and machinery). The medium and long term debt is R114 058. The yearly fixed expenses are shown in Table 1 and the crop rotation in Table 2. The area planted to peas is limited to 18 hectares and the area planted to cotton is 36 hectares. The normal water quota is 770 mm/year.

Water production functions

The PUTU-IR crop growth model (De Jager, Van Zyl, Kelbe & Singels, 1987) was used to develop water production functions for wheat, maize, cotton, groundnuts and peas. The model utilised daily weather data of Vaalharts to calculate relative yield (YR) for 12 seasons for each of 10 flood irrigation schedules. (See De Jager, Viljoen & Singels (1990) for details regarding irrigation schedules).

A third-order polynomial was statistically fitted to the 120 data points for each crop. The form of the equation fitted was as follows:

$$YR = a + bx + cx^2 + dx^3 \quad (1)$$

where YR is the relative yield (%), x is the water applied (mm) and a, b, c and d are constants determined by regression analysis. Variable x is the water required, at the end of the season, to fill root zone to initial content.

Table 1 Yearly farming and household expenses (at 1988 prices).

ITEM	R
Payment on long-term loan	14 341
Payment on medium-term loan (years 1-4)	10 109
Water tax	8 250
Repair and insurance (buildings)	2 260
Permanent labour	16 630
1-ton truck	2 277
8-ton truck	3 134
Electricity	1 770
Division board tax	682
Bookkeeping, telephone, etc.	5 828
Total years 1-4	65 281
Total years 5-10	55 178
Household expenses	26 574

Results are presented in Table 3.

Absolute yields (Y) were derived from relative yields (YR) using water production functions and maximum yield (YMAX) (see Table 3):

$$Y = YR/100 * YMAX \quad (2)$$

For cotton the absolute yield was not allowed to exceed 3 t/ha because of the suboptimal temperature climate at Vaalharts.

In this case maximum yield was defined as the yield obtainable at Vaalharts with above average management and zero water limitation.

Crop enterprise budgets

The water production functions were used to determine the yield of each crop for three different levels (low, medium and high) of water application. This information was combined with the enterprise budgets of the Directorate of Agricultural Economics,

Table 2 Crop rotation.

YEAR	MONTH	CROP			
1	Jun			Peas	Wheat
	Jul			Peas	Wheat
	Aug			Peas	Wheat
	Sep	Groundnuts	Cotton	Peas	Wheat
	Oct	Groundnuts	Cotton	Peas	Wheat
	Nov	Groundnuts	Cotton	Peas	Wheat
	Dec	Maize	Groundnuts	Cotton	
	Jan	Maize	Groundnuts	Cotton	
	Feb	Maize	Groundnuts	Cotton	
	Mrch	Maize	Groundnuts	Cotton	
	Apr	Maize	Groundnuts	Cotton	
	May	Maize	Groundnuts	Cotton	
2	Jun	Maize		Peas	Wheat
	Jul	Maize		Peas	Wheat
	Aug	Maize		Peas	Wheat
	Sep		Groundnuts	Cotton	Peas	Wheat
	Oct		Groundnuts	Cotton	Peas	Wheat
	Nov		Groundnuts	Cotton	Peas	Wheat
	Dec	Maize	Groundnuts	Cotton	
	Jan	Maize	Groundnuts	Cotton	
	Feb	Maize	Groundnuts	Cotton	
	Mrch	Maize	Groundnuts	Cotton	
	Apr	Maize	Groundnuts	Cotton	
	May	Maize	Groundnuts	Cotton	
3	Jun	Maize			
	Jul	Maize			
	Aug	Maize			

Table 3 Water production functions

Crop	YMAX	a	b	c	d	r^2	R	MFP	GFP
		10^0	10^{-3}	10^{-5}	10^{-8}				
	t/ha	-----	%/mm	----------			--------	cm	--------
Wheat	7	0,9	-253	166	-160	0,86	20-60	34	52
Maize	14	23,7	-246	87	-56	0,64	20-90	51	72
Cotton	5	8,0	-67	35	-21	0,88	10-100	56	70
Groundnuts	4	8,3	-132	64	-42	0,81	10-90	51	75
Peas	3	3,5	-77	138	-160	0,85	8-50	29	43

YMAX = maximum yield used to calculate absolute yields (see equation 2).

a to d = constants for water production functions (see equation 1).

r^2 = coefficient of determination.

R = range for which the function is valid.

MFP = water application rate which resulted in the marginal physical product.

GFP = maximal physical product.

(Combud, 1988) to calculate three enterprise budgets for each crop (see Table 4).

The dynamic linear programming model

The information on annual farming and household expenses (Table 1), crop rotation (Table 2), water production functions (Table 3) and enterprise budgets (Table 4) was utilised to build a dynamic linear programming model (covering a ten-year period) for the typical farm. Interest was charged at a rate of 16 per cent on working capital and any cash surplus could be invested at 10 per cent per annum. Income tax payment was not taken into account. The model was formulated to maximize cash surplus (at constant 1988 prices) over a ten-year period. (See Dent, Harrison and Woodford (1986) and Hazell and Norton (1986) for details regarding formulation of dynamic linear programming models).

The cash surplus was determined after deduction of all cash farming and household expenses, excluding

Table 4 Summary of crop enterprise budgets at 1988 prices.

	WHEAT	MAIZE	GROUNDNUTS	COTTON	DRY PEAS
LOW WATER APPLICATION					
Yield/ha (ton)	6,3	11,9	3,7	2,8	2,7
Price/ton (R)	390,0	235,0	755,4	1 122,0	744,0
Crop remains/ha (R)	120,0	180,0	255,0	0,0	85,0
Cost 1*/ha (R)	244,1	259,4	324,7	415,5	311,2
Cost 2*/ha (R)	844,1	800,7	535,6	1 143,8	617,6
Cost 2*/ton (R)	153,5	133,4	306,0	394,4	205,9
Water/ha (mm)	500,0	700,0	750,0	650,0	425,0
Income/ha (R)	2 577,0	2 976,5	3 050,1	3 141,6	2 093,8
Total cost/ha (R)	1 210,9	1 847,4	1 457,0	1 519,9	867,1
Gross margin/ha (R)	1 366,1	1 129,1	1 593,0	1 621,7	1 226,7
Gross margin/mm (c)	273,2	161,3	212,4	249,5	288,6
Income/mm (c)	515,4	425,2	406,7	483,3	492,7
Yield/mm (kg)	12,6	17,0	4,9	4,3	6,4
MEDIUM WATER APPLICATION					
	WHEAT	MAIZE	GROUNDNUTS	COTTON	DRY PEAS
Yield/ha (ton)	6,8	13,5	3,9	3,0	2,9
Price/ton (R)	390,0	235,0	755,4	1 122,0	744,0
Crop remains/ha (R)	120,0	180,0	255,0	0,0	85,0
Cost 1*/ha (R)	244,1	259,4	324,7	415,5	311,2
Cost 2*/ha (R)	844,1	800,7	535,6	1 143,8	617,6
Cost 2*/ton (R)	153,5	133,4	306,0	394,4	205,9
Water/ha (mm)	550,0	800,0	800,0	700,0	450,0
Income/ha (R)	2 772,0	3 352,5	3 301,1	3 366,0	2 242,6
Total cost/ha (R)	1 287,7	2 060,9	1 518,2	1 598,7	908,2
Gross margin/ha (R)	1 484,3	1 291,6	1 682,9	1 767,3	1 334,4
Gross margin/mm (c)	269,9	161,5	210,4	252,5	296,5
Income/mm (c)	504,0	419,1	400,1	480,9	498,4
Yield/mm (kg)	12,4	16,9	4,9	4,3	6,4
HIGH WATER APPLICATION					
	WHEAT	MAIZE	GROUNDNUTS	COTTON	DRY PEAS
Yield/ha (ton)	7,0	13,7	4,0	3,0	3,0
Price/ton (R)	390,0	235,0	755,4	1 122,0	744,0
Crop remains/ha (R)	120,0	180,0	255,0	0,0	85,0
Cost 1*/ha (R)	244,1	259,4	324,7	415,5	311,2
Cost 2*/ha (R)	844,1	800,7	535,6	1 143,8	617,6
Cost 2*/ton (R)	153,5	133,4	306,0	394,4	205,9
Water/ha (mm)	600,0	900,0	850,0	700,0	500,0
Income/ha (R)	2 852,0	3 399,5	3 276,7	3 366,0	2 317,0
Total cost/ha (R)	1 318,4	2 087,6	1 548,8	1 598,7	928,2
Gross margin/ha (R)	1 531,7	1 311,9	1 727,9	1 767,3	1 388,2
Gross margin/mm (c)	255,3	145,8	203,3	252,5	277,6
Income/mm (c)	475,0	377,7	385,5	480,9	463,4
Yield/mm (kg)	11,7	15,2	4,7	4,3	6,0

* Cost 1 remains constant while cost 2 varies according to yield.

expenses necessary for the replacement of vehicles and machinery. The present value of the cash flow was then calculated using a discount rate of 8 per cent.* Thus, in order to assess the financial viability over the 10-year period, the initial own working capital and machinery was deducted from the present cash flow value.

Results

Effect of change in availability of water

Results obtained by reducing the water quota from 1 100 to 914, 770 and 550 mm/year are given in Table 5. Own working capital of R70 000 and borrowed capital of R100 000/year were assumed. The results are summarised below.

- As water availability was reduced, the percentage of land utilised for irrigation decreased from 150/153 to 139 to 121 to 100 respectively. These percentages stayed constant throughout the 10-year period for

* An 8 percent rate was used because it was assumed to be an appropriate discount rate for a typical Vaalharts farmer.

water quotas of 914, 770 and 550 mm. With a water quota of 1 100 mm consecutive years differed, but every second year stayed the same.

- The optimal composition of crops in the rotation changed for each water application level, but stayed the same within each water application level over the 10-year period.
- With a quota of 1 100 mm, water was generally applied at a high level, but with lower quotas it was applied to all crops at a medium level.
- Discounted net cash surplus over the 10-year period was positive for water quotas of 1 100, 914 and 770 mm and negative (-R27 662) for a quota of 550 mm. This showed *inter alia* that with the present water allocation of 770 mm it is possible for a farmer to survive financially in the long run if working capital is not limited.

Table 5 Influence of change in water application on optimal crop composition and cash surplus over a 10-year period.

Water quota (mm)	1100	914	770	550
Area	ha	ha	ha	ha
YEAR 1				
Wheat	16H*	18M**	18M	42M
Maize	34H	28M	15M	0
Groundnuts	2H	0	0	0
Cotton	36H	36M	36M	12M
Dry peas	18H	18M	18M	18M
Total	106	100	87	72
Area utilised (%)	150	139	121	100
YEAR 2, 4, 6, 8 and 10				
Wheat	38H	18M	18M	42M
Maize	14H 24M	28M	15M	0
Groundnuts	0	0	0	0
Cotton	34H	36M	36M	12M
Dry peas	0	18M	18M	18M
Total	110	100	87	72
Area utilised (%)	153	139	121	100
YEAR 3, 5, 7 and 9				
Wheat	34H	18M	18M	42M
Maize	34H	28M	15M	0
Groundnuts	2H	0	0	0
Cotton	36H	36M	36M	12M
Dry peas	0	18M	18M	18M
Total	108	100	87	72
Area utilised (%)	150	139	121	100
Discounted net cash surplus over 10 years	R450 395	R332 013	R194 546	-R27 662

Assumptions

Maximum cotton = 36 ha; maximum dry peas = 18 ha; working capital (own) R70 000, working capital (loan) R100 000/year.

* H = high water application
** M = medium water application

The effect of a 50 per cent water restriction (of the present quota of 770 mm) on the typical farmer (with own working capital fixed at R70 000 plus the facility to borrow an additional R100 000 per year) was also investigated. It was found that the ability of the farmer to survive (earning a discounted net cash surplus over 10 years) depended on when the restrictions occurred. If more than 2 consecutive years of restrictions occurred in the beginning of the 10-year cycle it was impossible for the typical farmer to survive. If it occurred at the beginning of the cycle, but with restrictions every second year the farmer was unable to survive more than 3 years of restrictions. If, however, the restrictions occurred at the end of the 10-year cycle it enabled the farmer to survive more than 4 consecutive years of restrictions (assuming that the farmer had built up a cash reserve during the years without restrictions to carry him through the restriction period). Table 6 shows the impact of restrictions occurring at the beginning of a 10-year cycle. The following can be seen from the table:

- The crop composition differed between years with and without restrictions, but stayed the same during restriction years and during years without restrictions.
- During restriction years only winter crops were grown (indicating that these made better use of water than summer crops). Furthermore, wheat was irrigated at the low level of water application. During years without restrictions water application was at the medium level for all crops.
- Discounted net cash surplus was negative w water restrictions occurred during more than 2 consecutive years.

Effect of change in availability of working capital

The analysis of the effect of working capital was done with water application kept constant at 1 100 mm while the initial available working capital (own money) was parametrically varied from R200 000 to R150 000, R100 000 and R80 000. Table 7 shows some of the results. The following conclusions were drawn:

- As available working capital was reduced from relatively unlimited (R200 000 in year 1) to more limiting situations (first R150 000, then R100 000, then R80 000 in year 1) the percentage of land utilised for irrigation decreased. For year 1 it decreased from 150 to 133 to 100 to 92 per cent. The decrease in land utilisation phased out after year 1, year 3 and year 5 for values of initial working capital of R150 000, R100 000 and R80 000 respectively. This was because the accumulated cash surplus became available as working capital for subsequent years. Thus, the initial working capital shortage was overcome.
- The composition of crops in the rotation changed as the available working capital was reduced but remained constant after 1, 2 or 5 years (depending on the amount of working capital available). This was the result of accumulated cash surplus being transferred to working capital for subsequent years.
- With only R80 000 initial working capital available, only the winter crops (wheat and peas) were planted during the first two years.
- With a few exceptions water was applied at the high application rate for all crops and all levels of

Table 6 Influence of water restrictions on optimal crop composition and cash surplus over a 10-year period.

Water quota (mm)	770	770	770	770
water restriction	None	50 %	50 %	50 %
water restriction year		year 2	year 2-3	year 2-4
Area	(ha)	(ha)	(ha)	(ha)
YEAR 1				
Wheat	18M*	18M	18M	18M
Maize	15M	15M	15M	15M
Groundnuts	0	0	0	0
Cotton	36M	36M	36M	36M
Dry peas	18M	18M	18M	18M
Total	87	87	87	87
Area utilised (%)	121	121	121	121
YEAR 2				
Wheat	18M	39L**	39L	39L
Maize	15M	0	0	0
Groundnuts	0	0	0	0
Cotton	36M	0	0	0
Dry peas	18M	18M	18M	18M
Total	87	56	56	57
Area utilised (%)	121	78	78	79
YEAR 3				
Wheat	18M	18M	39L	39L
Maize	15M	15M	0	0
Groundnuts	0	0	0	0
Cotton	36M	36M	0	0
Dry peas	18M	18M	18M	18M
Total	87	87	57	57
Area utilised (%)	121	121	79	79
YEAR 4				
Wheat	18M	18M	18M	39L
Maize	15M	15M	15M	0
Groundnuts	0	0	0	0
Cotton	36M	36M	36M	0
Dry peas	18M	18M	18M	18M
Total	87	87	87	57
Area utilised (%)	121	121	121	79
YEAR 5 TO 10				
Wheat	18M	18M	18M	18M
Maize	15M	15M	15M	15M
Groundnuts	0	0	0	0
Cotton	36M	36M	36M	36M
Dry peas	18M	18M	18M	18M
Total	87	87	87	87
Area utilised (%)	121	121	121	121
Discounted net cash surplus over 10 years	R194 546	R117 149	R49 035	-R14 607

Assumptions

Maximum cotton = 36 ha; maximum dry peas = 18 ha; working capital (own) R70 000, working capital (loan) R100 000/year.

* M = medium water application
** L = low water application

working capital availability.

- For all levels of available working capital the discounted net cash surplus was positive. This shows that with enough water the typical farmer could survive when an initial amount of not less than R80 000 own working capital was available. With less than R80 000 own working capital it would be problematic to keep on farming even with an abundance of water. (If the farmer had to borrow all working capital at an interest rate of 16 per cent, he would need more than R100 000 each year to make a living).

Discussion

It must be emphasized that the results obtained were very dependent on the accuracy of water production functions, the exact specification of the dynamic linear programming model, the data used in the model and the assumptions made. A change in any of these components could have a severe impact on the results.

With this qualification in mind it can, however, be concluded that the availability of both working capital and irrigation water have major effects on the ability of a typical Vaalharts farmer to survive financially on a three-unit irrigation farm. With a water quota of 770 mm/year it can become problematic for such a farmer to survive financially over a 10-year period if the water is restricted to 50 per cent of the quota for more than 2 consecutive years in the beginning of a 10-year cycle. If the occurrence of water restrictions are spread over the 10-year cycle, it may be possible to survive more than 3 or 4 years. However, this situation will differ amongst farmers according to *inter alia* the

Table 7 Influence of change in working capital on optimal crop composition and cash surplus over a 10-year plan.

Working Capital (R)	200 000	150 000	100 000	80 000
Area	ha	ha	ha	ha
YEAR 1				
Wheat	36H*	6H	2H	48H
Maize	36H	24H	0	0
Groundnuts	0	12H	52H	0
Cotton	36H	36H	0	0
Dry peas	0	18H	18H	18H
Total	108	96	72	66
Area utilised (%)	150	133	100	92
YEAR 2				
Wheat	36H	41H**	0	53H
Maize	36H	41M**	11H	0
Groundnuts	0	0	18H	0
Cotton	36H	31H	36H	0
Dry peas	0	0	18H	18H
Total	108	113	83	71
Area utilised (%)	150	157	115	99
YEAR 3				
Wheat	36H	31H	16H	0
Maize	36H	31H	34H	0
Groundnuts	0	5H	2H	48H
Cotton	36H	36H	36H	6H
Dry peas	0	0	18H	18H
Total	108	103	106	72
Area utilised (%)	150	143	147	100
YEAR 4				
Wheat	36H	41H	38H	0
Maize	36H	41M	19H20M	12H
Groundnuts	0	0	0	18H
Cotton	36H	31H	34H	36H
Dry peas	0	0	0	18H
Total	108	113	111	84
Area utilised (%)	150	157	154	115
YEAR 5				
Wheat	36H	31H	34H	17H
Maize	36H	31H	34H	35H
Groundnuts	0	5H	2H	1H
Cotton	36H	36H	36H	36H
Dry peas	0	0	0	18H
Total	108	103	106	107
Area utilised (%)	150	143	147	149
YEAR 6, 8 AND 10				
Wheat	36H*	41H**	38H	37H
Maize	36H	41M**	19H20M	28h9M
Groundnuts	0	0	0	0
Cotton	36H	31H	34H	35H
Dry peas	0	0	0	0
Total	108	113	111	109
Area utilised (%)	150	157	154	151
YEAR 7 AND 9				
Wheat	36H	31H	34H	35H
Maize	36H	31H	34H	35H
Groundnuts	0	5H	2H	1H
Cotton	36H	36H	36H	36H
Dry peas	0	0	0	0
Total	108	103	106	107
Area utilised (%)	150	143	147	149
Discounted net cash surplus over 10 years	R593 270	R523 600	R385 035	R217 863

ASSUMPTIONS

Maximum cotton = 36 ha, maximum dry peas = 18 ha, water quota 1 100mm/year.

* H = high water application
** M = medium water application

amount of own capital available and the debt ratio.

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ECONOMIC IMPACT OF WATER RESTRICTIONS ON IRRIGATION FARMING AT VAALHARTS AND TAUNG

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Introduction

As a result of severe droughts over large parts of South Africa during the 1980's the Department of Water Affairs had to institute water restrictions on users of public water in various river systems. Restrictions were in force in these systems since April 1983. One year after the introduction of the water restrictions the Water Research Commission initiated research to determine, for the different river systems, the impact of the restrictions on various sectors of the economy for the first year of the restrictions. Three research institutions were involved in the research, namely the Institute for Social and Economic Research at the University of the Orange Free State, the Applied Social Study Centre at the University of Natal and the Bureau for Market Research at the University of South Africa. Each research institute focused on separate sectors of the economy and had to research them for each of five water schemes/systems, namely the Ngagane River Government Water Scheme, the Umgeni Catchment Area, the Riet River Government Water Scheme, the Vaal River System and the Vaalharts Government Water Scheme. In the Vaal River System the restrictions applied until 1987, and after termination the Department of Agricultural Economics at the University of the Orange Free State was asked to research the impact for the rest of the restriction period.

The purpose of this publication is to compare, for the Vaalharts area, the impact of water restrictions on the Vaalharts irrigation farmers with the impact on the Taung irrigation farmers. These two schemes are adjacent (Vaalharts in South Africa and Taung in Bophuthatswana; see Figure 1) with certain similarities, but also with important differences which make the comparison an interesting exercise.

Study area

Figure 1 shows the location of the study area with respect to national and provincial boundaries, the Vaal and the Harts Rivers, the Ghape Plateau and important towns. It also shows Taung situated immediately to the north of Vaalharts. In Table 1 the irrigation characteristics at Vaalharts are compared with those at Taung. Similarities in irrigation characteristics in the

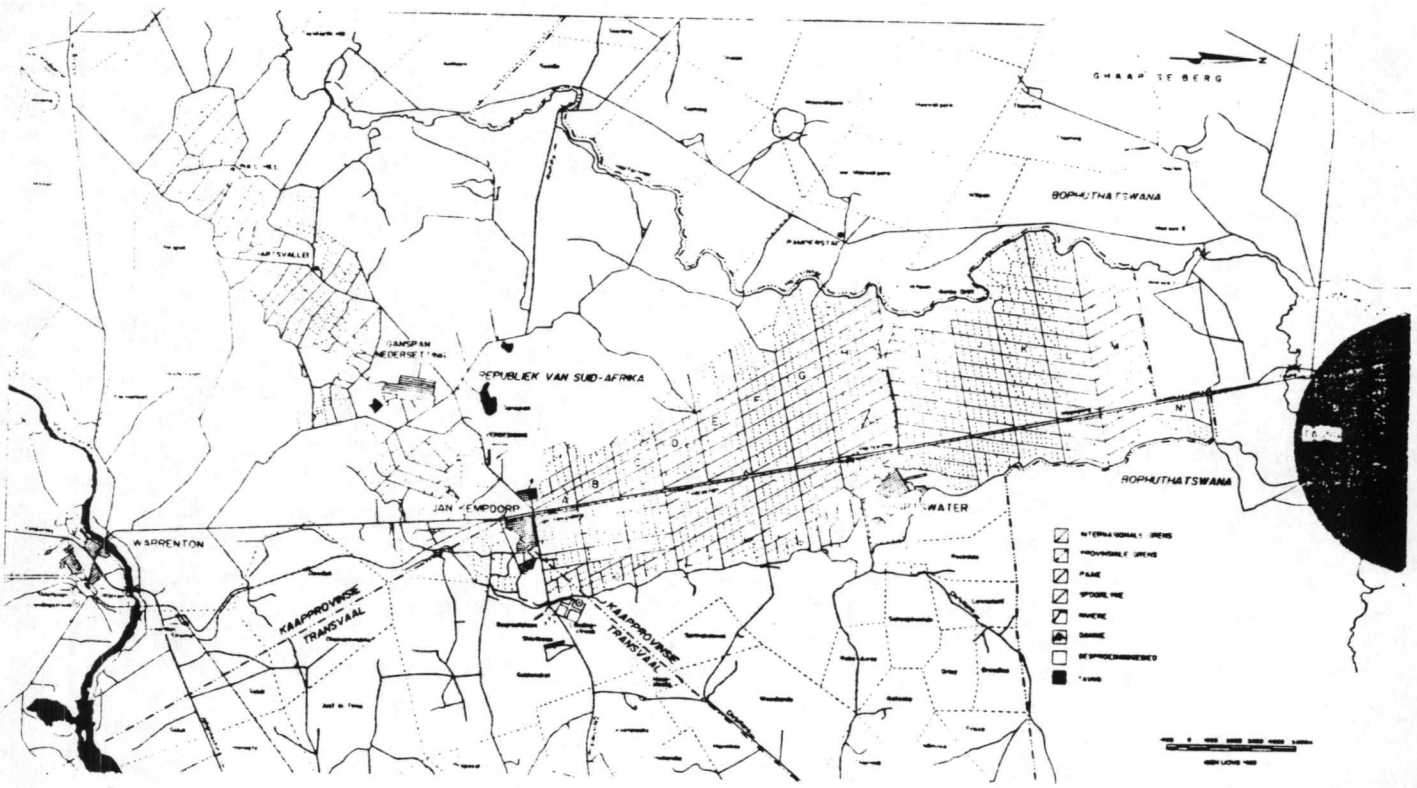


Figure 1 Vaalharts Government Water Scheme.

two areas include climate, soil type, main crops planted, water source and the water allocation, both normally and during periods of water restrictions. However, important differences exist in respect of irrigation systems, ethnicity of farmers, size of farms and ownership and management of irrigation land. At Vaalharts the main irrigation method is flood irrigation, while at Taung it is predominantly sprinkler irrigation with centre pivots. At Vaalharts all farmers are white South Africans, while at Taung all are black Bophuthatswana citizens. Sizes of farms at Vaalharts differ and are on average 45 ha, while all farms are more or less of the same size (10 ha) at Taung. Private ownership and management of irrigation land prevails at Vaalharts, while at Taung the system consists of rented land under predominantly centralised management. Also important is the tradeability of land and hence the opportunity to disengage from irrigation farming. This view is considered to be of relevance to the Taung situation from the sociological impact point of view.

Table 1 Similarities and differences in irrigation characteristics at Vaalharts and Taung, 1983 to 1988.

Similarities:		
Soil type:	Hutton form	
Main crops:	Wheat, cotton, lucerne and peas groudnuts, cotton, maize	
Climate:	Average yearly rainfall = 440 mm Average yearly temperature = 18.5°C	
Water source:	Vaal River	
Water quota:	770 mm/year	
Water restrictions:	1983/84 - 58% 1984/85 - 50% 1985/88 - 45%	
Differences:	**Vaalharts**	**Taung**
Enlisted area (ha)	29117	4447
Irrigated area (ha)	30122	3500
Average farm size (ha)	45	10
Irrigation system	Flood	Sprinkler/Pivot
Ethnicity of farmers	White (S.A.)	Black (Boph.)
System of land tenure	Landownership	Rented land
Farm management	Private	Central Place

Methodology

The methodology to determine the impact of water restrictions was developed during the course of the research. On the theoretical level it boiled down to determining the viewpoint (individual, regional or national) from which the determination should be done, choosing between the "before" and "after" as against the "with" and "without" approach, identifying potential impacts on a particular sector and determining standards for measuring each impact.

The viewpoint is important, because it determines which impacts to include in measurement and which standards to apply. In the case of the research, measurement was done from a national point of view in order to determine the impact on the national economy and the "with" and "without" approach was used. The latter means that the situation resulting from the application of water restrictions was compared with the situation that should have prevailed if it was not necessary to impose restrictions. The difference in impacts between the two situations is assumed to be the impact of the water restrictions.

Table 2 presents a classification of the potential impacts on irrigation farming. It can be seen from the table that a distinction was made between tangible and intangible, short term and long term and between direct and indirect impacts. Tangible impacts refer to influences which can be measured in monetary terms, while intangible influences can only be described in non-monetary quantitative and/or qualitative terms. Short term impacts are impacts which are only present during the duration of water restrictions, while long term impacts persist after the water restrictions measures have been lifted. Direct impacts are impacts experienced by parties who are directly affected by water restrictions, while indirect impacts refer to impacts on parties who are connected (doing business) with parties experiencing direct impacts.It is c from the potential impacts that various measures are needed to measure them. As far as monetary measures are concerned, great care has to be taken to determine the correct prices (market or shadow) to be used. In the case of the study, base year market prices were used. With this approach it was easier to compare the relative impact of water restrictions between years.

Practical aspects of the methodology dealt with identifying data sources, developing questionnaires, sampling, gathering and processing data. The main data sources were the Vaalharts and Lesedi agricultural co-operatives and the farmers on the schemes. Both co-operatives were approached for data while a questionnaire was developed and completed by personal interview involving a representative sample of farmers at Vaalharts. Processing of data was done mainly by hand.

Results

For the purpose of this analysis the focus will be on the direct tangible impacts which will be discussed under the following headings:

- Utilisation of irrigation area and crop yields
- Livestock enterprises
- Water supply
- Labour
- Additional income
- Long-term planning

Utilisation of irrigation area and crop yields

Table 3 gives an overview of the area planted at Vaalharts and Taung during the period of restriction.

Table 2 Example of tangible and non-tangible impacts of water restrictions on irrigation farming.

Tangible impacts
Short Term Direct
- Reduce area cultivated and irrigated
- Reduce income of farmers
- Reduce crop yields / total volume produced
- Change enterprise composition on farms
- Change type and quantity of inputs bought by farmers
- Investment in water supply systems
- Increase debt of farmers
- Reduce employment of labourers by farmers
- Promote bankruptcy amongst farmers
- More efficient utilization of available water
- Undertaking of contract work off the farm to compensate for loss in farm income
- Saving in input costs
Short Term Indirect
- Decline in turnover and profits of institutions doing business with farmers
- Decline in tax income of the central government resulting from reduced income by farmers
- Increase in subsidy payments by the central government
- Changing in financial position of financial institutions
- Loss in export currency as a result of reduced exports of irrigation crops
Long Term Direct
- Damage to perennial crops
- Increased salinity of irrigation soils
- Change in debt of farmers
- Decrease in numbers of farmers
- Lowering in property value of irrigation land
- Changes in long-term planning
- Increased protection against future water restrictions as result of the necessary provision of own water facilities in the short term
- More efficient utilization of water based on the greater awareness of the value of water
- Outdating of machinery and implements in cases where water restrictions were applied for a number of years
Long Term Indirect
- Termination of business activities by enterprises who did business with the farming community
- Increased interest cost as the result of increased debt
- Expansion of other indirect short term impacts to the long term
Non-tangible impacts
Short Term
- Activities in and around the house
- Curtailment of sport and recreational activities
- Degradation of the quality of life of irrigation communities
- Negative impact on the state of mind of members of a household
Long Term
- Continuation of short-term impacts where the restrictions applied for a number of years
- Reduction in numbers of farmers
- Deteriorating towns and declining population
- Depopulation of rural area
- Increase in social problems such as misuse of liquor, theft, etc.

From the table it is clear that (although the same restrictions applied in both areas) a larger portion of the available land was utilised at Vaalharts than at Taung. In the case of Vaalharts there was a tendency for farmers to try to secure a good winter crop (wheat or peas) with the allotted water. A consequence of this practice was insufficient water to irrigate summer crops (maize and groundnuts). Average per-hectare profit during the 1984/85 year for instance confirmed this. For groundnuts and maize it was only 16 and 12 per cent of profits in normal years, while for peas and wheat 40 and 45 per cent of profits in normal years were obtained.

Table 3 Area planted at Vaalharts and Taung during the restriction period, 1982 to 1988.

Year	Vaalharts		Taung	
	ha	%	ha	%
1982/83	47386	100	5100	100
1983/84	39905	88	2550	58
1984/85	33683	75	2496	53
1985/86	33711	75	3013	61
1986/87	30039	66	2958	58
1987/88	36005	80	3158	61

At Taung the cropping area was reduced but the water application per hectare stayed the same as for a normal year. No reduction in yield per ha was thus recorded.

Livestock enterprises

Thirty two per cent of the Vaalharts farmers kept livestock, and 94 per cent of these farmers mentioned that their livestock enterprises were detrimentally affected by the water restrictions. The negative impact was predominantly on the income side and amounted to R1 118 000 for the total area in 1984/85. The dairy enterprise suffered the greatest "loss" (R823 000), followed by sheep (R222 000). On the cost side there

was a positive effect of R66 000 in total, due to the replacement of fodder that was normally bought, by cheaper, farm-produced fodder.

At Taung no negative impact was recorded on the livestock enterprise.

Water supply

Due to the fact that a smaller quantity of water was used during the restriction period there was a saving in water cost to the Vaalharts farmer. The total saving, including a reduced water tariff, amounted to R1 580 000 for 1984/85. In contrast to this saving, additional investments of R4 970 000 were made on boreholes, borehole equipment, sprinkler irrigation systems, pumps, pipes and dams. Because these investments were made as a result of the water restrictions, they were fully booked against the restrictions.

At Taung, since farmers did not pay for water there was no saving in water cost as a result of less water use. No additional investment in water supply equipment was made as a result of the restrictions but capital cost, however, accumulated.

Farming debt

The farming debt increased considerably during the period of water restrictions. For instance, after the second year of water restrictions at Vaalharts the total loans of farmers increased by R26 610 000. In the case of Taung the total outstanding debt of farmers also increased dramatically. Between 1983/84 and 1987/88 (the total period of water restrictions) the debt increased by R6 350 000. These increases in debt/loans were not taken into account separately as an impact of water restrictions, because they would have led to a double counting of the monetary loss. This is because farmers took up loans to help them bridge the negative financial impact of the water restrictions, the latter of which was fully recorded as an impact of the restrictions. Although the interest cost on loans should be included as an effect, it was not done in the research. Difficulty to separate loans as a result of water restrictions from other loans was the main reason for this "conservative" approach.

Labour

As a result of declining activities on farms, farmers decreased their labour force. At Vaalharts the decrease in permanent black labour was 37 per cent resulting in a R1 014 000 saving in labour expenses for farmers for the 1984/85 year. The use of seasonal labour decreased by 65 per cent.

At Taung the farmer himself supplied permanent labour. No farmers stopped farming as a result of water restrictions, but unemployment amongst casual labour increased. In full-time job equivalents the total decrease in casual labour jobs was 255 units with a total wage of R222 900 in 1984/85.

Additional income

Twenty-six per cent of Vaalharts farmers became involved in other economic activities as a result of the water restrictions. Fourteen per cent of farmers' wives took full-time jobs outside farming. The total additional income for the 1984/85 year was R293 000.

The government of Bophuthatswana introduced a labour scheme in 1985 to counter unemployment at Taung. Labourers were paid a wage of R3.50 per day and had to do maintenance work. The amount paid out was not booked against water restrictions, because the general recession in the economy also made a contribution to unemployment.

Long-term planning

A total of 76 per cent of Vaalharts farmers mentioned in 1985 that they had postponed long-term projects due to water restrictions. Improvements of existing infrastructure was the activity generally affected most; 35 farmers mentioned it. Other projects postpc were the introduction of new irrigation systems, expansion of irrigation area and the establishment of perennial crops.

At Taung the expansion and upgrading of irrigation systems were also postponed. Money was also provided for necessities like housing and maintenance of existing irrigation systems.

Discussion and conclusion

Table 4 presents the total net direct tangible impact of water restrictions on Vaalharts and Taung over the restriction period. In order to compare the relative severity of the impact in the two areas it is necessary to examine the net impact per hectare. The other figures are not directly comparable, because the total irrigation area and the average farm size differ considerably between the two areas.

It is clear from the per hectare figures that the overall impact was more severe at Vaalharts than at Taung. This is especially obvious for the first two years of the restrictions after which the difference tended to phase out. The main reasons for the much higher impact at Vaalharts during the first two years were investment by Vaalharts farmers in additional water supply and irrigation infrastructure to try to compensate for the negative effects of water restrictions (which the Taung farmers did not do), and also attempts by farmers at Vaalharts to plant too large an area with the available water, while central management at Taung from the outset decided to reduce the area and to apply water at the same rate as under normal quota. (However, this does not necessarily mean that reducing the area and applying the water at the same rate as with a normal quota is the optimum strategy for a water restriction situation). Another reason for the lower per hectare impact at Taung was that although the same percentage of water restrictions applied to both areas, in the case of Taung

the real restriction was much less, because the water allocation was based on the total enlisted area of which only 79% has been developed as irrigated land. Relatively more water was thus available per hectare at Taung than at Vaalharts. Also, where the Vaalharts farmers were fully responsible for all costs involved in irrigation farming, some of the overhead cost at Taung was carried by large organisations, viz. Lesedi and Agricor.

An interesting fact which should finally be borne in mind when evaluating the relative impact, is that the Taung farmers had no security base for their accumulated debt that resulted from the water restrictions. In the case of Vaalharts the security base was the value of privately owned farm property.

Table 4 Net tangible impact (R) of water restrictions on irrigation farmers at Vaalharts and Taung, 1983 to 1988.

Year	Vaalharts	Taung
	In total	
1983/84	24 716 614	1 472 866
1984/85	20 033 016	1 143 493
1985/86	15 164 558	1 715 485
1986/87	18 132 902	2 483 294
1987/88	13 002 854	1 107 225
	Per farmer*	
1983/84	38 026	3 796
1984/85	30 820	2 947
1985/86	23 330	4 421
1986/87	27 897	6 400
1987/88	20 004	3 276
	Per ha*	
1983/84	821	421
1984/85	665	327
1985/86	504	490
1986/87	602	709
1987/88	432	316

* These figures are calculated for the irrigated areas.

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VIABLE SOLUTIONS TO THE WATER TABLE PROBLEM IN THE LOWER ORANGE RIVER AREA

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Abstract
The decline in crop production as a result of high water tables and soil salinity has been investigated in six irrigation districts along the lower Orange River. The main causes of the permanent water table within 1.2 m of the soil surface were found to be over-irrigation, leaking canals, stratified soils, lack of natural drainage, impermeable underlying material, topography and irrigation on the foothills outside the alluvium. The problems, solutions to which are proposed, can be addressed by farmers individually or by the relevant irrigation board. Individual farmers are permitted to drain their land under the Soil Conservation Act, while irrigation boards fall under the jurisdiction of the Water Act with subsequent different subsidy and loan facilities.

Introduction

A high water table and salt accumulation in the soil severely impeded crop production on the irrigation schemes of the lower Orange River. The affected areas enlarged with time and farmers were forced to replace dying vineyards with cash crops and, in severely affected cases, lands were withdrawn from irrigation as even the most salt-resistant crops died. A multidisciplinary approach to the solution of the water table problem in the lower Orange River area was therefore initiated.

Method

A team consisting of an economist, a soil scientist and an engineer was appointed to investigate the problem and to report on the underlying causes, present possible solutions, and examine the economic and financial feasibility of the solutions.

Surveys done by the investigating team from 1987 to 1989 showed that 45% to 75% of the area of individual irrigation districts has a permanent water table. However, it was found that only a very small area is saline and brack enough to prevent plant growth.

The proposed solutions for the different irrigation districts varied according to the cause of the water table and the feasibility of implementing corrective measures.

An economic investigation of the alternatives was done by evaluating the present economic situation and comparing it to the future expectations of the different solutions.

All the necessary information described here has been extracted from De Jager, Burger, Le Roux, Human, Stassen, Van der Ryst, Viljoen & Oosthuizen (1987), Le Roux, Van der Ryst, Viljoen & De Jager (1989) and Van der Ryst C. & Viljoen M.F. (1990).

Causes

Various factors contribute to the water table. Salts accumulate in the topsoil and on the soil surface, in cases of where the permanent water table is less than 500 mm deep.

Over-irrigation

Due to the continuous availability of water since 1972, with the commissioning of the Verwoerd Dam, there has been an overall increase in the rate of irrigation application in the study area. Additional areas have been developed for irrigation since 1972. This has increased the average intake of water in all the water districts investigated.

Canal leakage

The earth canals are constructed from material with a low clay content and high permeability, resulting in severe leakage. A water table exists next to all earth canals and in some instances even next to concrete lined canals. This phenomenon was observed at all the locations investigated.

Increased leakage is possibly due to a lack of clay particles in the irrigation water which would seal the canals. This could however not be proved beyond reasonable doubt. Neither could the contribution to the water table from concrete lined canals be accurately assessed.

Soils

The soils are generally sandy with a clay content varying between 10% and 20%. The silt content tends to have similar values. The soil is classified as a Dundee soil form with stratified alluvium as subsoil. Although the topsoil is well mixed by ploughing, the underlying subsoil is severely stratified which has a negative influence on the hydraulic conductivity and crop root development. Root development of the crops, especially vines, is retarded, even on well drained lands, due to these unfavourable conditions. A prerequisite for all internal drainage works is the alleviation of the stratification present in the alluvium by deep ripping or ploughing, to improve the

hydraulic conductivity of the subsoil. This was found true for all the plots investigated in all irrigation board areas.

Channels
On Kanoneiland a natural channel is used to transport irrigation water onto the fields, resulting in saturation of the surrounding area due to lateral drainage. The use of this channel as a supply canal reduces the existing natural drainage facilities.

Impermeable underlying material
Wherever it was possible to reach the underlying material with augers, impermeable dorbank or solid rock was identified.

Topography
As the underlying material is impermeable and deep percolation cannot take place, excess irrigation water must drain laterally to natural channels and the river. Leaking canals situated on the levees cause hydraulic pressure to build up in the soil thus preventing lateral drainage and further contributing to the water table already permanently present.

Irrigation of the foothills
The practice of irrigating the areas outside the alluvium and above the main water canals is expanding rapidly. The highly permeable soil in these areas is mainly of the Hutton form. Excess irrigation water drains effectively, including laterally to the existing irrigation areas on the river alluvium. The geological formations vary from permeable vertically orientated shifts to an impermeable granite/gneiss. This situation is apparent at Friersdale and Noord-Oranje irrigation districts.

Solutions

General
Individual farmers in the RSA are responsible for the drainage of their irrigation farms or plots, in terms of the Soil Conservation Act. The act makes provision for drainage works to be subsidized as well as a loan facility at 8% interest payable over a period varying from 10 to 20 years. The subsidy is paid according to fixed tariffs which are revised from time to time by the Department of Agriculture. The construction of drainage systems on an irrigation farm and the associated costs, consists of two independent components viz. the cost to drain an irrigation plot internally; and the cost of drainage water disposal to an approved waste site. Possible solution scenarios can be classified under one of four physical and/or financial situations:

(a) An owner is solely responsible for both components of the drainage scheme. He thus qualifies for a subsidy and loan for both components under the Soil Conservation Act.

(b) If more than one owner is involved, they are individually and separately responsible for the first component according to the Soil Conservation Act. The provision of the disposal point is designed as a communal scheme and the cost and subsidy thereof is divided in proportion to the area drained by each individual participant farmer. This type of scheme qualifies for a loan and subsidy under the Soil Conservation Act.

(c) In the case where two or more farmers wish to drain their properties, a minor irrigation board scheme may be implemented to supply the disposal point. The difference between this type of scheme and the communal scheme under (b) lies in its financing. As this is classified as a board scheme, the financial help for which the board qualifies under the Water Act is a subsidy of 33⅓% of the cost and a loan to finance the remainder of the cost at 16% interest, payable over a period of 30 years. The loan is repaid by the board by means of a differential tax levy on the irrigators who benefit directly from the scheme. This difference in financing facilities exists because an irrigation board operates under the Water Act while the Soil Conservation Act is applicable to individual farmers.

(d) The last alternative is where the board provides a central drainage system in the irrigation district. Individual farmers are still responsible for the internal drainage of their plots under the Soil Conservation Act and the irrigation board levies a tax to finance the central drainage scheme. Under the Water Act this type of scheme qualifies for a subsidy of 33⅓ of the cost as well as a loan to finance the remainder at 16% interest, payable over 30 years. As a result, all the farmers in the irrigation district are burdened with the cost of the central drainage scheme whether they benefit from this facility or not.

Proposed solutions
The solution to the problem lies not in a single act but rather in a number of measures which affect different aspects of the production system. These measures were proposed for all the irrigation board districts investigated.

(i) Preparation of the soils by very deep ripping and ploughing to alleviate the stratification present in the alluvial soil.
(ii) The selection of adapted plant material and root stocks.
(iii) The internal drainage of the wet areas.
(iv) The introduction of a scheduling programme to minimize over-irrigation.
(v) The phased concrete cladding of irrigation

canals to minimize leakage.

(vi) The clearing and maintenance of the natural river channels through the districts to ensure the effective drainage of excess water.

(vii) The effective drainage of surface water that accumulates naturally in any low lying area.

Due to the topography of the river course, the second component namely the supply of the disposal point, was the major engineering problem encountered. Generally a levee is found immediately next to the river with the irrigated field on the low lying alluvium between the levee and the surrounding foothills. The least expensive solution suggested in all the districts, invariably implied breaching of the levee and construction of drainage structures to depths of up to 4 metres in saturated soil. These deep excavations are usually problematic due to slipping and hence particular care needed to be taken in the construction process. It was suggested that excavations should be temporarily drained to prevent cave-ins and this cost was reflected in the estimate of construction costs.

Economic investigation

Introduction

The aim of the economic investigation was to make a financial and economic evaluation of the different solutions to the water table problem. The following procedure was applied to each irrigation district:

- The present economic situation was described, addressing aspects that include number of farms, farm sizes, tenure system, age distribution of farmers, pattern of land use, crop composition, income statement and the ability of farmers on different sized farms to afford development works, i.e. to obtain a cash surplus after all farming and household expenses had been deducted.
- Next a prediction of crop composition, crop areas, crop yields, prices and expenses for a period of 30 years on a yearly basis, was made. This was done for the different scenarios, as well as examining the case of taking no action.
- Development budgets were then drawn up for each of the proposed solutions.
- After this the proposed solutions were economically evaluated.
- Finally the different solutions were tested for financial viability.

For the purpose of this exposition the focus will be on the Friersdale irrigation area.

Present economic situation

Only two aspects of this stage will be discussed, namely the income statement and the affordability to the farmers.

An income statement (Table 1) was drawn up for the affected area to show the income obtained from each crop, the composition of expense and the net cash surplus. This statement plays a crucial role in estimating the net cash flow for the total affected area as well as for different sized farms. It also provides basic information for the construction of the long-term development budgets.

Information on the ability of farmers to pay is important for the determination of the financial affordability of the various proposed solutions and this information is also gleaned from the income statement. It was found that the ability to pay differed amongst farmers according to size of farms, enterprise composition, extent of farming debt and extent of the drainage problem on individual farms.

Prediction of the future

It is predicted that the situation will deteriorate further if the water table problem is not solved. As an example it is estimated that over the next 25 years, the area presently under rotation crops will deteriorate to waste land and the area under vineyard to rotation crops, with the exception of the 30% of land already drained which is assumed to stay constant over time. Nevertheless, for evaluation purposes it was assumed that without solving the problem the present situation would continue without any further deterioration. It was further assumed that the water table problem would be solved entirely by any of the alternative solutions here described and that the area planted to vineyards would increase over time so that after 25 years vineyards would occupy the total area. Details of predicted changes in crop area over time are specified in the development budgets.

Development budgets

Table 2 is a summary of a development budget on an annual basis. Such budgets which specify the area planted to different crops, farming income, farming expenses, development costs and certain other financial and economic criteria, are the basis for the financial and economic evaluation of the various solutions. Besides the assumptions that apply to the income statement, the following two procedures were adopted in constructing these budgets:

- Any expected increase in crop yield over time as a result of technological development was not taken into account.
- Constant 1988 prices were used under the assumption that the relationship between prices will remain constant over time.

Economic evaluation

Economic evaluations of two solutions were made from a communal viewpoint, for the total area affected. Loans, taxes and subsidies were not taken into account. The two systems were (i) a centralized drainage system and (ii) a system of drainage by individual farmers. In the latter case adjacent farmers use a communal drain and disposal point. It was found that both systems were economically viable, but that

Table 1 Income statement, Driersdale affected area, 1987/88.

	HA	TON	R/TON	TOT.INC	VAR.C/HA	TOT.VAR.C	TOT.G.MARG	FIXED.C	NFI	INT.C	NFP	HH+TAX	NET.CFL
VINEYARD													
Total	126			936306		344051	592255	137620.4	454634.6	80010	374624.6		
FLOOD PLAIN													
Raisin-A	40	22	315	277200	2152	86080	191120	34432	156688	25400	131288		
Raisin-B	49	18	315	277830	2065	101185	176645	40474	136171	31115	105056		
Wine-A	10	28	250	70000	2325	23250	46750	9300	37450	6350	31100		
Wine-B	7	22	250	38500	2152	15064	23436	6025.6	17410.4	4445	12965.4		
Grapes-A	8	14	1828	204736	11764	94112	110624	37644.8	72979.2	5080	67899.2		
NON FLOOD PLAIN													
Raisin-A	12	18	315	68040	2030	14360	43680	9744	33936	7620	26316		
ROTATION													
Total	182			506363		262462	243901	104984.8	138916.2	115570	23346.2		
FLOOD PLAIN													
SUMMER													
Cotton-A	28	2.2	1122	69115.2	1130	31640	37475.2	12656	24819.2	8890	15929.2		
Cotton-B	80	1	1122	89760	844	67520	22240	27008	-4768	25400	-301268		
WINTER													
Wheat-A	0	2.5	345	0	1089	0	0	0	0	0	0		
Wheat-B	80	1.9	345	69000	859	68720	280	27488	-27208	25400	-52608		
Lentil-A	14	3	1313	34925.8	576	8064	26861.8	3225.6	23636.2	4445	19191.2		
Peas-A	14		744	31248	757	10598	20650	4239.2	16410.8	4445	11965.8		
Fallow	0												
ALL YEAR													
Lucern-A	6	18	125	13500	726	4356	9144	1742.4	7401.6	3810	3591.2		
NON FLOOD PLAIN													
SUMMER													
Cotton-A	0	2.2	1122	0	1130	0	0	0	0	0	0		
Cotton-B	12	1	1122	13464	844	10128	3336	4051.2	-715.2	3810	-4525.2		
WINTER													
Wheat-A	0	5	345	0	1089	0	0	0	0	0	0		
Wheat-B	12	2.5	345	10350	859	10308	42	4123.2	-4081.2	3810	-7891.2		
ALL YEAR													
Lucern-A	56	25	125	175000	913	51128	123872	20451.2	103420.8	35560	67860.8		
TOTAL	308			1442669		606513	836156	242605.2	593550.8	195580	397970.8	220000	177970.8
											FARMERS	11	

An A behind a crop name means soil without a water table problem
An B behind a crop name means soil with a water table problem
TOT.INC = Total income, VAR.C/HA = Variable cost per hectare, TOT.VAR C = Total variable cost, TOT.G MARG = Total gross MARGIN, FIXED.C = Fixed cost, NFI = Net farm income, INT.C = Interest cost, NFP = Net farm profit, HH+TAX = Household EXPENSES AND INCOME TAX, NET.CFL = Net cash flow

Table 2 Extract of development budget, Friersdale, 1989, individual drainage.

YEARS	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999
VINEYARD:	126	126	127	133	139	145	151	157	163	169
FLOOD PLAIN	114	114	114	119	124	129	134	139	144	149
Raisin-A	40	40	89	93	97	101	105	109	113	117
Raisin-B	49	49	0	0	0	0	0	0	0	0
Wine-A	10	10	17	18	19	20	21	22	23	24
Wine-B	7	7	0	0	0	0	0	0	0	0
Grapes-A	8	8	8	8	8	8	8	8	8	8
NON FLOOD PLAIN	12	12	13	14	15	16	17	18	19	20
Raisin-A	12	12	13	14	15	16	17	18	19	20
ROTATION:	182	182	181	175	169	163	157	151	145	139
FLOOD PLAIN	114	114	114	109	104	99	94	89	84	79
Cotton-A	28	28	108	105	102	99	94	89	84	79
Cotton-B	80	80	0	0	0	0	0	0	0	0
Wheat-A	0	0	80	78	75	73	70	66	62	58
Wheat-B	80	80	0	0	0	0	0	0	0	0
Lentils-A	14	14	14	14	13	13	12	12	11	10
Peas-A	14	14	14	14	13	13	12	12	11	10
Lucerne-A	6	6	6	4	2	0	0	0	0	0
NON FLOOD PLAIN	68	68	67	66	65	64	63	62	61	60
Cotton-A	0	0	11	10	9	8	7	6	5	4
Cotton-B	12	12	0	0	0	0	0	0	0	0
Wheat-A	0	0	11	10	9	8	7	6	5	4
Wheat-B	12	12	0	0	0	0	0	0	0	0
Lucerne-A	56	56	56	56	56	56	56	56	56	56
TOTAL	308	308	308	308	308	308	308	308	308	308
INCOME	936306	936306	1014216	1054606	1094996	1135386	1175776	1216166	1256556	1296946
Vineyard	506363	506363	705388	683668	661896	640125	614135	588144	562154	536164
Rotation crops	1442669	1442669	1719604	1738274	1756892	1775511	1789911	1804310	1818710	1833110
TOTAL										
EXPENSES										
Variable cost	606513	606513	673915	748065	744288	747412	747769	748126	748484	748841
Fixed cost	242605	242605	269566	299226	197715	298965	299108	299251	299393	299536
Interest cost	195580	195580	195580	195580	195580	195580	195580	195580	195580	195580
Household Exp + Tax	220000	220000	220000	220000	220000	220000	220000	220000	220000	220000
TOTAL	1264698	1264698	1359061	1462871	1457584	1461957	1462457	1462957	1463457	1463957
Net cash before dev cost	177971	177971	360543	275403	299309	313554	327454	341354	355253	369153
Marg net cash before dev cost	-1	-0	182572	97432	121338	135583	149183	163383	177282	191182
Net cash without drainage	177971	177971	177971	177971	177971	177971	177971	177971	177971	177971
Development cost										
Internal drainage	547600	0	0	0	0	0	0	0	0	0
Soil preparation	0	0	1140	6840	6840	6840	6840	6840	6840	6840
Maintenance	0	3700	3700	3700	3700	3700	3700	3700	3700	3700
Pumping cost	614200	17760	17760	17760	17760	17760	17760	17760	17760	17760
TOTAL	1161800	21460	22600	28300	28300	28300	28300	28300	28300	28300
Net cash after dev cost	-983829	156511	3379343	247103	271009	285254	299154	313054	326953	340853
Marg net cash after dev cost	-1161800	-21460	159972	69132	93038	107283	121183	135083	148982	162882
Cum net cash with drainage	-983829	-827318	-489375	-242272	28737	313991	613145	926199	1253152	1594005
Cum net cash without drainage	177971	355942	533913	711884	889855	1067826	1245797	1423768	1601739	1779710
Summary:										
	Pre dev cost net cash			13455519						8116389
	At 6% discounting			5296518						2846777
	At 10% discounting			3312938						1635221
	At 15% discounting			2104723						936169

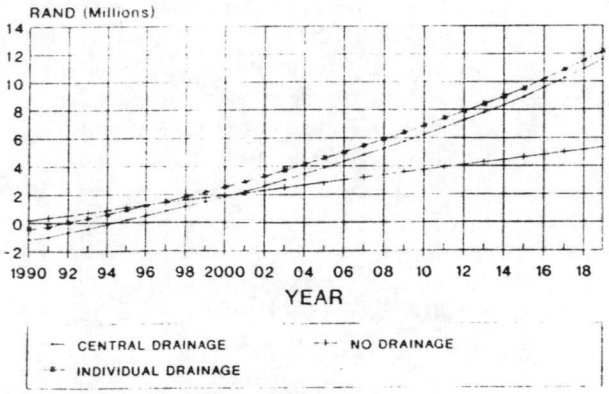


Figure 1 Cummulative net cash flow for total affected area at Friersdale.

the individual system was superior with a higher net present benefit and net benefit cost ratio. Figure 1 which shows the cumulative net cash flow of the two systems and compares it with the situation without drainage, confirms the benefit from drainage and the superior benefit from the individual drainage system. This cumulative net cash flow was R12.2 million for individual drainage, R11.6 million for centralized drainage and R5.3 million if no drainage was undertaken.

Financial viability

The situation for typical 13 ha and 20 ha farms was investigated, to determine the financial viability. Only the scheme with the lowest cost was evaluated, because the ability of farmers to pay was not favourable. The planned cash flow over a 30-year period was determined for the selected scheme and compared to the situation without drainage. Next the trends of the yearly net cash flows were examined. If the annual net cash flows were negative for more than 3 consecutive years, the scheme was not considered executable from a financial viewpoint under the fiscal arrangements that applied. Figure 2 shows the trend of the net cumulative cash flow for a farmer on a 13 ha farm with 5 ha cotton on waterlogged soil and 8 ha vineyard on well drained soil. It is clear from the figure that it will be financially worthwhile and affordable for a farmer with average household expenses of R21 000 per year and a debt ratio of 22.4% to drain his farm under the subsidy system that applies. However, should the starting position be different, for instance a crop composition of 5 ha vineyard and 8 ha cotton, while all other factors remain unchanged, it would not be financially viable for the farmer to drain his land as is shown in Figure 3.

On a 20 ha farm, however, the farmer will not be

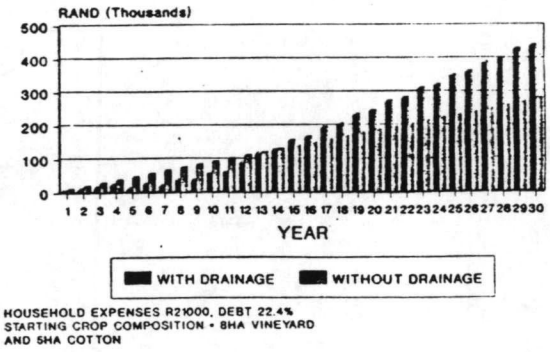


Figure 2 Cumulative net cash flow after subsidy - Friersdale farmer on 13 ha farm.

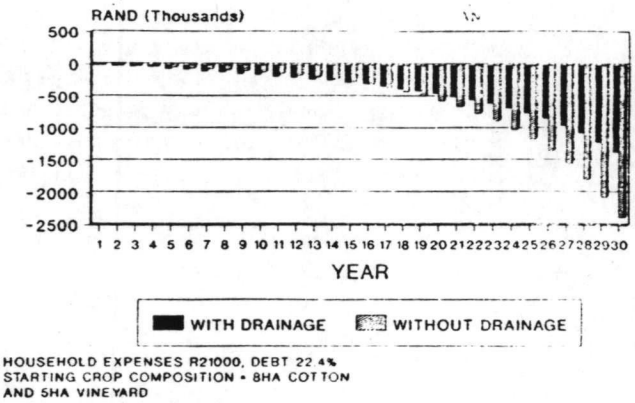


Figure 3 Cumulative net cash flow after subsidy - Friersdale farmer on 13 ha farm.

able to afford drainage under the present subsidy scheme if he has average yearly household expenses of R27 000 and a debt ratio of 22.4%. It may be beneficial over a longer period as illustrated in Figure 4. Drainage can become affordable in this case, with the provision of bridging finance.

Conclusions

(i) The waterlogging on the flood plains of the Lower Orange River is a worsening problem with the main causes being the following:
- A natural permanent water table exists due to the close proximity of highly permeable arable soils to the water on the flood plain of the river.
- Over-irrigation and leaking canals contribute to the accumulation of water in the soil.
- The lowlands between the levee and the foothills act as an area of concentration for all surface run-off water, which also contributes

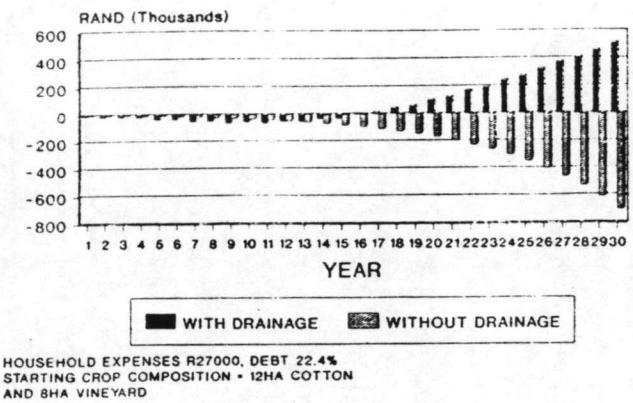


Figure 4 Cumulative net cash flow after subsidy - Friersdale farmer on 20 ha farm.

to the existing natural water table.

- The stratified nature of the subsoil affects the hydraulic conductivity of the soil profile detrimentally. This results in a further building-up of the water table.

(ii) The extent of the water table problem is severe in the sense that crop production on between 45% and 75% of the irrigated area, on the different irrigation schemes, is detrimentally affected.

(iii) The water table problem has become more severe with the passing of time, and it is expected that if it is not solved, irrigation farming might cease in certain areas.

(iv) Drainage is the only feasible solution. Waterlogged soils can be improved from a low to a high yielding resource within one season.

(v) Although alternative solutions for the water table problem were suggested for each irrigation area, the solution is never a single action but always requires several measures.

(vi) Most solutions were economically viable with benefit/cost ratios larger than one and impressive net cash flows. The solutions which call on small groups of farmers to drain communally were always more beneficial financially than a central drainage system.

(vii) Financial viability differed considerably between farmers due to the influence of factors such as farm size, cropping programme, extent of water table problem, debt ratio and household expenses. A significant number of farmers in each irrigation area are not in a position to undertake drainage works under the existing subsidy and loan scheme. Besides the upward adjustment of the tariffs on which subsidies are based it was shown necessary to provide special bridging finance over a 10-year period in order to make it possible for these farmers to participate in drainage schemes.

Acknowledgement

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APPROACHES TO IRRIGATION TECHNOLOGY TRANSFER

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Abstract

The mere existence of innovations does not necessarily lead to their implementation. Rather, the successful transfer of technology in irrigation is dependent on the mobilisation of motivational forces in a way that will promote adoption. Problems need to be identified, prioritised and linked to the felt needs of a target community to ensure success in technology transfer. Different perceptions of problems must be eliminated to ensure a clear understanding of present and optimum situations. The extension organisation should have the ability to integrate technical, economic and management messages into an extension message that will be understood and accepted by a target audience. The paradox of specialisation and "whole farm approach" complicates this. Three instances of irrigation technology transfer are used as case studies in which extension theory is linked to practice. Some of the data included in this paper as case study material is based on unpublished work done by the author in the Great Fish River Valley.

Introduction

Adoption of innovations is a human trait and therefore the problem of successful technology transfer should be approached from the human and not the technological side. The mere availability of new technology is not a guarantee for the adoption thereof. On the contrary, the creation of a climate conducive to adoption is most often the real vehicle for change.

The point of departure of most development strategies is an awareness of a problem which refers to the difference between "what is", and "what could be". This particularly applies to programmed extension with its commitment to maximum impact per extension input. The most important extension problem is seldom known and needs to be established before embarking on a programme. Where there are a number of alternative solutions, the best solutions, in order of priority or in terms of potential changes, need to be established and implemented (Düvel, 1990: 31).

Technology transfer in irrigation usually necessitates multi-disciplinary counselling which places a heavy responsibility on the extensionist and forces him to adopt a team approach in problem solving. A single problem on a farm could include a variety of disciplines such as soil science, agronomy, horticultural science, viticulture, engineering, economy and sometimes even intensive livestock production. These disciplines are usually interdependent. Therefore, due consideration must be given to the impact that change in one discipline or enterprise could have on the others.

Other factors that complicate the problem are the costly development necessary for proper water control (usually more than R5 000 per hectare); relatively low average crop production levels, as found by Scotney, Le Roux, Van Heerden & Aucamp (1990: 46), the apparent low efficiency of irrigation management found in some irrigation areas (Shone, 1965; Coetzee, 1967; Streutker, 1971: 94-95; Nel, Department of Agricultural Development, Bloemfontein. Personal communication, 1988), as well as the water shortages experienced from time to time and the expected shortage of usable runoff water early in the next century (Department of Water Affairs, 1986: 1.38).

Three instances of irrigation technology transfer are linked to theories concerning producer motivation, the need for problem identification and prioritisation and the extension organisation and its approach. All unreferenced comments in this paper are based on observation and experience, and still have to stand the test of scientific observation and interpretation.

Background information on case studies

Great Fish River Valley.

The major development of this area, which is an Irrigation Board irrigation area, took place during the early 1920's. Some of the present canals were built during 1862 to 1875, and apart from some upgrading, are still in use as originally constructed (Van Heerden & De Kock, 1980: 2-5).

The scheme was constantly plagued by water shortages. The result was that the Government bought out approximately 5 800 hectares of the scheduled 18 000 hectares as so-called uneconomic farms during 1961. These farms were consolidated into 45 economic units and sold to farmers after the completion of the Orange-Fish River Tunnel in 1977. The new farmers were settled amongst the approximately 250 farmers who had remained in the irrigation area. The contract signed by the new farmers stipulated that they had to follow departmental recommendations for irrigation design and management (Van Heerden & De Kock, 1980: 7-8).

The present irrigation area is approximately 27 000 hectares, farmed by approximately 300 farmers. Farms are fairly large. Crops produced are mainly lucerne, maize, wheat and pastures, with approximately 60 percent of the irrigated area being utilised for some form of animal production. Flood irrigation is predominant with irrigation efficiency and average production at a relatively low level (Scotney *et al.*, 1990: Tables 3.5, 4.1, 5.3, 7.2).

An intensive extension programme with the aim of improving irrigation efficiency was carried out in the area.

Riet River Irrigation Scheme

The Riet River State Water Scheme is one of the irrigation schemes that was developed by the State with the socio-economic aim of alleviating the so-called "poor-white" problem resulting from white unemployment and a lack of labour-related skills associated with the depressed economy of the 1930's. The aim in the short-term, was to create jobs during the construction of the scheme and in the longer term, to solve the problem by settling of some of the "poor-white" people on irrigation plots. The actual building of the scheme was started in 1940 (Visser, 1965: 2-7; Department of Water Affairs, 1986: 1-10).

The plots were small, one of the guides to determining size being double the area which could be handled by a farmer with one span of draught animals. The reasoning was that one half of the farm could be intensively cultivated and cropped, whilst the other half could be used as a fodder production unit for the draught animals (Myburgh, Verwoerdburg. Personal Communication, 1988).

Chronic water shortage was experienced. This led, *inter alia*, to the Orange Riet River Scheme (Sarel Hayward Canal), which was completed during 1987 and which diverts Orange River water from the P.K. le Roux Dam to the Riet River Scheme (Department of Water Affairs, 1987: 2). The present scheduled area under irrigation is approximately 6 289 hectares, farmed by 142 farmers. Crops produced are mainly wheat, maize, peanuts, potatoes and cotton, with yields being relatively low. Flood irrigation is predominant but efficiency is low (Nel, Department of Agricultural Development, Bloemfontein. Personal Communication, 1988; Scotney *et al.*, 1990: Tables 3.5, 4.1, 5.3, 7.2). During 1988 an extension programme with the aim of improving irrigation efficiency was started in the area (Nel, Department of Agricultural Development, Bloemfontein. Personal Communication, 1988).

Kiepersol Banana Study Group

The Study Group consisted of 20 members in the vicinity of Nelspruit. The median age of the ten respondents who were included in an extension research study was 29, and all respondents had post-matric training in agriculture. The area in which they farm is within the direct influence sphere of the Burgershall Experimental Farm of the Citrus and Subtropical Fruit Research Institute (CSFRI) of the Department of Agricultural Development. Irrigation water is applied through micro-, drip- and overhead spray systems (Du Toit, 1987).

Experimental work done on the Burgershall Experimental Farm found that the cooling effect of spray irrigation resulted in a production drop of 30 percent, compared to drip irrigation (Du Toit, 1987). Drip irrigation was therefore recommended.

Drip irrigation was adopted within five years by most of the members of the study group, even though the high iron hydroxide content of the water placed a very high maintenance requirement on this practice. The relatively quick adoption of this practice was researched by Du Toit (1987).

Linking some extension theories to cases

Producer motivation

Theory: The motivation of a producer can be described as a goal-directed behaviour or change in behaviour arising from needs and aspirations. This behaviour or behavioural change can be seen as the result of an interaction between positive and negative forces, where the exertion of positive forces promotes change while negative forces have a restraining effect on behavioural change. Positive forces represent the challenge characteristics of an innovation. The bigger the challenge, the more readily will a person try to overcome the negative forces that act as barriers on the way to objective achievement (Scholtz, 1988: 169; King, 1989: 103; Terblanche, 1989: 118-119).

Problems can temporarily assume goal characteristics when a farmer's attention is focused on them, with the immediate goal to overcome them. It is essential to think and plan from the client's understanding of his world and from his actual behavioural field (King, 1989: 103; Dũvel, 1990: 31).

A widely accepted definition of an extension problem is that it is the difference between "what is" (present situation) and "what could be" (desired or optimum situation). Perceiving this difference is equivalent to perceiving a need to overcome the problem. The bigger the perceived difference, the bigger the problem or need tension. Studies indicate that less efficient producers tend to have a reduced or lower need tension because they tend to over-estimate their present situation and underestimate the potential or the achievable. This usually results in no change occurring due to a limited need tension and consequently a lack of motivation (Dũvel, 1990: 103).

Great Fish River Valley

The many years of non-reliable water supply experienced before the arrival of Orange River water during 1977, led to a conviction that the cost of applying irrigation must always be kept as low as possible, regardless of the consequences for irrigation efficiency, level of crop production or whether the proposed economising was justifiable or not. This seemed to have had a very negative effect on the farmer's motivation for improving his irrigation efficiency.

Traditional, standardised, rule-of-thumb irrigation bed layout was perceived as being correct, irrespective of differences dictated by different soil characteristics. The perceived application depth per irrigation was 75 mm. Actual irrigation depths varied from 30 to 225 mm. Scheduling efficiency was perceived as

being high, while actual scheduling efficiency averaged 39 and 51 percent for two consecutive water years.

The recommended application depth for crops grown in the area was 75 mm per irrigation. With the farmers perceiving their actual application depth as being the same as the recommended, no difference between their present situation and the required or recommended was perceived. The above resulted in an absence of need tension (motivation).

New farmers, who accepted recommended management practices and irrigation designs, achieved conspicuously higher production levels than "old" farmers in the area. These higher production levels served as an example of potential and immediately increased the need tension by setting new standards for the achievable. Irrigation evaluation results, indicating low levels of efficiency, were presented to the irrigators in an effort to correct their wrong perceptions as to what the present situation was. The combination of upward adjustment of the perceived level of the achievable in irrigation management and the apparent downward adjustment of the perceived present level of efficiency, apparently increased the need tension and thus the motivation for improved irrigation efficiency.

It seemed as if results obtained on a governmental experimental farm were perceived by the farmers as being largely unachievable and therefore the motivational value of those results was possibly less than the motivational value of achievements by fellow farmers.

Riet River Irrigation Scheme

Few farmers had made use of the water-use figures, as supplied by the extension team, to schedule their irrigation. It seemed as if the farmers did not understand scheduling and that they had problems with the implementation thereof. Newsletters were then distributed, lectures were given, demonstrations were presented and meetings were held in an effort to increase the understanding of irrigation scheduling (Nel, Department of Agricultural Development, Bloemfontein. Personal Communication, 1988).

The irrigators seemed to lack the necessary motivational forces that would compel them to accept the concept of better irrigation management. Increasing their knowledge through lectures and demonstrations could have helped in this regard, because it might have enabled them to be more objective regarding their perceptions of present and achievable levels of management.

Kiepersol Banana Study Group

Ten positive and ten negative motivational forces were identified. Positive forces included elements like higher production, more effective irrigation, ease of management, while negative forces included poor water quality, lack of capital and high interest rates. Respondents were asked to rate each of the forces in terms of importance on a 10-point scale (Du Toit, 1987). The positive and negative forces, as well as the total points given to each force, are indicated in Table 1.

The total value of positive forces was nearly double that of the negative forces, and the value of the lowest positive force was higher than the highest negative force (Du Toit, 1987).

Relating these findings to the theory, one can conclude that:

* The positive forces for change were so much stronger than the negative, that goal directed behaviour became self-motivating.
* Perceptions regarding present and potential levels of achievement were clear enough, with a large enough difference, to ensure the existence of a need tension, which acted as a motivator for change.

The fact that members of the study group were fairly young and were relatively highly educated, could have resulted in more rational perceptions.

Table 1 Positive and negative forces, as well as weights given to each, that played a role in the adoption of new irrigation technology by the Kiepersol Study Group (Du Toit, 1987).

Positive forces		Negative forces	
Force	Weight	Force	Weight
Higher production	87	Poor water quality	55
More effective irrigation	85	Lack of capital	49
Ease of management	81	High interest rates	47
Economically advantageous	80	Purhcase price	46
Reduced risk	72	Service by supplier	44
Labour saving	72	Technology is confusing	35
Time saving	70	Water supply	28
Knowledge	67	System Technology	26
Product quality	66	Distance from water source	26
Influence of CSFRI	66	Terrain	22
TOTAL	746	TOTAL	378

Felt and unfelt needs- and the need for problem delimitation and prioritisation

Theory: The likelihood that the extensionist and the target community shares the same view regarding problems or their priorities, seems to be the exception rather than the rule. There is also seldom consensus regarding the priorities of problems among the members of a target audience. Therefore, there is a practical need to reconcile the divergent views of the extensionist and the farmer to formulate a single general problem, thereby presenting a basis of consensus. If this is done in association with clients or their representatives, differential perceptions could be eliminated (Düvel, 1990: 32).

The extensionist seldom finds himself confronted with a single problem or task. In order to achieve optimum impact, problems must be delimited and prioritised. Extension philosophy and approach will largely influence the relative importance attached to the different views of the change agent and the community. This does not necessarily imply that the extensionist has a more realistic view, but his wider system of reference deters him from easily becoming used to, and thus blinded by, the existing situation (Düvel, 1990: 32).

The identification of the biggest development problem is important in order to focus the major extension effort in that direction. This identification should be based on the amount of change in terms of production efficiency or economic gain that could be brought about per unit input. According to Düvel (1990: 33), a purely quantitative comparison is seldom possible and numerous other factors need to be considered.

In the promotional extension approach, the farmer's perception of his needs cannot be decisive, except as a starting point for winning him over to the extensionist's point of view. If, for example, the State extension service is responsible for the promotion of sound irrigation management, but farmers do not share this point of view, then the aim must be to persuade them to voluntarily change their behaviour. In specific circumstances there may be justification for a temporary concentration on the farmers' needs with the object of satisfying those, and then starting from that base to make the farming community more perceptive of other, perhaps more important, problems (Düvel, 1990: 34).

Great Fish River Valley

No formal, complete situational survey was done by the author. Instead, the results of previously completed surveys were used for problem identification. The commitment of the local community was obtained by including them in the problem identifying and prioritising process. Problems thus identified included:

* sub-standard water distribution systems
* management of irrigation board canals which was incompatible with crop water requirements (not enough water in summer, too much in winter)
* lack of knowledge of individual crop water requirements
* on-farm irrigation design and irrigation layout that was not compatible with good irrigation management.

In subsequent irrigation extension initiatives, priority was given to those fields where substantial improvement in irrigation efficiency would be possible with a minimum of expense to the irrigator and where evaluation could be fairly easily done.

About eight years after the onset of irrigation extension work, the author and members of the target audience took part in a nominal group technique exercise with the aim of more formal problem identification and prioritisation. Felt and unfelt needs were identified in the process. An interesting point was that the irrigation problems thus identified, were the same as those identified previously by the author in conjunction with farmers' associations and irrigation boards.

Riet River Irrigation Scheme

Problems identified were: low crop yields, waterlogging and salinisation which could be ascribed to bad irrigation management and extension staff that were perceived as having a low credibility (Nel, Department of Agricultural Development, Bloemfontein. Personal Communication, 1988).

The involvement of the local community in the identification of problems could not be ascertained from existing reports, with the result that one could not be sure whether problems identified were those of the extension staff only, or whether the target community had also accepted the identified problems as their own. If the community were not involved, one could expect very little acceptance of the extension programme by the irrigators.

The problem of low irrigation efficiency seems to be an unfelt need of the irrigators, but is perceived as a very real need by the Department (Nel, Department of Agricultural Development, Bloemfontein. Personal Communication, 1988). If this problem could be converted to a felt need of the community, a bigger commitment for participation could be achieved.

Kiepersol Banana Study Group

By the time the extension survey was done, the members of the study group seemed to have developed a strong felt need for higher banana production as one of the outcomes of their study-group meetings. The need could also have been stimulated by results from experimental work done at the CSFRI.

Extension organisations, available manpower and professional ability

Theory: According to Beukman (1988: 60), the situation that normally exists in an extension organisation is that it has an audience (farmers or producers), a technical (agricultural) message, an economic message, a management message and a need to effectively integrate and transfer the message. This can only be done with an effective extension service. Diagrammatically this concept could be represented as in Figure 1:

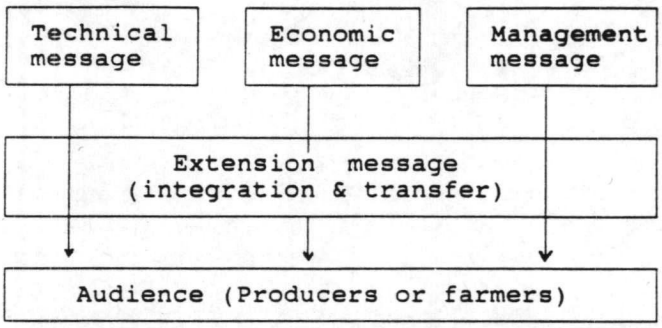


Figure 1 Diagrammatic representation of message inter-relationship in extension.

This implies that an effective extension service must have the required expertise and the necessary management capability to integrate the different messages with the aim of reaching a common goal. Furthermore, a climate and opportunities, conducive to effective operation by the extension workers, should be established by the organisation (Beukman, 1988: 62).

The "technology/information explosion" that characterises the present era, is one reason why it has become necessary to include a subject matter specialist in the communication chain between researcher and the end-user of technology (Düvel, 1988: 89, 96).

The paradox of specialisation and "whole farm" approach, as well as the high level of technico-economic sophistication of the present day farming, places a high demand on extension. The strength of universities lies in promoting specialised knowledge and thus a better understanding of problems relating to specific subject matter. This is contrary to the needs of the farmer, whose problems are seldom compartmentalised but are of a multi-disciplinary nature (Düvel, 1988).

Great Fish River Valley

The team directly responsible for the execution of the programme consisted of an agriculturist/extensionist, a technician who was capable of designing irrigation systems and a technician versed in soil science. This team was supported by specialists who worked in the area from time to time. These included engineers, agronomists, economists and animal scientists. In the main, the extensionist used his scientific background as well as his knowledge of the area and the community to design extension messages that would be credible and acceptable by the community. Subject matter specialists were actively involved in the programme.

Riet River Irrigation Scheme

The team approach followed in this project is perhaps the best example of the three case studies as to how this should be done. Planning committees which gave direction to and co-ordinated extension efforts in the area, included people from outside the Department, as well as members of the target audience (Nel, Department of Agricultural Development, Bloemfontein. Personal communication, 1988). Meteorologists, crop scientists, engineers, economists, extensionists were all members of the team. The extension personnel used their expertise to combine technical, economic and management messages into a single meaningful extension message.

Kiepersol Banana Study Group

No combination of technical, economic and management messages into extension messages seems to have been necessary, and was apparently not done. Due to the self-motivational forces encountered, members of the group selected whatever they needed in terms of the available technical, economic or management information.

Du Toit (1987) found that a subject matter specialist was actively consulted by members of the study group without the intervention of the extensionist.

Conclusion

The problem of technology transfer in irrigation is complicated by the multi-disciplinary nature there-of. Success seems to be found where motivational forces are strong enough to induce motivation and in those cases where the community has been actively co-opted as a partner in problem identification and prioritisation. Non-success seems to be associated with a top-down approach, where the extensionist tells the community what is wrong, an approach which could be equated to paternalism.

It is necessary that the extension organisation be fully co-ordinated to tackle irrigation problems on a team basis, where the team should consist of specialists in different relevant fields, and where technical, economic and management messages are integrated into meaningful extension massages with which the target audience can identify as being related to their felt needs.

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HIGHEST PRIORITY IRRIGATION RESEARCH FIELDS AND OBJECTIVES AS IDENTIFIED BY THE CCIR MASTER PLAN

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Introduction

The Water Research Commission (WRC) of South Africa has three primary functions namely:

* The co-ordination and promotion of water research in South Africa.
* The dissemination of water research results via technology transfer actions.
* The funding of water research, in its broadest sense, in South Africa.

In order to achieve the above the WRC makes use of, *inter alia*, prioritized master research plans or guidelines in each identified field of water research. Furthermore, in each research field there exists a Co-ordinating Committee which hosts representatives of both the managerial and research sectors. The Committees, of which the Co-ordinating Committee for Irrigation Research (CCIR) is one, play a leading role in the establishment of prioritized master research plans.

To date priorities and identified research needs in the irrigation sphere have been entirely discipline orientated i.e. they have been classified as agronomic, soil science, engineering, etc., research needs and priorities. This approach makes it virtually impossible to accomodate interdisciplinary research and to compare priorities among the various disciplines. A method of overcoming this problem is to restructure research guidelines in such a manner that they are based on goals and objectives as opposed to the discipline orientated approach.

There exist a number of methods for research goal and objective identification and prioritization. Each of the methods have their own strengths and weaknesses. The WRC, in the establishment of other Master Plans/ Guidelines, has favoured the approach set out in an Expert Choice (1986) package (Cousens, 1986), which incorporates the Analytical Hierarchy Process (AHP), developed by Saaty (1980). In conjunction with the CCIR, the WRC again adopted this approach for the irrigation Master Plan/Guideline.

Method

Over a period of nearly two years, via a process of negotiation and consensus, a number of irrigation research goals and objectives were identified. Throughout the whole process care was taken to include the views of not only irrigation and water resource managers but also of research workers, active in all fields pertaining to irrigation research.

Once the goals and objectives had been identified and agreed upon it became possible to subject these to a prioritization process. A representative panel of experts in the irrigation field, led by an experienced facilitator from the CSIR, was responsible for the final prioritization.

The prioritization exercise lasted two full days. Initially an overview of the Expert Choice - AHP tool to be used for prioritization was presented by the facilitators. Thereafter the group discussed and reached consensus on the wording of the overall objective and the various goals. For the purpose of this exercise five primary goals were defined, each with its own secondary goals.

These primary and secondary goals were then prioritized utilizing the Expert Choice package.

Results

The overall objective, the various primary and secondary goals that were identified and their priority rankings are given below:

Overall objective: The optimum development, management and conservation of irrigation resources in South Africa.

This is the main objective that has to be achieved through research in the irrigation field. The widest possible meaning is attached to the word "resources". This includes natural resources, as well as irrigation farmers' existing infrastructure and capital. The region of concern to the overall objective comprises the whole of South Africa south of the Limpopo River.

Below the overall objective there are two further levels of goals. Each lower level in this hierarchical structure of objectives comprises goals that should be "easier" to conceptualise as they are practical manifestations of the higher level objectives. By attempting to achieve them systematically, the objectives at the next higher level should also be addressed in the best possible way.

The following goals on the lower level of the hierarchy were decided upon. For the purposes of this document they will be referred to as primary goals.

Primary Goals:

1. Refinement of data bases and planning methods for optimizing irrigation development. (Code: Planning)
   Implicit in this goal is the existence of certain planning methods and data bases that need some refinement.
2. Optimize efficiencies of storing, distributing and applying irrigation water. (Code: Efficien.).
   This goal can be interpreted as the efficient

management of dams, channels, systems, etc. as seen from an engineering viewpoint. All systems involved in storing, distributing and applying irrigation water have to be used optimally.

3. Optimize crop yield and quality per unit of water used. (Code: Yield).
   The combination of crop yield and quality of crop has to be optimised and as water is a limiting resource, it has to be done per unit of water used.
4. To ensure the long-term conservation of natural irrigation resources. (Code: Conserv.).
   By conservation is meant the prevention of degradation as well as reclamation of already degraded natural resources. The emphasis should be on natural resources, thus excluding human and capital resources.
5. Optimize economic and socio-economic efficient allocation and use of resources in irrigated agriculture. (Code: Econ/Soc.).
   The emphasis of this goal is on the socio-economics of irrigation agriculture in contrast to the other four goals where the emphasis has been on the technical side.

The priority rankings of the primary goals with respect to the attainment of the overall objective, are shown in Figure 1.

Secondary Goals:

The secondary goals listed below are those considered most important in trying to attain the applicable primary goal.

Secondary goals for Primary Goal 1:

(i) Acquisition of relevant knowledge of climate, soil, water and human resources and technological options to enable sound decisions to be made concerning irrigation development. (Knowled.).
(ii) Prediction of future needs for agricultural commodities wholly or partially dependent on irrigation water supplies. (Needs).
(iii) Identification of data base requirements for irrigation development. (Database).
(iv) To develop standardized methods for the comprehensive and integrated planning and evaluation of irrigation projects. (Methods).
(v) Developing methods of reconciling various goals of irrigation development (socio-political, economic, environmental) with each other and with various design options in order to obtain balanced cost-benefit estimates. (Reconcil.).

Secondary goals for Primary Goal 2:

(i) To identify and quantify losses due to seepage, evaporation, deep percolation and run-off. (Losses).
(ii) To optimize the management of storage, distribution and application systems in order to satisfy irrigation demand and to minimize operational losses. (Optimise).
(iii) To refine norms and procedures for systematic selection, design and construction of most appropriate irrigation storage, distribution and application systems. (Refine).

Secondary goals for Primary Goal 3:

(i) To provide the knowledge for establishing crop water use in different environments. (Wateruse).
(ii) To establish relationships between environmental variables and crop water stress. (Env/Stre.).
(iii) To relate yield and quality to crop water stress at various growth stages. (Stages).
(iv) To develop irrigation management methodologies which permit the most efficient use of all available water (initially stored plus rain plus irrigation). (Management).
(v) To breed and select crops for improved water use efficiency. (Breed).
(vi) To develop appropriate crop growth models. (Models).

Secondary goals for Primary Goal 4:

(i) Minimize structural degradation of soils under irrigation. (Degradat.).
(ii) Minimize the accumulation of harmful substances in soils under irrigation. (Accumult.).
(iii) Minimize unnecessary solute return flow to surface or underground waters. (Ret. flow).
(iv) Effective reclamation of degraded irrigation soils. (Reclamtn).
(v) Prevention of harmful water table development. (Table).

Secondary goals for Primary Goal 5:

(i) To establish optimum crop production systems and relevant technology as determined by natural and human resources, and economic factors. (Prod/Tch).
(ii) Establish the long-term economic viability of irrigation farming. (Viabilit).
(iii) To determine optimum combinations of farm enterprises, organizational structure and infrastructure, size as well as utility and risk of irrigation farming. (Combinat).
(iv) To determine a methodology to integrate the demographic, public service, fiscal, social, economic and environmental impact of irrigation development. (Integrat).
(v) To compare the rehabilitation or reconstruction of existing irrigation schemes to alternative development of new irrigation schemes, by means of cost-benefit analysis. (Compare).

The rankings of the secondary goals, each prioritized with respect to their importance for the achievement of the applicable primary goal, are shown in Figure 1.

Discussion

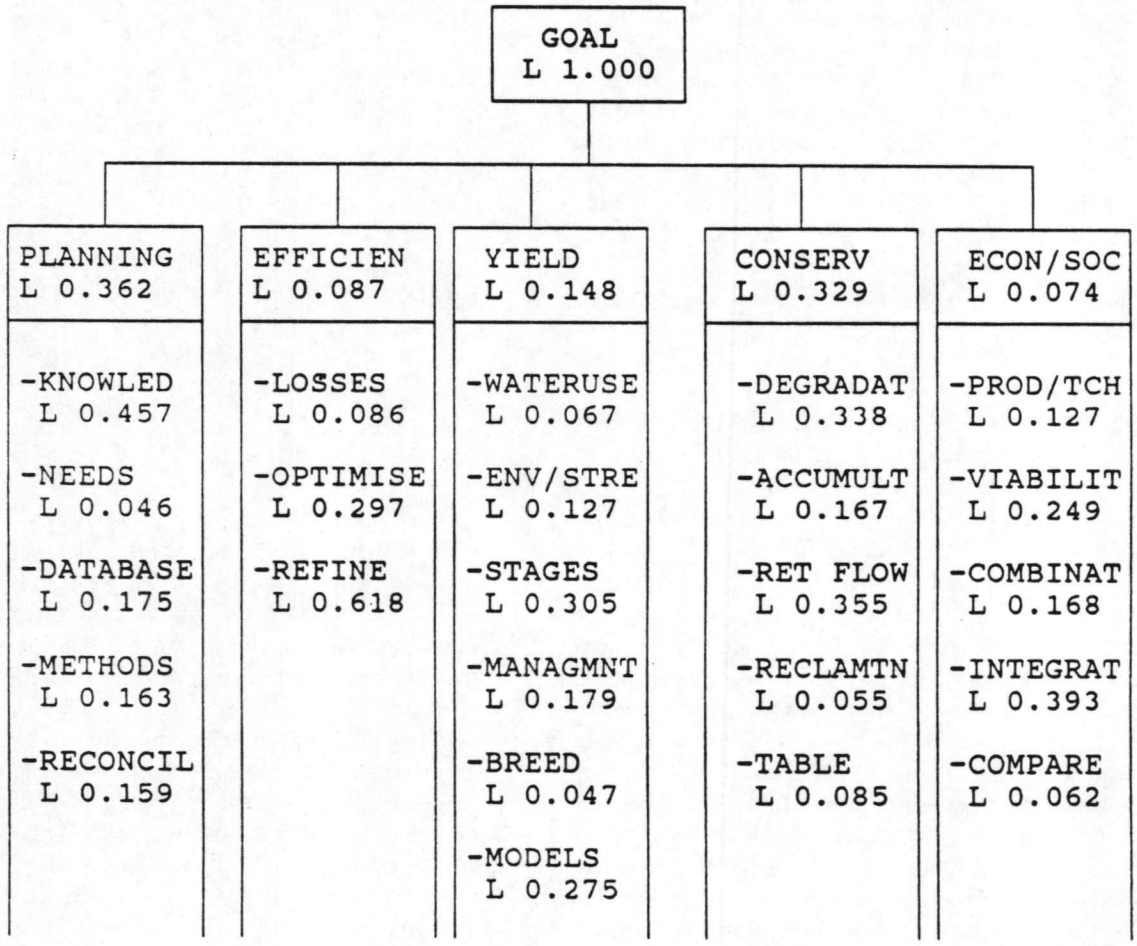
As can be seen from Figure 1, the primary goal "Refinement of planning methods for optimising irrigation development" has the highest priority

assigned to it (0.362), implying that this primary goal is the most important one when trying to optimize the development, mnagement and conservation of irrigation resources in South Africa. The next highest ranking primary goal is the long-term conservation of natural irrigation resources, with the priority of 0.329, followed by the optimization of crop yield and quality per unit of water used (0.148), the optimization of efficiencies of storing, distributing and applying irrigation water (0.087) and the optimization of economic and socio-economic efficient allocation and use of resources in irrigated agriculture as the lowest ranked goal (0.074).

A possible interpretation of this result is that 36% of the money available for irrigation research should be allocated to the highest ranking primary goal, followed by 33%, 15%, 9% and 7% to the lower ranking primary goals.

A similar approach could be followed in the interpretation of the prioritized secondary goals (Figure 1) related to the achievement of each primary goal. For instance, it could be argued that, of the total funds allocated to the achievement of the "Planning" primary goal, 46% must be allocated to the secondary objective "knowledge", roughly 5% to "needs", etc. The format of Figure 1, however, makes it difficult to directly compare the relative ranking of each secondary goal with respect to achievement of the overall objective. The integrated, and ordered, ranking of secondary goals *vis a vis* the overall objective, shown in Table 1, overcomes this problem. Table 1 indicates that, of the total funding available for research directed toward achieving the overall objective, 16.5% needs to be directed to upgrading our knowledge of climate, soil, human and water resources, and technological options, so as to ensure sound decision-making concerning irrigation development. The second most important secondary goal, rating 11.7% of total fund allocation, is the minimization of unnecessary solute return flow to

Figure 1 Prioritized primary and secondary goals in relation to achievement of overall objective.



surface and underground waters. It should be noted (Figure 1) that this specific secondary goal related to the second most important primary goal. A further study of Table 1 reveals the following:

* Of the five secondary goals pertaining to the most important primary goal, only four are rated within the top 10 most important secondary goals. The lowest secondary goal in this category is ranked 16th overall.
* The secondary goal pertaining to the lowest ranked primary goal, which rates highest in the overall list, is rated 11th.

Due to the undoubted uncertainty as to the absolute accuracy or correctness of the individual values used for ranking purposes, the "Proposed Ranking" of goals (Table 1) is probably more meaningful.

It is furthermore suggested that the gap between proposed rankings 1 and 2 is such that there should exist no confusion as regards which are the more important goals.

However, the gap between proposed groups 2 and 3, 3 and 4, etc., is not that clear cut. In this regard the differentiation would probably be that group 2 goals are substantially more important than group 4 goals, group 3 more important than group 5, etc. In terms of probable research funding, therefore, any project proposals related to groups 1 and 2 are clearly definable, with group 1 having priority. Similar priority differences will exist between groups 2 and 4, 3 and 5, 4 and 6. The choice of project to be funded from the intermediate groups i.e. 2 and 3, 3 and 4, etc. will rely on pragmatic evaluation not only of the project but also of, for instance, the track record of the research group involved.

Table 1 Grouping of secondary goals as related to achievement of overall objective.

Secondary goal	Value ranking	Proposed ranking
Knowledge	0.165	
Ret. flow	0.117	1
Degradat.	0.111	
Database	0.063	
Methods	0.059	
Reconcil	0.058	
Accummult	0.055	2
Refine	0.054	
Stages	0.045	3
Models	0.041	
Integrat	0.029	
Table	0.028	4
Optimise & Management	0.026	
Env/Stre	0.019	
Reclamtn & Viability	0.018	5
Needs	0.017	
Combinat	0.012	
Water use	0.010	
Prod/Tch	0.009	
Losses & Breed	0.007	6
Compare	0.005	

Conclusion

With the use of the Expert Choice package a ranking of the primary and secondary goals has been obtained with respect to the achievement of the overall objective. A modicum of manipulation of the rankings produced the guidelines shown in Table 1.

It must however be emphasised that the achieved ranking of any one goal or group of goals can only be seen as a guideline to its importance. The final decision as to what amount of research money needs to be spent on what specific research area within the field of irrigation still depends entirely on the decision maker.

It should also be borne in mind that this Guideline is a living entity and is thus by no means rigid or inelastic. The Guideline will thus be regularly reviewed and upgraded where and if necessary. This aspect is particularly true of the current Guideline as this is the first edition thereof and errors in emphasis could have occurred.

It is also true that the output of this exercise can only be as meaningful as the inputs provided by the decision maker(s) involved. The identification of the various goals and their positions within the hierarchy of objectives, plays a major part in the outcome of the decision process and has to be done with great care and consideration of various factors. It is only once agreement has been reached regarding the structure of the problem, that the outcome thereof can be accepted with confidence. In this regard, the CSIR, in its role as facilitator, was satisfied with the process followed. There was agreement and consensus amongst the panel members regarding the overall goal and subsequent objectives. The prioritization process itself was also conducted and concluded satisfactorily.

References

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