APPLICATION OF WATER FOOTPRINT ACCOUNTING FOR SELECTED FRUIT AND VEGETABLE CROPS IN SOUTH AFRICA

Michael van der Laan (Editor)

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Application of water footprint accounting for selected fruit and vegetable crops in South Africa

Report to the

Water Research Commission

by

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EXECUTIVE SUMMARY

Introduction

This research report represents the first of a series of Water Research Commission (WRC) projects on water footprint (WF) assessments for different crop types, and focuses on fruit and vegetable crops. Prior to this study, a review of the applicability of water footprints in South Africa was commissioned and published by the WRC (TT616/14), which identified several potential benefits as well as shortcomings in the use of WFs. The research conducted in this project, therefore, aimed not only to estimate WF metrics for important fruit and vegetable crops, but also to explore the use of different WF assessment approaches and to interpret the usefulness/applicability of the information generated. To aid in this objective, two catchment case studies were selected at the onset of the project, the first being on the Steenkoppies Aquifer located in Tarlton, Krugersdorp, and the second being the Olifants-Doorn Water Management Area (WMA). This WMA was one of an original 19 WMAs in South Africa which have subsequently been consolidated to 9, and now forms part of the new Berg-Olifants WMA comprising the original Berg WMA and the Olifants-Doorn WMA. For the purposes of this project it was analysed as the original Olifants-Doorn WMA.

Knowledge review

As the first step, a literature review was conducted on important agricultural WF studies that have been published, and three dominant WF methodologies were identified. The first was the original approach according to the Water Footprint Network (WFN), which involves estimating a blue, green and grey WF. The second is based on a life cycle assessment (LCA) approach, and only accounts for a blue WF, which is stress-weighted in an attempt to better characterize it according to local conditions. The third is the hydrological-based approach, which essentially accounts for net changes in soil water and groundwater over a hydrological year to estimate blue and green WFs, and uses the same approach as the WFN for estimating grey WFs. During this project, the ISO14046 standard was released, which, while somewhat vague in its prescription on how to calculate a WF, aligns most closely with the LCA approach.

Tartlon is one of the major vegetable producing regions in Gauteng, and relies heavily on the Steenkoppies Aquifer for irrigation water. Since 1996, agricultural activities on the Steenkoppies Aquifer have increased significantly, sourcing irrigation water directly from the aquifer through numerous boreholes. Flow of water from Maloney's Eye, the only known natural outlet from the Aquifer, was drastically reduced as a result. This reduction in flow resulted in conflict between farmers on the aquifer and downstream users, especially following two major droughts from 1990-1992 and 2002-2005. The Olifants-Doorn WMA is also a region experiencing extreme water scarcity, with a particularly high dependence upon groundwater (as a direct source of supply) in the Sandveld Region. More than 90% of the land in the WMA is used as grazing for livestock, predominantly for sheep and goats. However, the principal economic activity is irrigated agriculture, and it is estimated that 87% of total fresh water is used by irrigation.

Water footprint calculation methods

A comparison of different WF methodologies (WFN, LCA, hydrological-based) using data generated within the two case studies as part of this research highlighted strengths and weaknesses associated with each approach. Because the most work on WF assessments around the globe has been done using the WFN approach, it was a useful exercise to calculate WFs for important South African fruit and vegetable crops according to this methodology and compare to the results of other researchers. Vast differences were observed between WFs as a result of crop species, growing conditions, inter-annual weather variation, and the growing season in which the crop was cultivated (spring, summer, autumn, winter). For example, WFs varied from 56 m^3 t^{-1} for lettuce (*Lactuca sativa*) grown in summer, to 327 m^3 t^{-1} for broccoli (*Brassica oleracea*) grown in autumn. The relative proportion of the blue/green WF was linked to whether the crop was grown in the dry season (winter for Gauteng, summer for the Western Cape) and therefore needed to be well-irrigated. In most cases, locally estimated WFs were significantly lower than global averages reported in the literature, and the relative proportion of blue water used was also higher locally.

As a modification of the original approach and similar to the ISO14016 recommendation, the LCA approach aims to adjust blue WFs according to local conditions using a water stress index, which has been calculated for the globe, but can also be calculated in more detail for a specific region of interest. Blue WFs for the LCA approach were lower than for the WFN approach as they were simply multiplied by the water stress index for the region, which was 0.78 in the case of Steenkoppies Aquifer. We find the recommendation to report the WF as water equivalents or 'H_2O-e' is a concept that people outside of the LCA community will have trouble grasping, at least initially. A major strength of the LCA approach, however, is the advanced methodology and databases that exist for the calculation of other environmental impacts such as the carbon footprint, eutrophication, freshwater ecotoxicity, aquatic and terrestrial acidification and human health. As the method takes multiple environmental impacts into account simultaneously, it can monitor for 'problem shifting' or 'pollution swapping'. In this regard, the LCA method rejects the use of the grey WF concept. Proponents of the LCA approach argue that green water use is not considered an impact, because of the inseparability of green water and land occupation. However, our judgement is that if less green water is used by a specific land use it may lead to increased blue water in rivers and aquifers as a result of higher levels of runoff or drainage.

Using the hydrological-based method for South African fruit or vegetable crops for which drainage plus runoff is higher than irrigation, a negative blue WF is possible. This was observed for apples grown in the Koue Bokkeveld (Olifants-Doorn WMA), where the blue WF was estimated to be -41 m^3 $tonne^{-1}$. While it may be useful to know that under this land use recharge of water resources is greater than irrigation, it is confusing to obtain a negative blue water footprint for a crop that is so heavily reliant on irrigation, even if deep drainage plus runoff is greater than the total amount irrigated. The attained result is largely because irrigation is applied during the dry summer season, which more than compensates for the water used by the orchard over this period, while rainfall during the wet winter months (when the orchard is dormant) results in recharge and runoff. While it was acknowledged that this approach can lead to further understanding of the hydrology of the system using the WF value alone, this method does not appear to be more effective in creating a WF that is useful for consumer awareness and is difficult to apply to hydrologically complex systems.

It was concluded that blue and green water footprints calculated according to the WFN methodology are most useful for a number of reasons, these include:

- The methodology is well-developed, and WFs are relatively simple to calculate and understand.
- The quantitative nature of these WFs makes them potentially useful in different information management systems, such as water use licensing services, and up-scaling to a catchment level and quantifying water consumed by different users for water allocation purposes.
- By altering the functional units these metrics can be used for applications such as understanding WFs per nutritional unit produced, economic gain or labour opportunities provided.
- These WFs can reveal impact on water resources in different seasons of a hydrological or calendar year.
- Can indicate high WFs of certain crop species, such as broccoli, or certain growing regions, such as those which experience relatively high vapour pressure deficits or with poor soils.
- It allows for local contextualisation if there is suitable information to conduct the sustainability assessment.

The concern over the way in which WFs of the WFN are communicated outside the context of the environment in which the water is used is, however, legitimate and such results should not be used 'as is' for awareness raising. The other two methodologies attempt to develop a single value that will indicate the sustainability of a water use, but due to the vast number of variables, complexities and trade-offs involved in sustainable water use, such a number seems to be an unrealistic goal. Product labels in the future will more likely be in the form of a symbol that indicates good water stewardship, no matter what WF method they are calculated according to.

Intricacies in the estimation of WFs

Water footprints for important fruit and vegetable crops have now been calculated for South Africa. Previous researchers have recognised the inter-annual variation in WFs of crops. Our results show that it is also important to interpret WFs with specific reference to the growing season, especially for short season crops with a range of planting date options. High inter-annual variation for this case study was illustrated by the high standard deviations of some crops during certain growing seasons. Other longer-term crops such as fruit tree orchards calculate WFs over a full calendar year, although annual variation is evident, due to changes in total evaporation and yield as the orchard matures. It should also be widely recognised that WF estimates can be significantly influenced by the quality of data used to parameterise and run crop models. We observed that daily ET_o estimates can differ significantly when either measured or estimated solar radiation data is used, so recommend that consistent weather data be used from the parameterisation stage through to model application. This was observed particularly for solar radiation during summer and spring for the Steenkoppies Aquifer Case Study. The functional unit used to calculate WFs has a significant impact on WF metrics. Grains with low moisture content, such as maize and wheat, will have a disproportionately high WF compared to vegetables when using fresh mass yields. Depending on the objective of the study, different functional units for various crops can be used to reveal which crops will be more efficient in producing important nutrients per volume of water. Assessing WFs in terms of other functional units such as economic gain and job creation is recommended for future research, because these alternative assessments can provide important information on how to allocate limited water supplies to achieve various objectives.

Steenkoppies Aquifer case study

Agricultural water consumption was calculated for the catchment of the Steenkoppies Aquifer using water footprinting in a modified framework that we call the ‘catchment WF approach’. This approach potentially provides relatively easily-generated, quantitative information to a catchment manager that can improve decision-making. Total ET from agriculture was estimated by linking WFs of crops with total yields produced on the aquifer, which is a key requirement in water management decisions and allocations and provides information on water productivity. Quantifying the ET from agriculture and natural vegetation also provides the data required to do a catchment water balance, which provided important insights into the hydrology of the case study aquifer.

Results indicated that when taking into consideration the need for an environmental reserve, although available blue water was not fully utilised prior to 1985, irrigated agriculture became unsustainable after 1986. This additional blue water is either sourced from groundwater stored in past years in the aquifer, or could also be explained by possible water movements across the boundary of the aquifer. Reductions in borehole level measurements confirm the results of this sustainability assessment that water from the aquifer is being used faster than it is recharged. Borehole levels decline from the average after 2005, roughly coinciding with the period when abstractions for irrigation reached peak levels. Methods such as optimising current irrigation systems, switching to more efficient systems such as drip irrigation, and/or water conservation techniques such as mulching are therefore strongly encouraged. Green water consumed by agriculture is less than available, so there is still capacity left to increase dry land agriculture within sustainable limits.

The catchment WF approach requires relatively little information for an agriculture-dominated catchment, including rainfall data, the total yield of different crops cultivated and their respective WFs, and the WF of natural vegetation. By using WFs according to the WFN method the approach automatically accounts for drainage of excess irrigation water that is applied, alleviating the need to measure or estimate abstractions or deep drainage back into the aquifer. In the past, total ET of the Maloney’s Eye Catchment has not been quantified in hydrological studies on the Steenkoppies Aquifer, and this information can potentially be used to improve hydrological models. Using WFs to determine a water balance of the catchment is also considered to be part of a process towards developing a simplified and more cost-effective approach to understanding water dynamics of an aquifer, in contrast to complex and expensive hydrological assessments.

The WFN calculations are formulated so that blue plus green WFs are equal to total ET of a crop over the growing season. Excess water applied through irrigation is considered to recharge the aquifer. The most important strength of this approach is its simplicity. For example, the blue plus green WF of carrots in a specific season on the Steenkoppies Aquifer will be relatively constant, despite the efficiency of the irrigation system and management of that system, which can be much more variable. This simplicity is an important part of the catchment WF approach proposed in this study. However, a potential weakness of this is that the consequences of over-irrigation can be underestimated. Over-irrigation is undesirable, because it can result in water logging, soil salinization, groundwater pollution, leaching of plant nutrients, and other impacts on the soil (Mostafa 1977, Postel 1999, Zilberman et al. 1997). Due to lags in the system, over-irrigation can also potentially impact on the water availability for an aquifer. The WFN calculations do, however, provide a way to identify and manage over-irrigation. If over-irrigation occurs, blue water use will equal ET of the crop and the green WF will be zero, thus precipitation is not utilised. A catchment manager should therefore use the size as well as the ratio between blue and green WFs to ensure efficient irrigation practices together with the catchment WF framework.

Olifants-Doorn case study

Blue, green and grey WF information was determined using the WFN method up to farm gate level for apple (*Malus domestica*) and citrus (*Citrus sinensis*) orchards growing under Mediterranean-type climate conditions in South Africa. WF_{blue} and WF_{green} were determined through field measurements of transpiration, total evaporation, rainfall, irrigation and other operational water uses, and WF_{grey} was calculated from fertilizer applications.

For the apples, orchard-scale WFs, taking into account all water uses and a fruit yield of 61.5 t ha^{-1}, was 212.1 $m^3\ t^{-1}$, comprising 62.7% WF_{blue}, 14.9% WF_{green} and 22.5% WF_{grey}. Irrigation thus contributed the bulk of the WF in the apple production chain. Resultant water productivity (WP) figures for the apple orchard averaged 4.72 kg m^{-3}.

For the oranges, orchard-scale WF, taking into account all water uses and a fruit yield of 79 t ha^{-1}, was 162.8 $m^3\ t^{-1}$, comprising 69.2% WF_{blue}, 14.2% WF_{green} and 16.6% WF_{grey}. Irrigation again contributed the bulk of the WF for citrus, with a lower WF_{green} due to the drier nature of the site. The resultant WP value for the citrus orchard was 6.14 kg m^{-3}.

Combined field-scale blue/green/grey WF data were extrapolated to quaternary catchment (QC) scale by means of representative monthly FAO-56 type reference potential evaporation (ET_o) values and crop factors derived from the field scale observations. Resultant water use values were converted to a volumetric equivalent by multiplying by the total area under apple and citrus orchards respectively in each QC (irrespective of orchard age). The volumetric equivalents were then summed for all QCs in the WMA to calculate the overall WF for apple and citrus production in the basin. Scaling up the apple orchard WF estimates to QC level gave an average value of 228.4 $m^3\ t^{-1}$ (WP = 4.41 kg m^{-3}). Scaling up the citrus orchard WF estimates to QC level gave an average value of 210.5 $m^3\ t^{-1}$ (WP = 4.77 kg m^{-3}). It was concluded that field scale estimates of the WFs of fruit tree orchards, based on actual measurements, provide valuable and detailed information for on-farm water use management. However, catchment-based WF assessments are more appropriate for large-scale water resources management beyond the farm boundaries. Accurate crop factors, representative weather / ET_o data and reliable crop areas within each QC are critical requirements in terms of upscaling WF estimates. The information then has potential application in water allocation decisions, cost-benefit analyses and other water resource management decisions.

Grey water footprints

The grey WF is a way of reporting potential impact on water quality, which is a very important aspect of water resource management. The concept has, however, often been criticized for being too simplistic. In a crop production context, water pollution, especially non-point source, is an especially complex issue. In addition to nitrate which is mostly commonly used as the criticial pollutant in these types of studies, phosphates, salts, sediments and pesticides are also pollutants associated with agriculture, and need to be taken into account when addressing water quality. Therefore it is not completely effective to assess the water quality impacts based on one pollutant, even if it is the one that requires the most dilution. Furthermore, South Africa does not have any maximum contaminant levels for pesticides (they are not supposed to be present at all) and the maximum concentration applied in the WF_{grey} equation has a significant impact on the final grey WF calculation, therefore making this method currently unusable for certain pollutants locally.

Final conclusions

The complexity of the ecological, social and economic factors which must to be considered when assessing the impact of water use and the trade-offs that are required to choose between one water use and another, highlights the complexity or even impossibility of calculating a WF as a single numerical value that will assist consumers to make wise decisions about their water use. It is recognised that change in consumer behaviour is key to achieving sustainable water use, but it is unlikely that a single numerical value can be developed to inform consumers to make wise decisions on their water use, which is a key aim of the LCA/ISO WF methodology. Other options, such as education, advertising and government subsidies should be considered in addition to creating consumer awareness, but the WF is not yet that far developed. Essentially, the choice of WF method selected will be based on the objectives of the exercise.

Although WFs can provide very useful information in an agricultural context, there remain major challenges involved in calculating WFs, interpreting the information and understanding the limitations of the information that need to be addressed. It is envisaged that the methodologies proposed in this report and the WF estimates for important fruit and vegetable crops will assist various stakeholders to think about and advance ways to manage their water resources better. In this regard, continued efforts to estimate the WFs of vegetable and fruit crops for different growing environments is encouraged.

Water footprints also have excellent potential in creating awareness and dialogue around the sustainable use of water resources. In the case of crop products, WFs are directly dependent on local growing conditions, however, and therefore it must be continually emphasized that they need to be estimated for these conditions if they are being used for any application more detailed than a first order estimate, for example, in the use of benchmarking or in water resources management.

Recommendations for future research

Based on the results of this project, our recommendations for future research are:

- Develop WF methodology to incorporate the beneficial uses of crop residues in the WF estimation. Linked to this, improve classification of wastage to account for other beneficial uses of biomass that is not suitable for direct selling.

- Determine how significant the variations in WFs are between different crops and crop cultivars.

- Further develop WF approaches using alternative functional units, such as crop nutritional content, economic gain or job creation per unit water used.

- Improve the understanding of how initial soil water content at planting, and where this water originated from, impacts the blue, green and grey WF.

- Begin compiling a national database of crop and cultivar WFs for specific regions under specific management practices.

- Consider the ecological and carbon footprints simulataneously to WFs when assessing potential impact.

- Record actual crop yields produced by the farmers at the catchment scale over the long term for more accurate estimation of catchment scale WFs.

- Improve the quantification of water use by natural vegetation.

- Further refine the catchment WF framework to accurately estimate outflows from an aquifer (assuming these can be accurately measured).

- Use catchment scale WFs to determine maximum allowable production on an aquifer (or in a catchment) to achieve multi-generational sustainability targets as proposed by Gleeson et al. (2012).

- Improve the interplay between WF accounting and hydrological assessments to improve the understanding of the dynamics and sustainable water use for a particular system.

- Blue and green WF sustainability assessments can be improved specifically with regards to determination of natural runoff, additional components that can be included in the calculation of blue water availability (such as water allocated to downstream users), and accounting for recharge of the aquifer (or other water resource) under natural vegetation, which may be defined as available blue water.

- Improve grey WF methodology to better understand the nutrient balances of intensive cropping systems on a catchment scale, as well as an improved means of accounting for pesticide / herbicide use and pollution.

- Conduct a catchment scale grey WF assessment to improve understanding on actual water quality impacts and how this can be represented in a simpler way.

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List of Abbreviations

ADP	Abiotic Depletion Potential
COD	Chemical Oxygen Demand
CPI	Consumer Price Index
CWR	Crop Water Requirement
CWU	Crop Water Use
DAFF	Department of Agriculture, Forestry and Fisheries
DEA&DP	Department of Environmental Affairs and Development Planning
DOC	Dissolved Organic Carbon
EF	Ecological Footprint
EFR	Environmental Flow Requirement
ET	Evotranspiration
FAO	Food and Agriculture Organization
FD	Freshwater Depletion
FEI	Freshwater Ecosystem Impacts
HPA	High Plains Aquifer
HPV	Heat Pulse Velocity
Hrm	Heat Ratio Method
ISO	International Standards Organization
LAI	Leaf area index
LCA	Life cycle assessment
MAR	Mean Annual Runoff
OP	Ortho-phosphates
OPEC	Open path eddy covariance
QC	Quaternary catchment
RDA	Recommended Dietary Allowance
SWB	Soil Water Balance
USDA	United States Department of Agriculture
VF	Variation factor

WA	Water Availability
WF	Water Footprint
WFN	Water Footprint Network
WMA	Water Management Area
WP	Water productivity
WRC	Water Research Commission
WS	Water Stress
WSI	Water Stress Indicator
WTA	Withdrawal to availability
WWF	World Wildlife Fund
WWTW	Waste water treatment works

1 INTRODUCTION

by

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1.1 Background

The Global Risk Report for 2015 and 2016 identified the reduction in good quality fresh water as the most important risk to society for the next ten years (World Economic Forum 2016). This is motivated by the significant impacts on human health and the economy that can be expected if fresh water becomes scarce. Climate change, population growth and improved standards of living will exacerbate fresh water scarcity even further in the future. Future water scarcities will present many challenges, of which global food production is of specific concern. The decline in good quality water will make it difficult to maintain current food production, while population growth places an increasing demand on water to produce more food (Postel 1999). Current food production often relies on the unsustainable use of groundwater: a study done by Wada et al. (2012) indicated that global abstraction of non-renewable groundwater abstractions increased by more than three times between the years 1960 and 2000. In the year 2000, unsustainable use of groundwater supplied approximately 234 km^3 yr^{-1}, which is 20% of gross irrigation water demand. Climate change is expected to increase the risks in food production as water becomes scarcer. According to Rosenzweig and Parry (1994), food production in developing countries will suffer most from the effects of climate change. Schulze (2000) illustrated the complexity of southern African hydrology and the difficulty in predicting the effects of climate change on freshwater availability.

Water management in South Africa is particularly challenging, because of severe waters shortages in most parts of the country and a highly variable climate (Smakhtin et al. 2001). In many catchments throughout South Africa, water supply no longer meets demand (Department of Water Affairs 2013). Irrigated agriculture uses approximately 40% of South Africa's exploitable runoff on around 1.7 million hectares of land (Backeberg and Reinders 2009). Agricultural products account for approximately 6.5% of total South African national exports, approximating 3% of Gross Domestic Product (South Africa Yearbook 2015). Nieuwoudt et al. (2004) estimated that 90% of vegetable and fruit products are grown under irrigation in South Africa, because of low and erratic rainfall and the high value of these crops. These industries are therefore highly dependent on the continued availability of irrigation water to remain sustainable. However, surface water resources in South Africa are already almost fully developed, and although alternative sources can still be exploited, it will be done at significantly higher costs than previously (Department of Water Affairs 2013). The vulnerability of food production in South Africa was emphasised by the drought of 2015 which was, according to the

South African Weather Bureau, the driest calendar year since nationwide recordings started in 1904 (de Jager 2016). As a result, preliminary estimates of crop production for the 2016 calendar year indicate that production of most crops is expected to decrease (Crop Estimates Committee 2016). One of the key findings of the Water Resource Reconciliation Strategies for major cities and towns in South Africa, was that little additional surface water can be made available to agriculture in the future, and that many areas are already considering the re-allocation of irrigation water to other users (Department of Water Affairs 2013). The Reconciliation Strategy for the Crocodile West Water Supply System, for example, suggested that leakages in the distribution network of irrigation water from the Crocodile catchment be addressed and that this water be reallocated to augment water requirements of the rapid developments in the Lephalale area or for urban and rural use (Nditwani et al. 2009). Improved water resource management practices that will inform water conservation at all levels to sustainably produce more food with the same or less water are essential. Ideally, these water resource management practices must be simple to use and easily adaptable in a changing environment.

The Water Footprint (WF) concept is an emerging approach, which first started when Allan (1998) introduced the term virtual water. He indicated that economically and logistically it is more reasonable to import, for example, one tonne of grain instead of the 1000 tonnes of water required to produce one tonne of grain. Hoekstra (2003), who initiated the Water Footprint Network (WFN) in 2008, further developed this concept of virtual water by saying that a nation's WF, for example, does not only consist of locally sourced water used, but also includes the water used to produce the products they consume. A water scarce country can import water intensive products thereby reducing the pressure on its own water resources.

The WFN published the first manual on WFs (Hoekstra et al. 2009), which were followed up with a later edition (Hoekstra et al. 2011), aiming to better quantify the impacts of human activities on water quantity and quality and guide improved decision-making and management. In this report, this methodology is referred to as the WFN methodology. The WFN quantifies water consumption along the entire production chain of products, processes and businesses and within nations or catchments (Hoekstra et al. 2011). In an agricultural context, a WF is the volume of water required to produce a certain mass of crop yield. A WF assessment consists of two phases, namely an accounting phase, where the volume of water used is quantified, and a sustainability phase. WFs can indicate water consumption, defined as the loss of water from a particular catchment, for example, through evaporation or transfers to other catchments, along the entire production chain per yield of product (Hoekstra et al. 2011). The sustainability of the WF is determined by comparing the volume of water used to the available water. Available water is defined as the total natural runoff minus the water requirements of the environment (Hoekstra et al., 2011). The availability of water is spatially and temporally variable and the sustainability of using a volume of water depends on the availability of water at a specific time and place. Thus, geographical and temporal components are included in the sustainability assessment step.

Whereas traditionally the focus has been on agricultural producers and the technical aspects of irrigation and drainage to reduce impacts on freshwater resources, WFs further potentially allow water issues to be addressed through regional trade policies and consumer attitudes (Deurer et al. 2011). Water footprint accounting has the potential to provide crop water use metrics in an easily understandable way, which can assist farmers to improve the management of their water resource by informing production decisions. If WFs can be established for a number of well-managed farms, these could serve as benchmarks that can be used by farmers to improve their blue, green and grey water use efficiency. Efficient use of green water in agriculture is important, in order to minimise exploitation of blue water resources by minimising irrigation requirements.

As a result of a number of short-comings that were identified for the approach developed by the WFN, new methodologies have been proposed by other scientists. For example, an approach that additionally accounts for regional water stress (i Canals et al. 2009, Pfister et al. 2009), and an approach that considers the hydrological system in which the water use occurs focusing on water flows and storage changes (Deurer et al. 2011). Depending on the method used, WF outcomes can vary significantly (Jeswani and Azapagic 2011), and there is a need for standardisation. In this regard, the International Standards Organization (ISO) published a WF standard in August 2014 (ISO 14046 2014). Despite this there remains a need to better understand the different methodologies and the application of each.

In a South African agricultural context, detailed WF information is envisaged to be useful for:

- Identifying opportunities to reduce the water consumption/impact at a local level, for example on-farm.
- Better understanding water-related risks and assisting with water allocation and management at a regional level, for example management of water resources at the catchment scale.
- Informing policy formulation and integrated resources management at the national level.

1.2 Aims and objectives of this study

This report represents the first of a series of WRC projects on WF accounting for different crop types, and focuses on vegetable and fruit crops. Prior to this study, a review on the applicability of water footprints in South Africa was commissioned and published by the WRC (TT616/14), which identified several potential shortcomings as well as benefits in the use of WFs. The research conducted in this project, therefore, aimed not just to estimate WF metrics for important crops, but also to explore the use of different WF accounting approaches and the usefulness/applicability of the information generated. To aid in this objective, two catchment case studies were selected, the first being on the Steenkoppies Aquifer located in Tarlton, Krugersdorp, and the second being the Olifants/Doorn Water Management Area (WMA). The aims of the study were to:

- Compare the different WF methodologies to better understand their ability to inform water users and decision makers on local, regional and national levels.
- Select the most appropriate methodology to be applied for water-stressed areas based on case studies on the Steenkoppies Aquifer and the Olifants-Doorn Catchment to:
  - Determine blue, green and grey WFs of cultivating fruit and vegetables and determine complexities associated with the use of the methodology;
  - Compare the WFs of vegetables at the packhouse level with the WFs of cultivation, to determine the relative importance of packhouse water use;

- Apply the selected methodology to estimate a catchment scale blue plus green WF for the Steenkoppies Aquifer and the Olifants-Doorn Catchment to:
  - Assess the sustainability thereof;
  - Determine whether the selected WF methodology can provide a more simplified way to manage water resources of a water-stressed aquifer, as opposed to complex hydrological assessments.
- Calculate the WFs of food wastage along the food supply chain for vegetables produced on the Steenkoppies Aquifer.
- Evaluate the ability of WFs to:
  - Provide the information needed to prioritise actions and measures required to achieve sustainable water use;
  - Create consumer awareness, to enable better decision-making to reduce an individual or entity's impact on the environment from a water perspective, and to encourage better water use along the supply chain as driven by consumer pressure.

2 LITERATURE REVIEW

by

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2.1 Introduction

This chapter reports on a comprehensive literature review on different, promising methodologies that have been proposed to estimate water footprints (WF). The methodologies proposed by the Water Footprint Network (WFN) (Hoekstra et al. 2011), the Life Cycle Assessment (LCA) communities (i Canals et al. 2009, Pfister et al. 2009), and the hydrological-based WF communities (Deurer et al. 2011) were evaluated in a literature review. Strengths and weaknesses for each are scrutinized in an attempt to inform the most appropriate methodologies based on specific scenarios as well as intended application of the information. This literature review served to inform the WF study that was conducted on vegetable production on the Steenkoppies Aquifer, but it is also envisaged that it will inform other WF studies conducted in South Africa.

2.2 Estimation of water footprints according to different methodologies

2.2.1 Water Footprint Network

2.2.1.1 Concept

In 2009, the WFN published the first comprehensive WF assessment manual (Hoekstra et al. 2009), which were followed up by a more comprehensive manual published in 2011 containing prescribed methodology to determine the impact on water resources by individuals, communities, businesses as well as during the production of products (Hoekstra et al. 2011). Hoekstra et al. (2011) distinguish between blue, green and grey WFs. Surface and underground water resources, which are available to multiple users, are defined as blue water. In a crop production context, the blue WF therefore consists predominantly of the irrigation water consumed. Green water is water originating from rainfall that is stored in the soil and available for vegetation growth only. In order to account for water quality impacts, Hoekstra et al. (2011) proposed the concept of a grey WF, which is the volume of water required to dilute emitted pollutants to ambient levels. Expressing water pollution impact in this way enables the reporting of a total (blue + green + grey) WF as a volume which includes water quality and quantity impacts.

2.2.1.2 Calculation

The WFN proposes two phases, namely a WF accounting phase and a sustainability assessment of the WF. During the accounting phase a volume of water used per product yield is determined. The WF for growing a crop can be calculated using one of two models, namely the Crop Water Requirement (CWR) option and irrigation schedule option.

- **CWR option**

The CWR option assumes optimal growing conditions with no diseases or shortages of water and fertiliser that limits evapotranspiration (ET). The evaporation requirement of a crop (ET_c) is calculated using **Equation 2-1**.

$$ET_c = ET_o \times K_c$$

Equation 2-1

Where ET_o is the ET rate of the reference crop, namely grass, ET_o is calculated using the Penman-Monteith equation and is only influenced by climatic parameters (Chapagain and Orr 2009). The crop coefficient, K_c, integrates the specific crop characteristics that differentiate its ET rates from that of the reference crop (Hoekstra et al. 2011).

The green WF is calculated as the minimum of ET_c and effective rainfall (P_{eff}). The blue WF is equal to the difference between ET_c and P_{eff}, if $ET_c > P_{eff}$. The blue WF is zero if $ET_c < P_{eff}$ (Hoekstra et al., 2011).

- **Irrigation schedule option**

The irrigation schedule option is more accurate than the CWR option, because it also accounts for environmental stresses that impact on water use. These stresses are incorporated into the ET_c through a stress coefficient (K_s) to determine the total water evapotranspired (ET_a) as follows:

$$ET_a = ET_c \times K_s = ET_o \times K_c \times K_s$$

Equation 2-2

The model requires climate, crop and soil data and can be used to estimate green and blue ET (ET_{green} and ET_{blue}) under both rain fed and irrigated conditions. In the case of rain-fed conditions, the ET_{blue} is zero. ET_{green} is calculated by specifying 'no-irrigation' when running the model. The model will then calculate the ET_a, which, in this case, is equal to the ET_{green} (Hoekstra et al. 2011).

The equations for blue and green WFs (**Equation 2-3** and **2-4**) were taken from the WFN manual. According to **Equation 2-3** and **2-4**, the blue and green WFs only include water evapotranspired by the crops during cultivation.

$$Blue\ WF = \frac{min\ (Crop\ ET,\ Irrigation)}{Yield}$$

Equation 2-3

and

$$Green\ WF = \frac{[Crop\ ET - min\ (Crop\ ET,\ Irrigation)]}{Yield}$$

Equation 2-4

where, *crop ET* is the crop evapotranspiration (mm) and *irrigation* is the total irrigation (mm) from planting to harvesting. Grey water is equal to the volume of freshwater required to dilute emitted pollutants to ambient levels. **Equation 2-5** shows the formula that is used to calculate the grey WF (Hoekstra et al. 2011).

$$\text{Grey WF} = \frac{L}{C_{max} - C_{nat}}$$

Equation 2-5

Where L is the load of pollutant released to the water source, C_{max} is the maximum concentration of pollutant at ambient water quality standards and C_{nat} is the natural concentration of the pollutant in the receiving water source. The natural concentration of the pollutant in the receiving water source and the ambient water quality standards differ from one country to the next. Therefore the same pollutant load will have different grey WFs depending on the natural background concentration and the chosen water quality standards (Hoekstra et al. 2011). The blue green and grey volumetric WF is divided by crop yield to give units in volume of water per mass of crop yield (Hoekstra et al. 2011).

- **Sustainability assessment**

According to Hoekstra et al. (2011), water use in a catchment is not sustainable when the environmental flow requirement (EFR) or ambient water quality standards are compromised, or when water allocation is inefficient or unfair. Two criteria for judging sustainability are proposed: (1) when a process is situated in a certain catchment at a certain time of year where the overall WF is unsustainable, and (2) when either the blue, green or grey WF can be reduced or avoided altogether at acceptable societal cost. Accordingly, the overall sustainability of the WF of the catchment or basin as a whole needs to be known before a sustainability assessment for a product or process can be assessed. The authors argue that the available waste assimilation capacity and issues of fair and efficient water resources allocation are best understood at this level.

Hoekstra et al. (2011) also propose that sustainability is assessed from three different perspectives as follows:

- Environmental – River and groundwater flows must be maintained at levels that adequately support the dependent ecosystems and human livelihoods. Pollutant levels must remain below water quality standards (although these standards are not always prescribed).
- Social – A minimum amount of safe and clean water is needed for basic human needs, namely drinking, cooking and washing (United Nations 2010). The Universal Declaration of Human Rights (United Nations 1948) established food as a human right, so the water required to produce this food can be linked and considered a right even if not formally established. As communities can import their food from other catchments, allocation of water to food security can be secured at a global level.
- Economic – The allocation and use of water needs to be done in an economically efficient way, and the benefits of use should outweigh the costs, including ‘externalities, opportunity costs and a scarcity rent’.

Identifying and quantifying sustainability criteria, followed by the identification of ‘hotspots’ are the first two steps of a site-specific sustainability assessment. Hotspots are defined as periods of the year for which WFs are regarded as unsustainable for specific (sub) catchments (Sustainability assessment is described in the next section). The WFN’s WF is placed in a geographic context by comparing the calculated WF with available water resources (m^3 yr^{-1}) in the same sub-catchment, catchment or basin (termed the hydrological unit). Specific time periods are also considered to account for seasonal variations and to place the WF in a temporal context. Deciding at which scale to look for hotspots appears to be a challenge, as hotspots may disappear at coarser resolutions, but much more data is needed to identifying hotspots at finer resolutions. In the case of pollution, pollutants may accumulate downstream, in which case problems might only emerge at larger scales.

According to Hoekstra et al. (2011) green water availability (WA_{green}) in a catchment *x* is calculated as the total ET of rainwater from land (ET_{green}) minus ET from land reserved for natural vegetation (ET_{env}) and minus ET from land that cannot be made productive (ET_{unprod}) (eg. mountainous areas with steep slopes, or periods not suitable from crop production) for month *t* (**Equation 2-6**). The level of green water scarcity (WS_{green}), or fraction of green water appropriation, is the ratio of the total green WFs (ΣWF_{green}) to green water availability (WA_{green}) (**Equation 2-7**).

$$WA_{green}[x,t] = ET_{green}[x,t] - ET_{env}[x,t] - ET_{unprod}[x,t] \qquad \text{[volume/time]}$$

Equation 2-6

$$WS_{green}[x,t] = \frac{\Sigma WF_{green}[x,t]}{WA_{green}[x,t]} \qquad \text{[volume/time]}$$

Equation 2-7

Hoekstra et al. (2011) acknowledge that the issue of quantifying green water scarcity is 'largely unexplored'. For example, data on the water use of natural vegetation is often lacking. The authors recommend that this approach therefore only be used in pilot studies to explore the usefulness of such an approach. The authors also note that the difference in green water use between crops and natural vegetation may affect blue water availability, but this will generally be small on the basin scale and can therefore be neglected.

The total blue water availability (WA_{blue}) for a catchment is defined as the natural runoff in the catchment (R_{nat}) minus the environmental flow requirement (*EFR*) (quanitities and timing of flows required to sustain freshwater and estuarine ecosystems) (Hoekstra et al., 2011):

$$WA_{blue}[x,t] = R_{nat}[x,t] - EFR\ [x,t] \qquad \text{[volume/time]}$$

Equation 2-8

If the blue WF exceeds WA_{blue}, then the EFR has been violated. It is possible that this may only be the case for certain months of the year. Note that natural and not actual runoff is used, because in most cases actual runoff has already been affected by upstream water consumption. As with WS_{green}, blue water scarcity (WS_{blue}) is defined as the ratio of the total blue WFs (ΣWF_{blue}) to blue water availability:

$$WS_{blue}[x,t] = \frac{\Sigma WF_{blue}[x,t]}{WA_{blue}[x,t]} \qquad \text{[volume/time]}$$

Equation 2-9

It is recommended that WS_{blue} be calculated on a monthly rather than an annual basis. In addition, the impact of the blue WF on 'blue water stocks' (water stored in dams and aquifers) should also be considered. Richter (2010) proposes that 'sustainable boundaries' should be established below which water levels should not drop.

From this it is clear that in an irrigated agriculture context, not only crop models, but also larger scale hydrological models (which range from simple to highly complex) are required to estimate blue and green water availability and scarcity. Both crop and large-scale hydrological modelling skills, which are often scarce, are therefore required for comprehensive WF sustainability assessments.

Finally, in order to make their WF accounting compatible with LCA studies and to better enable visualisation of local impact, Hoekstra et al. (2011) propose the calculation of WF indices. These are calculated using the blue/green WF of a product specified by catchment *x* and month *t*, and blue/green water scarcity by catchment and month. The two matrices are multiplied and the resulting matrix is summed. The grey WF index is based on the grey WF and the level of water pollution, both specified by catchment and month. Hoekstra et al. (2011) caution that these impact indices can add limited value as it is the underlying variables that contain information that can guide mitigation measures.

2.2.1.3 Strengths and weaknesses

The WFN approach is useful, because it provides guidelines for carrying out a water use inventory assessment. The strong points of the method are the inclusion of:

- Blue, green and grey WFs.
- EFR in the sustainability assessment.
- Temporal and geographic components.

The WFN approach, however, has been criticized for having a number of shortcomings as described by (Pfister et al. 2011, Ridoutt and Pfister 2010, Wichelns 2010, Wichelns 2011):

- The method does not provide information on the opportunity costs of inputs or compare the incremental costs and benefits of water uses. This information is required by policy makers.
- Representing water quality impacts, i.e. grey water, in terms of a volume, has limitations (reffered to in **Section 2.4.3**).
- The summation of blue, green and grey water is problematic, because of differences in their associated impacts and costs (refer to **Section 2.4.4**).
- It does not adequately characterise impacts on local water resources (referred to in **Section 2.4.5**).
- The proposed sustainability assessment does not give a clear indication of how information can be obtained to give the volumetric WF a stress weighting.
- Meaningful comparison between different volumetric WFs is not possible, because of the lack of local impact characterisation. Consuming the same volume of water in two different places will have different environmental impacts due to differences in water availability and demand.
- While a monthly WS_{blue} is envisaged to be valuable information from a water resources management perspective, it may not adequately account for the buffer capacity during dry periods provided by water stored in aquifers or dams (which is replenished in wet periods). This will require WF accounting at a larger temporal scale, for example taking into account dry-wet year cycles of a particular region.

2.2.1.4 Examples of application in agriculture

Several WF studies have been conducted, which indicated that WFs can be a useful tool to quantify direct and indirect water use with its flexibility being particularly advantageous, as it can be applied to various entities, including products, consumers, businesses and catchments (Ranchod et al. 2015).

- **Water footprints of products**

A number of studies have been conducted on the WFs of various crops. The WFN calculated the WFs for several crops from global databases on a high resolution at a 5 x 5 arc minute grid (Mekonnen and Hoekstra 2011). In South Africa, WFs were calculated for the cultivation of various crops, including cabbage (*Brassica oleracea*), tomatoes (*Solanum lycopersicum*), spinach (*Spinacia oleracea*), potatoes (*Solanum tuberosum*) and green beans (*Phaseolus vulgaris*) cultivated under different smallholder irrigation schemes (Nyambo and Wakindiki 2015), for lucerne (*Medicago sativa*) that serves as livestock feed for milk production (Scheepers and Jordaan 2016), for sugarcane (*Saccharum officinarum*) (van der Laan et al. 2015) and for the biodiesel crop *Jatropha curcas* (Jongschaap et al. 2009). A product WF was calculated for producing beer by SABMiller in South Africa (SABMiller and WWF 2009). The importance of calculating WFs with local data and interpreting WFs within the local context were noted (Nyambo and Wakindiki 2015, Scheepers and Jordaan 2016).

Chapagain and Orr (2009) calculated the virtual WF of tomatoes consumed in Europe, but originating from Spain. Tomatoes in Spain are cultivated in open systems and in plastic covered houses. The virtual water content of tomatoes is defined as crop water use per yield. Crop water use is classified as evaporative water use, i.e. blue and green water use, and non-evaporative water use, i.e. grey water use. Green and blue water use is determined by the evaporation requirement of the specific crop and the availability of soil water, which are both calculated using the CROPWAT model as discussed in **Section 2.2.1.2**.

The study indicated that the evaporative virtual water content of tomatoes grown in open systems is 63.7 m^3 t^{-1} and in covered systems it is 33.5 m^3 t^{-1}. Non-evaporative water use, i.e. grey WF, resulted in 8 m^3 t^{-1} and 4 m^3 t^{-1} for open and closed systems respectively. Tomatoes exported from Spain have a green, blue and grey WF of 13.6 m^3 t^{-1}, 60.5 m^3 $tonne^{-1}$ and 7.2 m^3 t^{-1}, respectively. The consumption of Spanish tomatoes in the European Union has a green, blue and grey WF of 13.6 Mm^3 yr^{-1}, 57.9 Mm^3 yr^{-1} and 7.2 Mm^3 yr^{-1}, respectively (Chapagain and Orr 2009). The study determined volumetric WFs only, but emphasised the need to integrate findings with Ecological Footprint (EF) studies and LCA to characterise water use in the context of local water availability (Chapagain and Orr 2009).

In a study to estimate the impact of food wastage on natural resources, the United Nation's Food and Agriculture Organization (FAO) used the WFN approach, together with assessments of the ecological footprint, and land-use and climate change impacts. It was determined that globally 1.3 G tonnes of food are wasted. This is more than 20% of global agricultural production of food and other crops. The consumptive blue WF of food wastage is approximately 250 km^3. Combining these four methods was considered useful because together they gave an indication of the extent and significance of the impacts of food wastage, and they made it possible to prioritise management actions and to identify opportunities (FAO 2013).

- **Water footprint of a nation**

Chapagain and Orr (2008) determined the WF of the United Kingdom from the consumption of agricultural and industrial products and the use of water in households. Both locally and globally sourced products were included in the analysis. In terms of agricultural products, the WF was calculated for 503 crops, including cotton, food and flowers and 141 livestock products sourced both from within the UK and from other parts of the world. Industrial products used in the analysis included chemicals, machinery etc. It was determined that the UK consumes 102 Gm^3 per annum, which amounts to an average of 4 645 ℓ per person per day. The WF of agricultural products consumed in the UK is 74.8

Gm^3 yr^{-1}, which is 73% of the total footprint. Industrial products consumed made up 24%, while household water use was only 3% of the total WF. The study identified sugar cane, tomatoes and cotton as crops of which high volumes are consumed in the UK that are grown in countries with water scarcity. WFs were calculated for South Africa as a whole, where WFs were considered useful to inform policy making and to improve sustainable development (Pahlow et al. 2015).

- **Water footprint in a catchment**

Hoekstra et al. (2012) calculated the footprint of water uses for 405 river basins from 1996 to 2005. The study focused on water consumption instead of water withdrawal and also used monthly water use data rather than annual data, which gave a complete picture of seasonal water scarcity. Only 20% of runoff is considered to be available for use, in order to account for flow requirements of the aquatic systems. Blue WFs were included in this assessment, but green and grey WFs were excluded. Blue water consumption was determined as the difference between water used under rain-fed conditions (green WF) and under irrigated conditions.

The study indicated that, on average, agriculture accounts for 92% of the global blue WF. This is, however, variable between seasons and from one year to the next. It was found that twelve river basins consume more than 40% of available runoff, thereby causing severe water stress, throughout the year. The Groot-Kei River Basin in the Eastern Cape, South Africa, has severe water scarcity for eleven months of the year. Several river basins, including most of South Africa, suffered severe water scarcity for only a few months in the year, highlighting the importance of analysing WFs on a monthly level (Hoekstra et al 2012).

Other WF studies have also been conducted on a catchment level. Water footprints were calculated for agriculture in the Breede Water Management Area and was considered to assess water used in terms of economic gains and job creation (Pegasys 2012). Water footprints of crops were used to assess agricultural water use on the High Plains Aquifer, which were linked to reductions in groundwater levels (Multsch et al. 2016).

- **Water footprint of businesses**

SABMiller, in partnership with the World Wildlife Fund (WWF) and the WFN, carried out WF assessments of their own operations in South Africa and the Czech Republic. Water footprints provide information to a business such as SABMiller as to how much water is used where, which enables them to identify operational, reputational and regulatory risks associated with water scarcity. A WF method must enable a business to reduce business risks and environmental impacts by improving management of operations and by informing collaboration with suppliers and government. The WF was calculated for the entire supply chain, starting with primary production and ending with the disposal and recycling of bottles. SABMiller provided datasets for all stages of its supply chain and from its suppliers. Data gaps were filled through literature surveys. The WFs were calculated for direct and indirect water uses but excluded the virtual water used to produce machinery and vehicles. It was determined that the blue and green WF of beer was 155 litres of water per litre of beer produced in South Africa and 45 litres of water per litre of beer produced in the Czech Republic was. The difference is attributed to water use during the crop production stage, where South Africa has higher evaporation rates and relies more on irrigation imported crops etc. Local impacts of crop water use were included by mapping all crops grown within the South African Water Management Areas (WMAs) and considering the constraints in each WMA. The information from the WFs were used to develop a water risk matrix, which led to the formulation of local action plans to mitigate these risks (SABMiller and WWF 2009).

The WFN approach assisted The Coca Cola Company to achieve a 20% reduction in its water use between 2004 and 2012 (The Coca Cola Company 2010). In 2004 The Coca Cola Company used 2.7 litres of water to produce 1 litre of product, and in 2009 this was reduced to 2.36 litres. The work done by the Coca Cola Company highlighted the high proportion of water used in the primary production stage of their supply chain.

Using the WFN methods, Unilever identified the water use for tomatoes and sugar production as being a priority. Locations were also identified where water use impacts have to be addressed. This enabled Unilever to prioritise actions and develop plans with their suppliers to reduce water use impacts (Unilever 2012).

2.2.2 LCA approach by Pfister et al. (2009)

2.2.2.1 Concept

Pfister et al. (2009) suggested a WF method based on the LCA approach. A regional Water Stress (WS) index is calculated to characterise local water use impacts. This method is therefore useful in showing the region-specific effects of water consumption (Ridoutt and Pfister 2010). The index follows a logistic function from 0.01 to 1, with a withdrawal-to-availability ratio of 0.4 (often referred to as the threshold between moderate and severe water stress) resulting in a WS index of 0.5. The results are a stress-weighted index reported as 'water equivalents' (H2O-e) which gives an indication of the product or activities' impact on water resources (Ridoutt and Pfister, 2010).

In this methodology, green water is not considered to have any direct impacts on water availability. It is argued that green water, like soil and solar radiation, is only available through occupation to land, leading therefore to an inseparability between green water and land. While changes in green water use by crops versus natural vegetation may have impacts on blue water resources, most agricultural systems have been noted to intercept less precipitation than natural vegetation (Scanlon et al. 2007). For this reason, this method does not include green water in WF accounting (Ridoutt and Pfister 2010). There is a recognised need to quantify water quality impacts as part of the WF, but the grey water concept is not considered to be ideal. An alternative method is proposed by Ridoutt and Pfister (2013), which makes use of advanced LCA modelling using eutrophication, freshwater ecotoxicity and human health impacts as impact indicators (Ridoutt and Pfister 2013).

The International Standards Organization (ISO) published a global WF standard in August 2014 (ISO 14046 2014). The Standard is closely related to the LCA method proposed by Pfister et al. (2009), it gives broad and flexible guidelines and includes a few important principles. Water footprints, according to the Standard, must consider the full life cycle of a product, must include an environmental impact assessment and must preferably be based on scientific evidences. The Standard also has specifications on how WF are reported, in order to ensure transparency. However, the scope of the ISO standard does not include a way to report the results as product labels. Similar to the LCA methodology of Pfister et al. (2009) it is suggested that results be reported as 'water equivalents' (H2O-e) and the Standard also proposes the use of other mid-point indicators firmly established in Life Cycle Assessment methodology, such as estimating eutrophication potential in 'phosphate-equivalents' in the case of nitrogen and phosphorus pollution from agriculture.

2.2.2.2 Calculation

A life cycle inventory is generated to determine all products consumed. The volume of water consumed to produce the relevant products is taken from the virtual water database published by Chapagain and Hoekstra (2004). This consumptive water use is further analysed using the WS Index (Pfister et al. 2009).

The WS index is determined using the WATERGAP 2 global hydrological and global water use models (Alcamo et al. 2003). The WS index is based on the water withdrawal (WU) to water availability (WA) ratio (WTA). Annual data is used to determine the WTA, but a variation factor (VF) is included to reflect the monthly and annual variation in precipitation. Dams reduce the variation in water availability; as a result the variation factor is reduced for regulated catchments (Pfister et al. 2009). **Equation 2-10** to **2-11** shows the calculation of the WS Index.

$$WTA\ in\ regulated\ catchments = \sqrt{VF} \times \frac{WU}{WA}$$

Equation 2-10

$$WTA\ in\ non-regulated\ catchments = VF \times \frac{WU}{WA}$$

Equation 2-11

$$VF = e^{\sqrt{\ln(S_{month})^2 + \ln(S_{year})^2}}$$

Equation 2-12

where S_{month} and S_{year} is the standard deviation of monthly and annual precipitation respectively. The VF is weighted by the mean annual precipitation. The WTA is used to calculate the *WS index* as follows (Pfister et al. 2009):

$$WSI = \frac{1}{1 + e^{-6.4\, WTA}(\frac{1}{0.01} - 1)}$$

Equation 2-13

The WS index follows a logistic function. The minimum WS index value is 0.01, which represents no stress and the maximum WS Index is 1, which represents extreme water stress. Minimal, moderate and severe water stress is linked to the WS index values based on expert opinions. It describes water stress at the local watershed level at a spatial resolution of 0.5 degrees (Pfister et al. 2009).

2.2.2.3 Strengths and weaknesses

The WS index approach of Pfister et al. (2009) has the following strengths:

- It compares impacts of activities on a local scale.
- The WS index reflects the volume of available water in the area where the activity occurs and.

- The method simultaneously determines the potential impacts of water pollution on human health, ecosystem quality and resource depletion. If these endpoint impact categories can be determined correctly it can assist in management decisions.

Weaknesses of this method include:

- Although a VF is included to account for seasonal variation in precipitation, this factor is calculated using the average variation in rainfall and does not reflect times of particularly high water scarcity or abundance.
- The WTA ratio requires that water inflows exceed outflows, because stored water cannot be sustainably utilised in the long term. However, this ratio does not take into account the important role of water storage in water attenuation in the short term (Berger and Finkbeiner 2013).
- Determining endpoint impact categories such as human health, ecosystem quality and resource depletion involves many assumptions and uncertainties (Goedkoop et al. 2013).

2.2.2.4 Examples of application in agriculture

This method was evaluated in case studies on the production of Dolmio ® pasta sauce and M&M® peanuts (Ridoutt and Pfister 2010) and cotton (Pfister et al. 2009). Ridoutt and Pfister (2010) demonstrated that the WS index-based approach successfully reflected regional impacts. The assessment resulted in a higher WF in areas with local water scarcity, despite low volumes of water consumption. The case study on cotton concluded that WF assessments should be done at a watershed level, because country level analyses do not reflect local variations (Pfister et al. 2009).

Allocation methods are required to identify the footprint of a product that is produced in a process where several other products are also produced. Each product should be allocated a portion of the impact that comes from the entire process. This allocation can, for instance, be made based on the mass or economic value of each product. Luo et al. (2009) compared different allocation methods with each other in a case study on maize stover-based fuel ethanol. Impacts on ozone layer depletion, climate change and eutrophication potential were considered, among others. The study indicated that there were significant differences between the allocation methods used, and this type of method in LCA should still be refined. This issue will likely be relevant to WF studies and should receive attention in further research (Luo et al. 2009).

2.2.3 LCA adapted approach proposed by i Canals et al. (2009)

2.2.3.1 Concept

A WF methodology adapted for use in LCA that differentiates between two main impact pathways, namely, Freshwater Ecosystem Impacts (FEI) and Freshwater Depletion (FD) was proposed by i Canals et al. (2009).

This method also distinguishes between blue and green water resources. The use of green water by crops is considered to have the same impact as green water used by natural vegetation. Green water is therefore only important because it is used to determine the portion of blue water used. Blue water resources are further classified as flow (such as rivers and rain), fund (such as groundwater) and stock (such as fossil water). Water uses are classified as evaporative and non-evaporative. Evaporative uses cause water to be temporarily unavailable to other users. Non-evaporative water use occurs when water is returned to the basin where it originates from and becomes available to other users (i Canals et al. 2009).

An important feature of this method is the inclusion of land-use impacts on the availability of water. Transformed landscapes can result in a reduction in infiltration and an increase in runoff. For transformed land uses where infiltration rates are reduced, the volume and velocity of runoff is increased. Such fast moving volumes of runoff are unlikely to replenish aquifers and may cause flooding and impact on aquatic ecosystems. Land-use impacts that result in increased runoff will therefore have an increased WF. The contribution of land use to the WF is calculated by the difference between the water loss of the specific land-use and the water loss of a typical forest, which is the reference land use (i Canals et al. 2009).

2.2.3.2 Calculation

A Water Stress Indicator (WSI) for FEI is calculated using the following formula:

$$WSI = \frac{WU}{(WR - EWR)}$$

Equation 2-14

Where *WU* is water use, *WR* is available water resources and *EWR* is ecological water requirement. Estimates of water loss for different land uses were presented by i Canals et al. (2009). This volume is added to the volume of blue water consumption before multiplying the total with the WSI as the characterisation factor.

Freshwater depletion is calculated using an Abiotic Depletion Potential (ADP) formula (Milà i Canals et al. 2009):

$$ADP_i = ER_i - RR_i \, (R_i^2)^{-1} \, x \, R_{sb}^2 \, (DR_{sb})^{-1}$$

Equation 2-15

where: *i* is relevant water resource, *sb* is antimony (serves as the reference resource), ER_i is the extraction rate of resource i, RR_i is the regeneration rate of resource i, R_i is the ultimate reserve of resource I, R_{sb} is the ultimate reserve of antimony and DR_{sb} is the deaccumulation rate of antimony.

2.2.3.3 Strengths and weaknesses

This method makes a contribution to WF assessments by:

- Accounting for changes in ET and runoff due to land-use changes, which makes it useful in transformed landscapes; and
- Including ecosystem water requirements.

However, the method excludes water required by the social and economic system and it has been criticised for:

- Providing complex results that are difficult to understand. Normalisation with the rate of depletion of antimony, for instance, doesn't give an indication of the sustainable use of water (Clothier et al. 2012).
- The regional average data that is used does not reflect water use efficiency on a specific farm (Clothier et al. 2012, Jeswani and Azapagic 2011).
- Annual data conceals seasonal water scarcity (Jeswani and Azapagic 2011).
- The WSI implies that water impacts will increase linearly with water use, which is improbable (Jeswani and Azapagic 2011).

2.2.3.4 Examples of application in agriculture

This method was tested on broccoli production in Spain and the UK (i Canals et al. 2010). The results indicated the following:

- The WF reflected local impacts on water resources. The calculated WF was higher for Spain, which is a water scarce country where irrigation is required. The footprint in the UK was low, because the country has abundant water and produces broccoli under rainfed conditions.
- The method proved to be useful in incorporating ecological sensitivities in the WF. This provided management priorities to save water in areas, and production steps that will have most benefit to aquatic ecosystems.
- The WF is based on ET, which has the potential to underestimate the WF of a farm where water is wasted and lost through leakages (i Canals et al. 2010).

2.2.4 Hydrological based water footprint approach

2.2.4.1 Concept

Deurer et al. (2011) introduced a WF method based on hydrology, considering all components of the water balance and not just water consumption. According to this method, a negative WF is possible if the recharge of the blue water resource through return flows and precipitation exceeds the volumes abstracted. A negative WF is therefore required to sustain ecosystems that are dependent on groundwater. A positive WF indicates that water abstraction exceeds recharge through return flows and precipitation (Deurer et al. 2011). A zero WF is possible if return flows and precipitation are equal to abstraction volumes. Data used to calculate WFs is obtained on a local scale and over an annual water cycle (Herath et al. 2013a). Formulae are provided to calculate blue and green WFs. Grey WFs are calculated in the same way as proposed by Hoekstra et al. (2011).

2.2.4.2 Calculation

This approach uses a hydrological water-balance method, considering inflows, outflows and storage changes (Deurer et al. 2011, Herath et al. 2013). The calculation of the blue WF is based on the following equation:

$$\Delta\ Blue\ Water = D^r + D^{ir} + R^r + R^{ir} - IR$$

Equation 2-16

Where D^r is drainage under rain fed conditions, D^{ir} is the difference between drainage under rain fed and irrigated conditions, R^r is runoff under rain-fed conditions and R^{ir} is the difference between runoff under rain-fed and irrigated conditions. Drainage and runoff collectively forms the inflow into the blue water resource. *IR* is the amount of water abstracted from the blue water resource for irrigation and represents the outflow from the blue water resource.

The calculation of the green WF is based on the **Equation 2-17**.

$$\Delta\ Green\ water = D^r + ET^r + R^r - RF$$

Equation 2-17

Where ET^r is the ET under rainfed conditions and *RF* is the effective rainfall, i.e. excluding any water that is intercepted by the plant cover. Collectively D^r, ET^r and R^r forms the outflows from the green water resource and RF is the inflow into the green water resource.

2.2.4.3 Strengths and weaknesses

This method has advantages because:

- It is the only method that considers all aspects of the hydrological system, including climatic conditions, topography and soil characteristics, which is useful to regulators that allocate water for irrigation (Herath et al. 2013).
- Important local scale information is generated.

However, the method has some shortcomings including:

- Drainage and runoff are excluded from the WF, therefore the results will underestimate the WF of a farm that loses water through leakages etc.
- The sustainability indicator does not consider water requirements in the ecological, social and economic systems.
- This method conceals seasonal water scarcity, because it calculates water use and availability over an annual hydrological cycle.

2.2.4.4 Examples of application in agriculture

This approach was used to calculate the WF of the production of kiwifruit (Deurer et al. 2011), export apples (Clothier et al. 2012), potatoes (Herath et al. 2013 a) and wine (Herath et al. 2013) in New Zealand. In all these studies the green WF was determined to be zero, because soil water is replenished during the rainy season. This approach gave negative blue WFs for the primary production of kiwifruit, export apples, potatoes and grapes because groundwater inputs from return flows and precipitation are higher than the volumes abstracted.

The study on potato production done by Herath et al. (2013 a) provided useful information that contributed to the reduction of the grey WF. During the first 60 days after planting, the seedlings required very little fertiliser. The results indicated that fertiliser application during the first 60 days after planting results in increased NO_3-N leaching. The grey WF could therefore be reduced significantly if fertiliser is applied at 55 days after planting without compromising yield. The study claims that these findings are a result of the WF method they propose, but it is more likely a result of developing good agronomic practices.

The hydrological WF assessment on wine production carried out by Herath et al. (2013) indicated that primary production of grapes had a significantly higher WF than all other activities associated with the winery. Grey WFs were higher for Gisborne than for Marlborough, which, according to Herath et al. (2013), could be explained by the possibility that higher rainfall in Gisborne increases NO_3 leaching.

Gleeson et al. (2012) used a method based on the hydrological concept and defined the groundwater footprint as the surface area required to sustain water users and the environment. This tool provides a way to evaluate water use and renewal rates as well as ecosystem requirements at the aquifer scale. It also provides information to assess potential increases in agricultural yields, by comparing the spatial distribution of areas with low groundwater stress with areas that present opportunities for agricultural expansion. Global groundwater footprints were determined by comparing water flows into and out of aquifers. The assessment indicated that global water users require 3.5 times the surface area of current aquifers. It also indicated that only 20% of aquifers are overexploited, therefore the global WF is concentrated in a few countries.

Wu et al. (2012) improved the calculation of the grey WF of Hoekstra et al. (2011) by using the hydrological SWAT model to determine the fate of nitrates after application. This case study also identified the need for field verification of data used in WF assessments.

2.3 A review of published comparisons between different methods

2.3.1 Life Cycle Assesment approach versus Water Footprint Network approach

To estimate the WFs of Dolmio ® pasta sauce and M&M® peanuts, Ridoutt and Pfister (2010) utilised the WS index approach proposed by Pfister et al. (2009), accounting for blue water with the primary objective being 'the avoidance of water scarcity'. Grey WF were calculated according to the WFN approach, because the LCA methodology for the WF of pollution (Ridoutt and Pfister 2013) has not been developed at the time. For the agricultural ingredients used in the products, a WS index of 0.011 was used for the Clarence River catchment of New South Wales, Australia, while a WS index of 0.996 was used for the San Joaquin Valley of California, USA). The authors observed that the grey WF contributed 30 and 62% of the total WF for the pasta sauce and peanuts, respectively. From the figures presented in Table 2-1, the authors concluded that simply judging a product's water impact from a volumetric WF can fail to direct attention to the ingredient of greatest concern. Ridoutt and Pfister (2010) observed that the agricultural stage of production contributed 97% of the total footprint for the two products.

Table 2-1: Major agricultural ingredients contributing to the volumetric and stress-weighted water footprints (including [gray] water) of Dolmio ® pasta sauce (575 g) and M&M® peanuts (250 g) (Ridoutt and Pfister, 2010)

Ingredient	Volumetic water footprint (ℓ)	Stress-weighted water footprint (ℓ)
Dolmio ® pasta sauce		
Tomato products	149.9	133.9
Sugar	22.9	<0.1
Onion	12	1.8
Garlic	5.9	0.1
Minor ingredients	3.3	1.9
M&M® peanuts		
Cocoa derivatives	690.1	4.1
Peanuts	140.2	1.1
Sugar	135.1	0.9
Milk derivatives	133.6	5.3
Palm oil derivatives	27.3	<0.1
Minor ingredients	17.8	0.2
Tapioca starch	7.9	0.5

The WFN has since proposed including a sustainablility assessment step which can include weighting of the WF according to water availability/scarcity in the catchment being considered, although no specific method is prescribed. This weighting will allow similar conclusions to be drawn using the WFN method as was established in the Ridoutt and Pfister (2010) study. What remains to be debated is the inclusion of the green WF, and this is addressed further in the Discussion (**Section 2.5**).

Jeswani and Azapagic (2011) compared WF methods in a case study of maize-derived ethanol. Water footprint methods compared in the study included the WFN approach, the LCA approach by i Canals et al. (2009) and the LCA approach by Pfister et al. (2009). The study revealed significant differences between the results of the various WF methods that were compared, and revealed the importance of a standardised methodology (Jeswani and Azapagic 2011).

Several problems with these methods were identified, namely:

- Data from national and river basin level, as used by i Canals et al. (2009), does not always reflect the observed spatial variation within a county or river basin. Data on this level is therefore inappropriate to fully describe the impacts of water users.
- Water footprints are highly dependent on climatic conditions and seasonal variations, especially with regard to rainfall. Annual average data, as used by i Canals et al. (2009), also does not capture temporal variation of water availability and stress within a year and is not considered suitable to reflect the impacts of water use. Average seasonal variations, as used by Pfister et al. (2009), still do not reflect specific seasonal variations.

- For each of the methods, availability of data to conduct site-specific assessments was simply lacking. Lack of measurement of groundwater usage and discharge volumes is a major issue.

2.3.2 Hydrological approach versus the Water Footprint Network methodology

Studies have been conducted in New Zealand to compare the outcomes of the hydrological WF approach with the WFN approach in terms of blue and green WFs. These studies did not compare grey WFs, as the hydrological-based approach employs the same method to calculate the grey WF as the WFN. Estimating the WF for kiwifruit production, Deurer et al. (2011) observed a negligible net change in soil water, concluding that it is replensihed by rain each year, and concluded that the green WF can be discarded in similar studies. The authors further found that a net depletion of groundwater only occurred in two kiwifruit growing regions, with the rest resulting in a negative blue WF. On a regional average, the blue WF of a tray of kiwifruit was -500 ℓ when calculated according to the hydroloically based approach, compared to 100 ℓ based on the WFN approach. The authors claim that their approach is more 'hydrologically rational' than the WFN approach, as it does not just focus on consumption. Similar conclusions were reached following WF studies for apples and for wine production (Clothier et al. 2012, Herath et al. 2013). It is unclear whether this approach can be applied to all hydrologic systems, or how to make virtual water flow calculations from WFs estimated according to the hydrologically based method.

2.4 Water footprints: potential shortcomings and key challenges

2.4.1 Defining the aim of water footprint assessments

According to Launiainen et al. (2014), the different WF methods address different questions related to water use. Water footprint assessments can measure the volumes of water utilised by humans, indicate the sustainability of water uses or provide a tool to manage and increase efficiency of water uses. The specific aim would determine which approaches and datasets are required (Launiainen et al. 2014).

2.4.2 Critique of the inclusion of green water in water footprint analyses

According to Hoekstra et al. (2011), green water must be included in the calculation of WFs because green water is a scarce resource and its availability can reduce the volumes of blue water required. In opposition to this view, several authors suggest that green water impacts are often zero, because green water stores are replenished during the following rainy season (Clothier et al. 2012, Deurer et al. 2011, Herath et al. 2013). However, considering impacts on green water sources over an annual cycle must be challenged, because it does not reflect seasonal variation, which could be very significant.

Ridoutt and Pfister (2010) argue that green water use is not considered an impact, because of the inseparability of green water and land occupation. However, if less green water is used by a specific land use it may lead to increased blue water in rivers and aquifers as a result of higher levels of runoff or drainage.

According to Wichelns (2011), the distinction between blue and green water does not capture the hydrological complexity of water moving from soil to groundwater or surface water bodies and vice versa, i.e. continuous changes between green and blue water. Rainfall can either infiltrate to become soil water or it can become runoff. However, only green water is considered to originate from rainfall. Wichelns (2011) argues that established terms such as rainfall, soil water, groundwater and surface water make for a better classification of water than blue and green water. However, although established water management practices are already better developed, the WF concept can add value by conveying information to the general public in a way that is easy to understand.

2.4.3 Critique of the grey water concept in water footprint analyses

Ridoutt and Pfister (2013) criticise the concept of a grey WF proposed by Hoekstra et al. (2011) concepts for the following reasons:

- The LCA provides other innovative methods to measure such impacts.
- There are compounds in polluted water that do not have specified standards.
- It does not reflect resident times of pollutants.
- The term ‘grey water’ creates confusion, because it is also used to describe waste water from households;
- It creates the impression that polluted water must actually be diluted to manage its impact.

Wichelns (2011) pointed out that the impacts of substances that bio-accumulate (e.g. selenium) cannot be prevented by dilution and the grey WF would theoretically be infinite. He also argues that the grey WF does not address the complexity of water quality management. Water quality management normally deals with the effects of different pollutants, interactions between the pollutants or the effect of the physical characteristics of the farms and the application methods on the fate of pollutants (Wichelns 2011).

The differences in water quality standards from one country to the next as well as different natural background concentrations of pollutants causes the grey WF of a certain mass of pollutant released into the environment to be different from one location to the next. This adds further complexity to the grey water concept. Nonetheless, the grey WF concept is giving the impact of human activities on water quality the necessary attention. While the method may not be suitable for pollutants where load is more important than concentration, or for pollutants where there is no prescribed standard, in agriculture, which makes up over 90% of the world’s footprint, eutrophication which results from N and P export from agricultural systems is extremely important. As eutrophication is related to the concentration of N and P in the water, the grey WF does add value.

2.4.4 Reporting a water footprint as an aggregated number

Reporting WFs of blue, green and grey water as a single value is justified by previous studies on climate change (Weidema et al. 2008). A single score is easy to understand and therefore useful for raising public awareness and motivating behavioural changes. However, according to Ridoutt and Pfister (2010), blue, green and grey water differ with regards to the implications of impacts on the water source and also with regards to the opportunity cost associated with the management of these impacts. Interpretation of WFs reported as one aggregated number is not possible.

2.4.5 Local nature of water

The WF of an activity differs from carbon footprints, where an activity that releases CO_2 will have an equal effect on the global atmosphere irrespective of where the activity takes place. The WF of an activity, on the other hand, will differ from one region to another (Ridoutt and Pfister, 2010). For example, using one litre of water in the Nama Karoo might have a much greater impact on the environment than using one litre of water in the Eastern Cape. This local nature of water resources complicates the assessment of WFs, because site-specific data is often not available (Alcamo et al. 2003, Hoekstra et al. 2011, Jeswani and Azapagic 2011, Launiainen et al. 2014, Pfister et al. 2009).

Hoekstra et al. (2011) consider water to be a global resource based on the concept of virtual water trade. They argue that countries with abundant water can produce and export products to relieve the pressure on water scarce countries. Poor water resource management and inefficient use will therefore have a similar impact on global water resources, regardless of local conditions. Therefore, according to this approach, the WF is only determined by the volume of water consumed. This has been criticised by subsequent literature (Deurer et al. 2011, Ridoutt and Pfister 2010, Wichelns 2011), because water use in one area will have different impacts on water resources depending on local environmental and hydrological conditions. The concept of virtual water trade as a means to relieve the pressure of water scarcity in a country is criticized by Wichelns (2011), because international trade depends on many factors, such as comparative advantage and economic and strategic factors, and is not driven by the availability or scarcity of water.

2.4.6 Sustainability assessment

Water footprint assessments should ultimately indicate the sustainability of a water use. This sustainability is influenced by water availability and demand, which is complex to determine. A number of methods have been proposed to determine water use sustainability. Most methods determine sustainability indicators based on withdrawal to availability or consumption-to-availability ratios. These ratios understandably do not quantify water stocks in aquifers and dams, because the use of these resources will result in depletion over the long term. However, these ratios do not take into account the important buffering function of stored water in aquifers and reservoirs (Berger and Finkbeiner 2013).

2.5 Discussion and recommendations

2.5.1 Summary of key features of the water footprint methods

Table 2-2 summarises the four WF methods in terms of their respective classification of water, spatio-temporal scales, sustainability indicators, strengths, weaknesses and usefulness in agriculture.

Table 2-2: Summary of the approaches and usefulness of the four water footprint methods

Water Footprint Method	Water Classification	Spatio-temporal Scale	Sustainability indicator	Strengths	Weaknesses	Application Potential (Usefulness)
WFN	Blue, green, grey	Geographical and temporal components are included and used to identify 'hotspots', which are defined as periods of the year for which WFs are regarded as unsustainable for specific catchments.	Unsustainable blue and green WFs = water used > availability. Available green water = Total ET minus ET of natural ecosystems and unproductive land Blue water availability = runoff minus ecological flow requirements The grey WF is unsustainable if ambient water quality standards are exceeded.	Accounts for impacts on water quantity and quality Temporal and geographic components are included Ecological flow requirements are included in the sustainability assessment	Results do not provide information on opportunity costs or compare incremental costs and benefits of water uses, which is required to inform policy Issues with the concepts of grey water and reporting water quality and quantity impacts as an aggregated number Water uses considered to have a global impact, which underestimate local impacts The sustainability assessment does not give a clear indication of where information can be obtained Volumetric WFs cannot be compared, because of the local nature of water use impacts. Blue water scarcity determined on a monthly scale does not give an indication of the buffering capacity of storage structure over the long term.	It provides a simple guideline to determine WFs Also useful to monitor virtual water flows
LCA approach (Pfister et al. 2009)	Blue	Spatial: Watershed, i.e. catchment of a smaller stream Temporal: Annual rainfall with consideration of	Midpoint indicator: Water Stress Index based on withdrawal to availability ratio Endpoint indicators: Impact of blue water use on human health,	Watershed scale provides information on local variation. Water Stress Index reflects water availability / scarcity	Average variation in monthly rainfall conceals specific variations (Jeswani and Azapagic 2011) Withdrawal to availability ratios do not consider the important role of stored water	Useful tool to determine local impacts of water use. Useful management tool, because it considers impacts on human health (**social**

Water Footprint Method	Water Classification	Spatio-temporal Scale	Sustainability indicator	Strengths	Weaknesses	Application Potential (Usefulness)
		average monthly variation	ecosystem quality and resource availability	Includes estimations of endpoint indicators. Easier to understand as only blue water is considered	Calculation of endpoint indicators involves uncertainties	**impact**), ecosystem quality (**ecosystem impact**) and resource availability (**economic impact**)
LCA approach: (i Canals et al., 2009)	Blue and Green Blue: Fund, stock and flow Water use classification: Evaporative and non-evaporative	Spatial: River basin level, i.e. catchment of large rivers Temporal: Annual	Indicator of freshwater depletion: abiotic depletion potential formula Indicator of freshwater ecosystem impact: Water Stress Indicator based on withdrawal to availability. Available water excludes volumes required by ecosystems	Considers loss of water due to land-use changes Incorporates ecological water requirements	Results are difficult to interpret (Clothier et al. 2012) River basin scale conceals local impacts (Jeswani and Azapagic 2011). Annual data conceals seasonal water scarcity (Jeswani and Azapagic 2011). WS Indicator implies linear increase in water impact with water use (Jeswani and Azapagic 2011).	Useful in transformed landscapes Useful to determine regional impacts of water use
Hydrological-based method	Blue, green (generally considered to be zero), grey	Spatial: Local Temporal: Annual averages	Extraction exceeds recharge	Considers all aspects of the hydrological cycle Valuable local scale information generated	Results will underestimate the WF of a farm that irrigates inefficiently, if excessive water is considered to be return flow, which is seen as an input in the blue water resource. Ecological, social and economic water demands are not included. Seasonal water scarcities are concealed	Useful to determine water availability vs. demand on a local scale.

2.5.2 Fundamental viewpoint

A fundamental viewpoint must be defined to give an indication of what is expected from a WF calculation method. Each WF method can be evaluated according to this viewpoint. This study is based on the fundamental viewpoint that WF assessments must primarily promote sustainable water use (Figure 2-1: A). Sustainable water use is determined by several variables (Figure 2-1: B), including:

- Variables in the hydrological system, i.e. the system that determines water availability:
    - Climatic conditions such as rainfall and evaporation rates
    - Soil types
    - Topography
    - Landscape characteristics and land use
- Variables that define the environment, i.e. the systems that determine water demands:
    - Ecological system
    - Social system
    - Economic system (including agriculture)
- Variables related to water use:
    - Water use management
    - Water use efficiency
    - Water productivity

Most of these variables are difficult to manipulate, but more efficient water use management can be enforced through policies and water use efficiency can be achieved through increasing public and commercial enterprises awareness (Figure 2-1: C). In order to manage water use and increase the efficiency of water use, the volumes of water consumed and degraded must be measured and characterised according to local water resource availability and sensitivity (Figure 2-1 E & F). Impact characterisation should be informed by both the hydrological system that influences water availability, as well as the setting where water is required. Current and future water demands and management practices should also be considered as part of the environmental assessment (Figure 2-1: B).

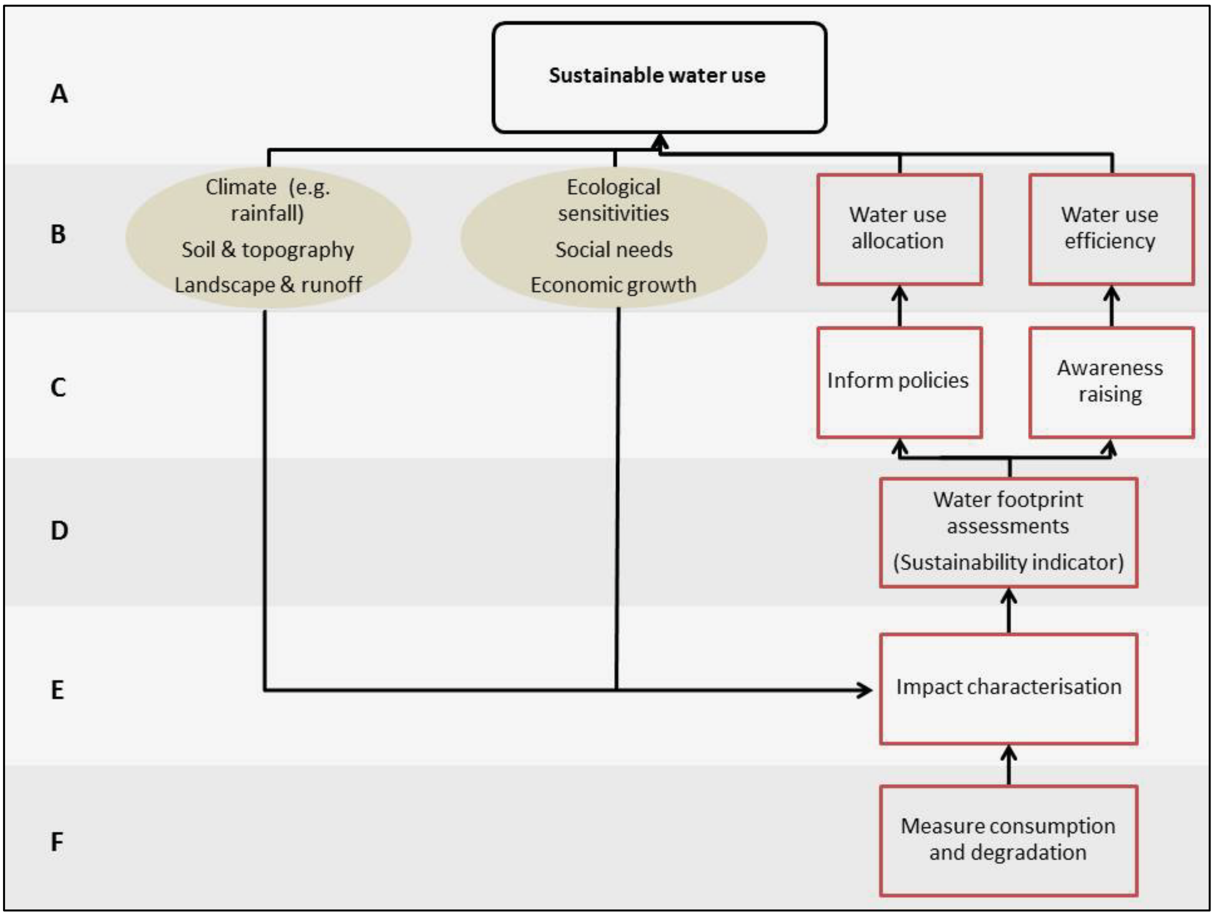

Figure 2-1: Schematic representation of the role of water footprint assessments towards the goal of sustainable water use. Brown oval boxes are variables that impact on sustainable water use, but is difficult to impossible to manipulate. Red rectangular boxes indicate variables that impact sustainable water use and how these impacts can be managed through water footprint assessments.

2.5.3 Assessment of water footprint methods

The fundamental viewpoints of the four WF methods were compared with the fundamental viewpoint defined for this review. It must be noted that the similarities identified here only reflects on the aspects that are considered by the various methods and are not an indication of how successfully these aspects are measured.

The WFN proposed a useful way to measure water consumption and degradation. Ecological impacts due to pollution are taken into account through grey WF and impacts due to consumption are included by subtracting ecological flow requirements from available water. The method highlights the need to reserve flow for basic human and economic needs, but does not provide a way to quantify these needs. Soil type is captured by the green WF, i.e. more green water will be available for soils with a higher water holding capacity. Climate data is used to estimate water availability, but landscape and land use effects on runoff are not considered. The method can inform policies by providing a simple universal way to estimate consumptive use for virtual water flows, and in later chapters it is illustrated how the method can assist catchment management practices. The WFN managed to raise awareness of water use impacts as a result of the consumption of products. Irrigation efficiencies are reflected by maximising green WFs (Figure 2-2).

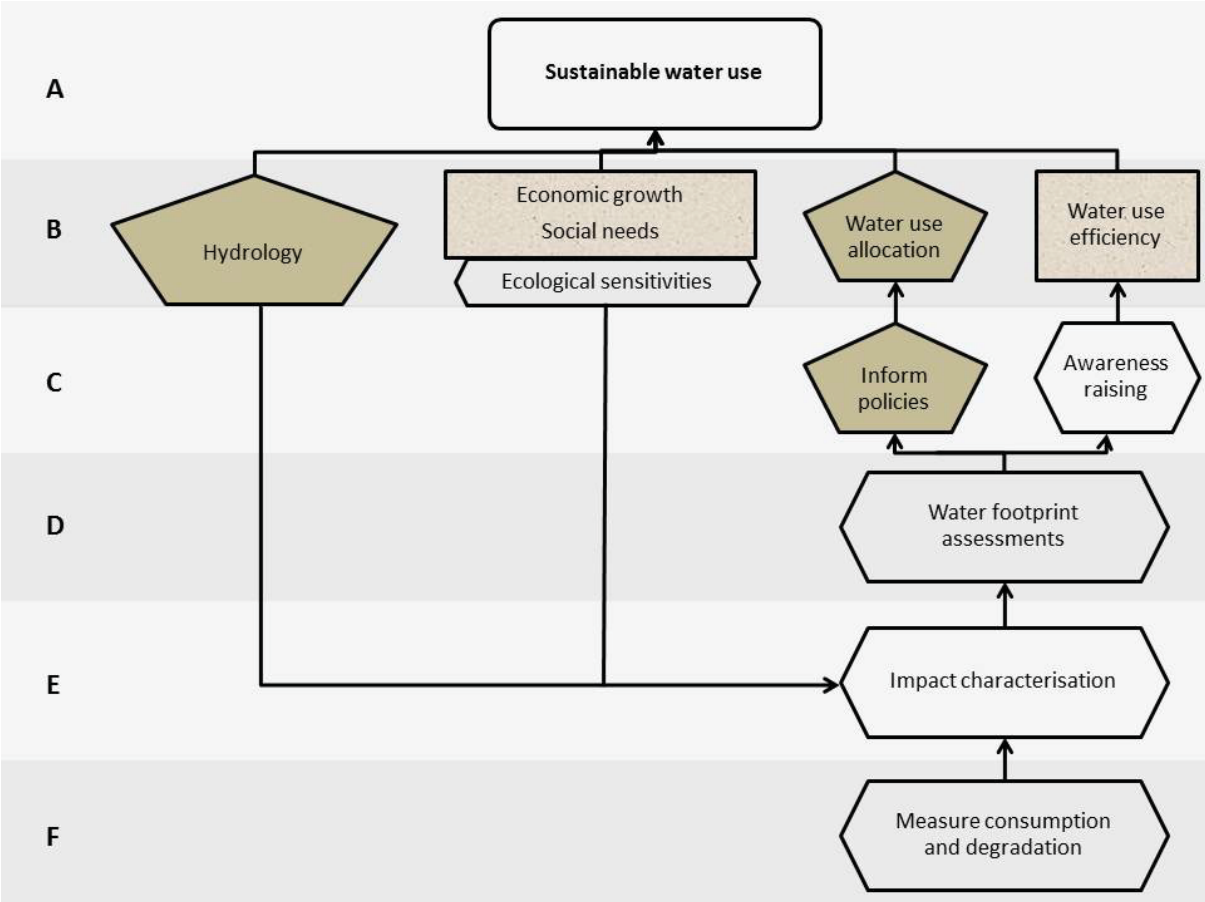

Figure 2-2: Similarities between the fundamental viewpoint of the WFN and the fundamental viewpoint proposed in Figure 2-1. Hexagon shapes indicate similarities in the viewpoints, square shapes indicate aspects lacking, pentagon shapes indicate aspects partly included in the WFN approach.

The LCA approach presented by Pfister et al. (2009) provides a stress-weighted method to characterise the impacts of volumetric blue water consumption. A sustainability indicator, namely the Water Stress Index, is based on the withdrawal to availability ratio. Water availability is determined using monthly and annual rainfall data. Landscape characteristics are considered in terms of stream flow regulation in the particular catchment. Green water is excluded, because it can only be accessed through occupation of land. Therefore, the effects of soil types and topography are not addressed. This indicator is used to determine impacts on human health (social need), ecosystem quality (ecological sensitivity) and resource depletion (economical requirements). However, ecological, social and economic systems are extremely complex and measurements of these endpoint indicators are mostly calculated with many uncertainties (Goedkoop et al., 2013). The methods might therefore require testing and continual improvements. The information generated by this method is believed to contribute to better resource management and more efficient water use. The fundamental viewpoint of this method therefore includes all variables that have an impact on sustainable water use, as defined in Figure 2-1, except the effect of soil types on water availability (Figure 2-3).

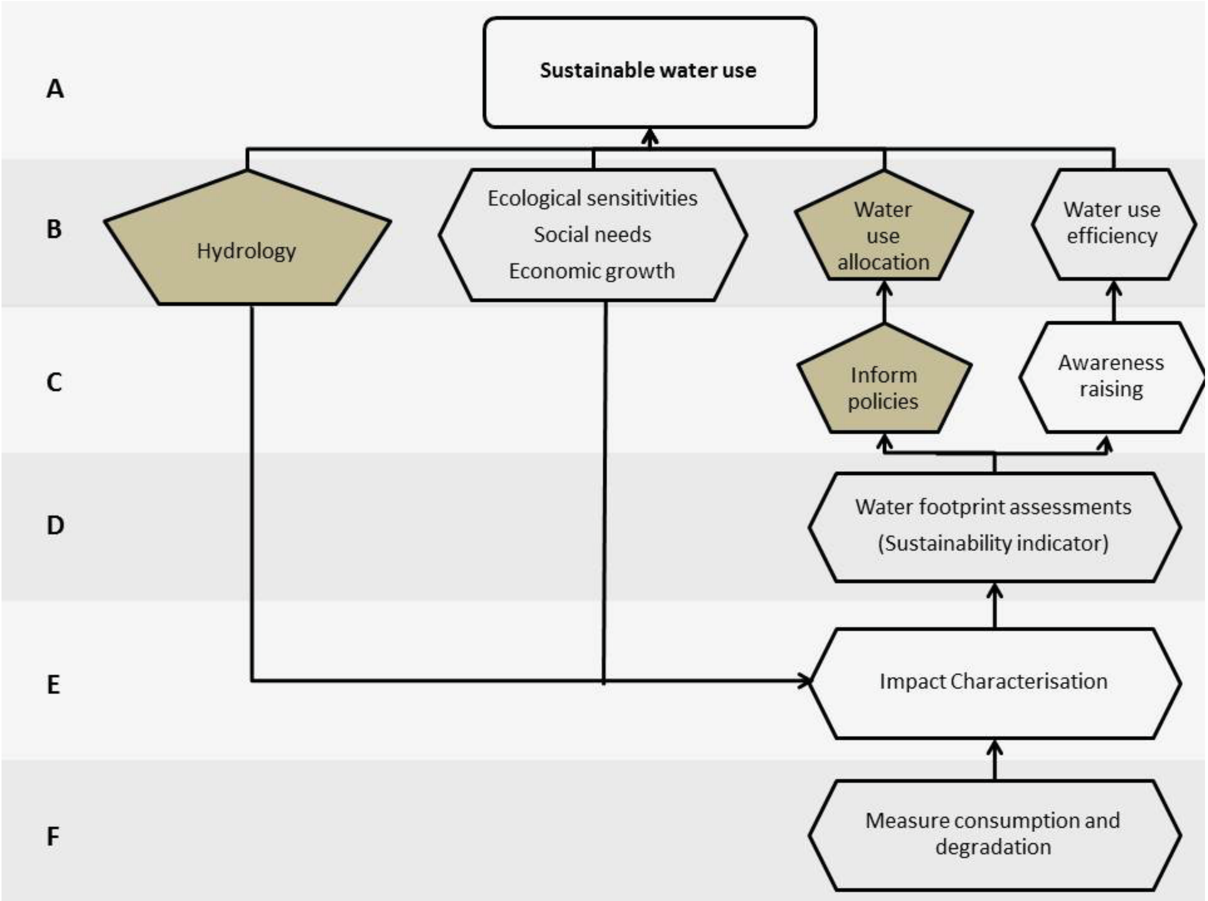

Figure 2-3: Similarities between the fundamental viewpoint of the LCA approach of Pfister et al. (2009) and the fundamental viewpoint proposed in Figure 2-1. Hexagon shapes indicate similarities in the viewpoints, square shapes indicate aspects lacking, pentagon shapes indicate aspects partly included in the LCA approach by Pfister et al. (2009).

The LCA-based approach proposed by i Canals et al. (2009) determines blue and green WFs. Water availability due to soil types and topography are reflected by the green WF. Water availability and the ecological water requirements are used to characterise water use impacts. Landscape characteristics are considered by calculating water losses due to various land uses. This approach excludes social and economic requirements from the sustainability indicator. Despite the potential of this method, it is complex to use and interpret, which may limit its impact and potential use for awareness raising (Figure 2-4).

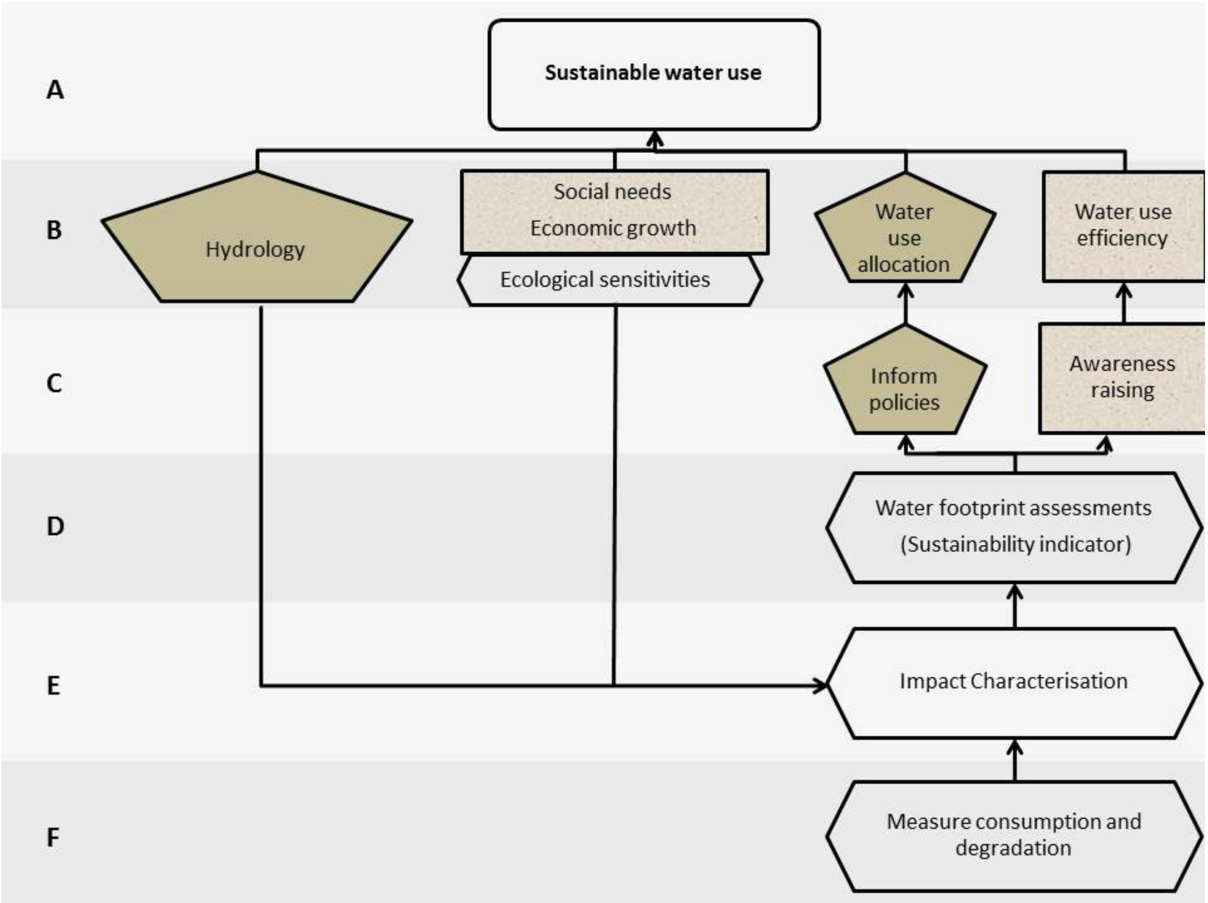

Figure 2-4: Similarities between the fundamental viewpoint of the LCA approach of i Canals et al. and the fundamental viewpoint proposed in Figure 2-1. Hexagon shapes indicate similarities in the viewpoints, square shapes indicate aspects lacking, pentagon shapes indicate aspects partly included in the LCA approach of i Canals et al. (2009).

The hydrological approach provides information on the local climate and geographical features that determine the inputs, outputs and storage changes of water to produce a sustainability indicator. The sustainability indicator of this approach does not address social needs and economic requirements. Ecological impacts due to pollution are taken into account through the grey WF, but the impacts on ecosystems due to a reduction in water availability and changes in river flows are not yet considered. It also does not consider current and future water use and environmental management practices. The WF according to this approach also does not reflect water use efficiency, because the volumes of return flows are not considered as part of the footprint (Figure 2-5).

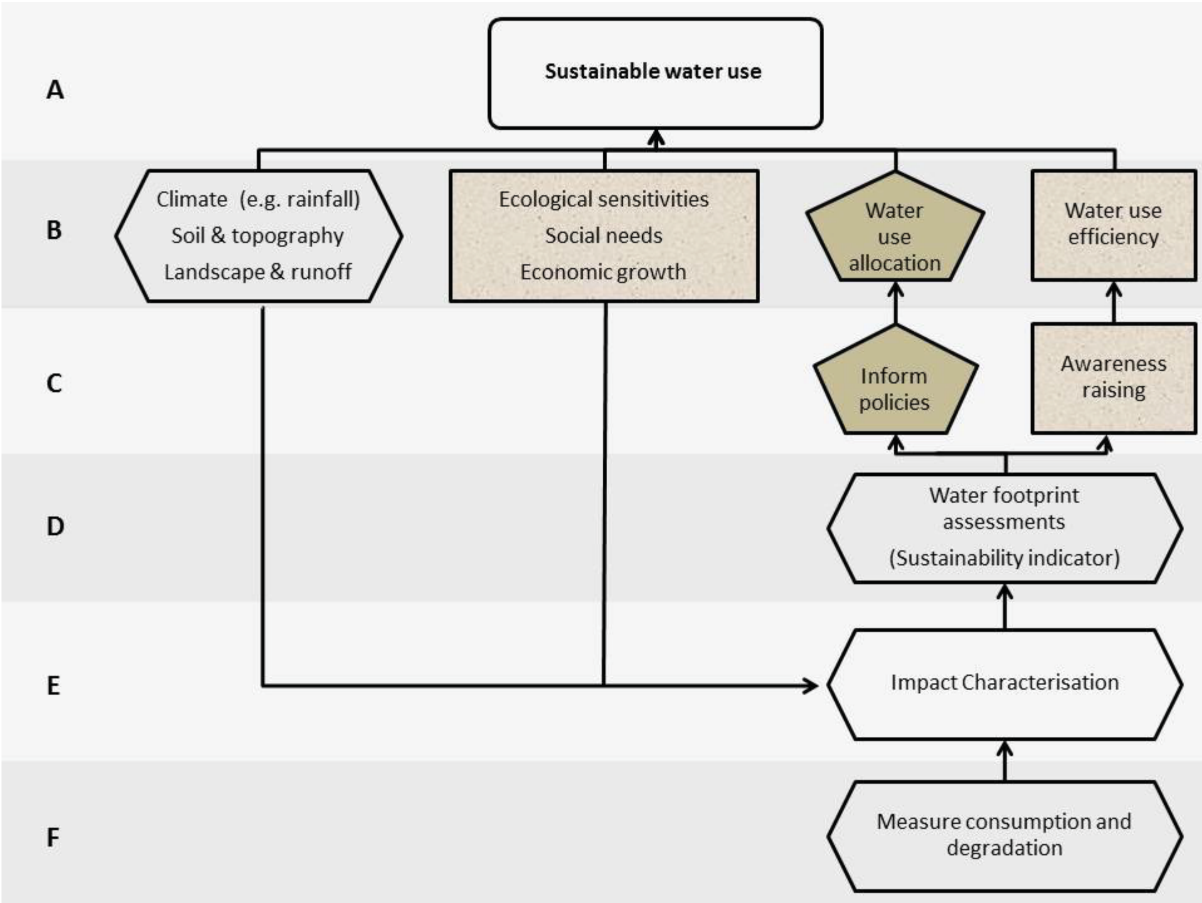

Figure 2-5: Similarities between the fundamental viewpoint of the hydrological-based approach and the fundamental viewpoint proposed in Figure 2-1. Hexagon shapes indicate similarities in the viewpoints, square shapes indicate aspects lacking, pentagon shapes indicate aspects partly included in the hydrological approach.

2.5.4 Can water footprint information be useful in a South African context?

South Africa is a water scarce country, and as a developing nation with many social issues, provision of freshwater to all users has proven to be extremely challenging. As a result, information to guide improved Integrated Water Resources Management can potentially be extremely valuable. Following this review, we envisage that WFs certainly has the potential to provide information for water management on a national scale (through policy making), on a regional scale (understanding water related risks and guide water allocation and management) and on a local or farm scale (identify opportunities to reduce consumption and degradation). Exploring ways that WF information can guide improved water management at these different levels (especially the latter two) is a key aim of this project. Universally, WFs has certainly raised awareness among various water users to better conserve this resource.

The WFN method has been heavily criticised by multiple groups, and has since been refined, most notably between 2009 and 2011 with the inclusion of a sustainability assessment step (Hoekstra et al., 2009; Hoekstra et al., 2011). What is still lacking is a more descriptive methodology for determining water availability/scarcity in a (sub)catchment. Conclusions on WF applicability following the review of the literature are summarised below.

2.5.4.1 *Use of water footprints on a national scale*

Hoekstra et al. (2011) point out that driven by growing international trade in water intensive commodities, fresh water is increasingly becoming a global resource. Users of water resources have 'become spatially disconnected from consumers', and as a result it is now possible for water scarce regions to attain food security through the import of agri-food products produced in regions where water is more abundant. Estimating the virtual water linked to food products that South Africa imports/exports according to the WFN's consumptive WF approach is envisaged to provide valuable information to policy makers who have the job of ensuring that South Africa is food secure, more especially as water becomes an increasingly scarce resource. Crude estimates have already been made, but local scientists should improve on these estimates using appropriate data. The WRC is already providing funding to address this issue.

2.5.4.2 *Use of water footprints on a regional scale*

Some of the concepts used in WFs are already covered in South African legislation. For example, accounting for changes in ET and runoff due to land-use changes (i Canals et al., 2009) is considered in the Water Act of 1998 as a Streamflow Reduction Activity, and accounting for ecological flow requirements (Hoekstra et al., 2011 and i Canals et al., 2009), is similar to our 'Ecological Reserve' concept. However, the WF concept can add much value and can potentially provide useful information to a catchment or aquifer manager. Linking WFs with total agricultural yields within a catchment or on an aquifer can provide information on the volume of ET used to obtain crop yields. Such information is seldom available and can also assist a manager to allocate water and monitor the water use according to crop yields.

2.5.4.3 *Use of water footprints on a local scale*

WFs can provide valuable information to farmers. A farmer can use WFs to determine which crops in the different seasons will provide the best yields when water limitations and allocations are enforced. Alternatively, a farmer can use WFs to determine which crops will provide the highest income or nutritional value with a certain volume of water. Currently, however farmers are making decisions about which crops to plant based on market demands.

There is growing interest in farm level assessments for the purposes of on-farm water management or planning and for emerging concepts such as Water Stewardship accounting (Alience for Water Stewardship 2012) and Global Gap certification (GlobalG.A.P. 2013). WFs can potentially become a metric used to indicate good irrigation management practices. Where over-irrigation occurs, irrigation volumes applied exceed crop water requirements, resulting in an entirely blue WF (consumption) despite significant rainfall during the growing season. Raising awareness of this issue among farmers so as to increase their ratio of green to blue water use has numerous advantages: it may lead to a greater volume of water remaining in the river as environmental flow or available to other users, reduced greenhouse gas emissions as a result of reduced pumping of irrigation water pumping and potentially fewer nutrients and pesticides leached from the system.

2.5.4.4 Merit of classifying water as blue, green and grey

It remains to be decided whether green water is important for inclusion in the overall WF. There is some merit to LCA groups' argument that green water consumption and land use are inseparable and should therefore be excluded from the quantification of water scarcity impact. Whether green water use of natural vegetation should be considered to establish a baseline also needs to be further assessed. The hydrological-based method, which quantifies green water uses by considering changes in soil water content over an annual hydrological cycle has weaknesses which need to be better understood.

Flaws in the grey WF have been discussed, but the major strength of this concept is that impact on water quality, often neglected in the past, is now getting the attention it deserves. This is particularly important in a South African context as we have some of the most polluted water bodies in the world. Quantifying non-point source pollution from agricultural systems is extremely complex and carries large uncertainties. Some advocate the use of LCA methodology to quantify water quality impacts (eg. potential eutrophication, potential exotoxicity), but for South Africa, locally relevant database information for LCA is largely lacking, making this option unavailable in many cases.

2.6 Conclusion

In order to conduct a WF assessment, active data collection for the product or process of interested in is required. This acquired data already has the potential to improve understanding of the system and, therefore, its management. How much value is added by placing this information in a WF framework is a question requiring further exploration. Following this review, it is believed that WF certainly has the potential to assist in improving the management of a water-stressed landscape. While the idea of accounting for blue water consumption is logical and universally accepted, the value of green water accounting is less clear, and weaknesses in the grey WF concept have constrained widespread application.

This review highlighted the strengths and weaknesses of four different WF methodologies, based on existing literature. Preliminary indications from this review have shown that choice of method may be driven by site-specific characteristics, and that the different methods can complement each other. Further comparisons between three of these methods, namely the WFN (Hoekstra et al. 2011), the LCA of Pfister et al. (2009) and the hydrological (Deurer et al. 2011) methods, were made by applying them to vegetable crops on the Steenkoppies Aquifer in **Chapter 3**.

3 SUGGESTED METHODOLOGIES TO ESTIMATE WATER FOOTPRINTS

by

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3.1 Introduction

In **Chapter 2** a literature review compared different water footprint (WF) methodologies according to published information. In this chapter, WFs of vegetables produced on the Steenkoppies Aquifer are calculated according to three methodologies, namely the Water Footprint Network (WFN) methodology (Hoekstra et al. 2011), the hydrological methodology (Deurer et al. 2011) and the Life Cycle Assessment (LCA) methodology (Pfister et al. 2009). The WF results that arise from each methodology are compared to better understand the usefulness of the information provided and to select a methodology that is most suitable for the Steenkoppies Aquifer case study.

The Steenkoppies Aquifer (Lat: 26.03° S to 26.19° S, Long: 27.65° E to 27.48° E; Altitude 1560 to 1650 m) located west of Tarlton, in Gauteng, South Africa, is a dolomitic karst aquifer and a source of irrigation water for one of the country's major vegetable producing regions. The Steenkoppies Aquifer is located in a summer rainfall region, average maximum temperatures range from 19°C in winter to 25°C in summer, and average minimum temperatures range from 4°C in winter to 12°C in summer (AgroClimatology Staff 2014). Mean annual rainfall for the past 60 years is 670 mm (AgroClimatology Staff 2014).

It is generally assumed that the evapotranspiration (ET) of a crop during the cultivation phase constitutes the largest portion of the total water used to produce agricultural products (Dominguez-Faus et al. 2009, Hoekstra and Chapagain 2011, Hoekstra et al. 2011b, Ridoutt and Pfister 2010). For this reason, most water footprint (WF) studies place a lot of emphasis on water used during the cultivation phase. In this chapter the blue and grey WFs of different vegetable crops are also quantified at the packhouse level. The water used in a packhouse on the Steenkoppies Aquifer was compared to the crop WFs during cultivation, to determine the relative impact the water use in the packhouse has on the sustainability of the water use on the catchment.

3.2 Materials and Methods

Carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) are the most important crops cultivated on the Steenkoppies Aquifer. The two grain crops are included here for comparative purposes. On the Steenkoppies Aquifer, these crops are mainly cultivated under pivot or sprinkler irrigation (Figure 3-1).

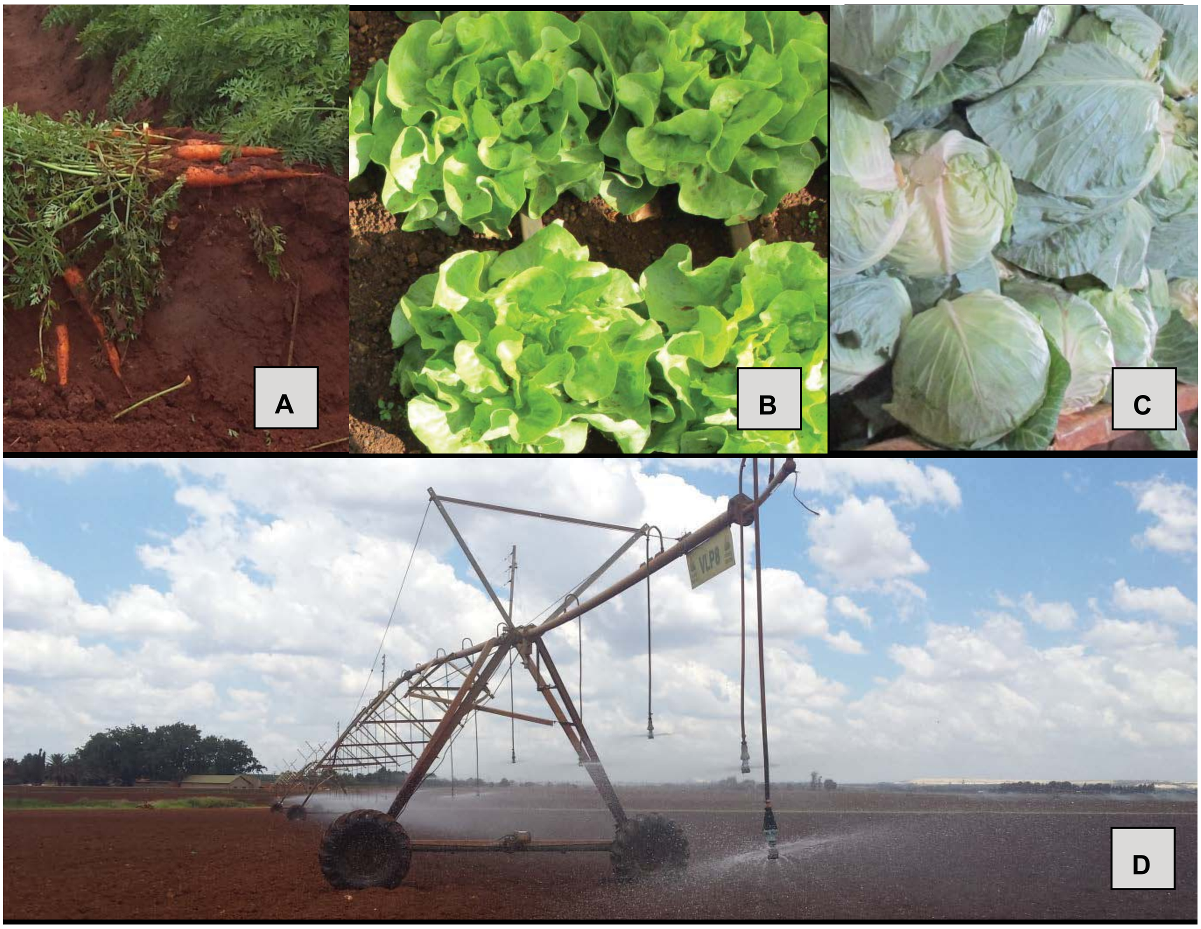

Figure 3-1: Carrots (A), and lettuce (B) cultivated and cabbage in a packhouse (C) on a farm on the Steenkoppies Aquifer and D. a pivot irrigation system on the Steenkoppies Aquifer

Vegetable crops generally have relatively short growing seasons, and are often planted at different times throughout the year, as is the case for the main vegetable crops on the Steenkoppies Aquifer. The planting schedule given in Table 3-1 shows crop sequences on one representative farm on the Steenkoppies Aquifer from 2011 to 2013, and illustrates the intensive nature of irrigated agriculture on the aquifer. Preliminary simulations indicated that the planting date and growing season have a significant impact on the magnitude of the WF. As a result, four seasonal WFs were calculated for each of the selected vegetable crops. The seasons are defined as follow:

- Summer: November – February, using 7 November as planting date.
- Autumn: March and April, using 1 March as planting date.
- Winter: May – August, using 7 May as planting date.
- Spring: September and October, using 1 September as planting date.

In South Africa, maize is only planted in summer and wheat is only planted in winter. WFs were therefore only calculated for maize planted on 7 November and wheat planted on 7 May each year.

Table 3-1: Growing season on a representative farm on the Steenkoppies Aquifer from October 2011 to January 2014 indicating the high intensity of irrigated agriculture

Field	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12	Sep-12	Oct-12	Nov-12	Dec-12	Jan-13	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14
A3	Carrots	Carrots	Carrots						Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Cabbage	Cabbage	Cabbage	Cabbage	Cabbage				Lettuce	Lettuce	
A4	Carrots	Carrots	Carrots	Carrots							Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots							
B1	Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots			Beetroot	Beetroot	Beetroot	Beetroot										
B2		Cabbage	Cabbage	Cabbage	Cabbage	Cabbage		Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots			
B3		Carrots	Carrots	Carrots	Carrots	Carrots			Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots										
B4										Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots								
C1											Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots				Carrots	Carrots	Carrots	Carrots	Carrots
C2											Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots				Carrots	Carrots	Carrots	Carrots	Carrots
C3	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots			Cabbage	Cabbage	Cabbage	Cabbage	Cabbage	Lettuce	Lettuce		Carrots	Carrots	Carrots	Carrots	Carrots	Carrots		
C4	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots		Cabbage	Cabbage	Cabbage	Cabbage	Cabbage	Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	
D2									Carrots	Carrots	Carrots	Carrots	Carrots	Lettuce	Lettuce				Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots
D3	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots		Lettuce	Lettuce	Lettuce								Cabbage	Cabbage	Cabbage	Cabbage
D4	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots			Lettuce	Lettuce	Lettuce								Cabbage	Cabbage	Cabbage	Cabbage
E4		Carrots	Carrots	Carrots	Carrots	Carrots	Carrots						Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots						
F1								Cabbage	Cabbage	Cabbage	Cabbage	Cabbage	Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots					
F2								Cabbage	Cabbage	Cabbage	Cabbage	Cabbage	Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots			
F3			Cabbage	Cabbage	Cabbage	Cabbage	Cabbage	Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots										
F4									Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots										
F5		Cabbage	Cabbage	Cabbage	Cabbage	Cabbage		Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Beetroot	Beetroot	Beetroot	Beetroot								
F8				Cabbage	Cabbage	Cabbage	Cabbage	Cabbage	Cabbage		Carrots	Carrots	Carrots	Carrots	Carrots										
G1	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots		Cabbage	Cabbage	Cabbage	Cabbage		Beetroot	Beetroot	Beetroot									
G4	Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Lettuce	Lettuce	Cabbage	Cabbage	Cabbage	Cabbage										
G6	Lettuce	Lettuce	Lettuce	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots	Carrots		Cabbage	Cabbage	Cabbage	Cabbage	Cabbage								

Field	Jan-12	Feb-12	Mar-12	Apr-12	May-12	Jun-12	Jul-12	Aug-12	Sep-12	Oct-12	Nov-12	Dec-12	Jan-13	Feb-13	Mar-13	Apr-13	May-13	Jun-13	Jul-13	Aug-13	Sep-13	Oct-13	Nov-13	Dec-13	Jan-14
G8					Carrots								Cabbage												
H1		Cabbage									Carrots					Cabbage					Lettuce				
H2										Carrots					Cabbage						Lettuce				
H3				Cabbage					Carrots						Cabbage							Lettuce			
I3						Carrots						Cabbage						Beetroot							
I4					Cabbage					Lettuce				Carrots							Cabbage				
I5											Carrots				Cabbage							Carrots			
I6						Cabbage					Lettuce				Carrots										
I7			Carrots										Carrots									Cabbage			
I8												Carrots					Cabbage						Lettuce		
J2						Carrots							Lettuce					Carrots							
J4				Cabbage							Carrots				Cabbage					Lettuce					
J5		Cabbage				Cabbage					Carrots					Cabbage									
J6			Carrots								Cabbage					Carrots									
J7			Carrots								Cabbage					Carrots									
J8		Carrots										Carrots						Cabbage							
K1									Carrots					Beetroot							Carrots				
K2		Lettuce										Carrots						Beetroot							
K3					Carrots						Lettuce			Carrots							Cabbage				
K4					Carrots						Lettuce			Carrots							Cabbage				
K5								Lettuce					Carrots												
K6							Lettuce						Carrots												
K7												Carrots				Cabbage				Lettuce					

Note: White spaces indicate fallow land

Evapotranspiration (ET) during the cultivation phase has been reported to have the highest WF along the supply chain. According to Ridoutt and Pfister (2010), the cultivation phase of production of Dolmio® pasta sauce and M&M® peanuts contributed 97% of the stress-weighted WF. The WFN regards the cultivation phase to be the most significant portion of the overall WF of agricultural products (Hoekstra et al. 2011), because agriculture is responsible for 86% of total water used worldwide (Hoekstra and Chapagain 2011). Any water consumed in the pack-house and along the supply chain to the consumer was considered ot be out of the scope for this comparison; the WFs of vegetables in the pack-house are calculated separately in this chapter. Further, water used to raise crop seedlings was excluded, because this water is often sourced from other catchments and the quantities are relatively small compared to total ET during cultivation. Water embedded in the crop was also excluded, because this only represents about 1% of total crop water use (Hoekstra et al. 2011).

3.2.1 Crop water use modelling

The data required for blue and green WF calculations were generated using the Soil Water Balance (SWB) crop model (Annandale et al. 1999). SWB is a mechanistic, daily time-step, generic crop model. Crop growth is simulated to be either water- or radiation-limited. SWB requires daily weather, soil and crop data as inputs. The SWB model was considered the most appropriate model for this application because it can simulate the growth of a range of different crops, it is able to simulate daily crop water use, has been extensively tested in South Africa, and is relatively simple to use (Annandale et al. 1999). For each crop, SWB provided daily and seasonal ET, irrigation applied and yield data for ten years from 2004 to 2013. Standard deviations were calculated for irrigation and yield over the ten years. A new functionality was programmed into SWB that automatically calculates the WF according to the WFN methodology (Hoekstra et al. 2011), using yield dry matter as the functional unit.

3.2.1.1 Weather data

Weather data inputs include rainfall (mm), minimum and maximum temperature (°C), relative humidity (%), solar radiation (MJ m^{-2} day^{-1}) and wind speed (m s^{-1}) which are used to calculate the reference ET (ET_o) using the Penman-Monteith equation (Allen et al. 1998). If wind speed, solar radiation and relative humidity are unavailable, SWB estimates these values according to FAO 56 recommendations (Allen et al. 1998). Wind speed is assumed to be 2 m s^{-1}, solar radiation is estimated based on latitude and temperature, and humidity is estimated based on minimum temperatures (Allen et al. 1998, Annandale et al. 1999).

Weather data for the Steenkoppies Aquifer was sourced from the Deodar Weather Station (Lat: S26.1426; Long: E27.57438; Altitude: 1591 m). This station is centrally located on the Steenkoppies

Aquifer and provided updated weather data from January 1983 to May 2014. The Deodar weather dataset had several data gaps, however, which were completed as follow:

- SWB database weather data (developed from the South African Atlas of Climatology and Agrohydrology by the team from the School of Bioresources Engineering and Environmental Hydrology, University of KwaZulu-Natal (Van Heerden et al. 2009)) for Krugersdorp was used to add missing rainfall data and minimum and maximum temperature data from 1 January 1950 to 31 December 1982.
- Rainfall and minimum and maximum temperature data gaps for the following dates were completed using the following data sources:
    - 1 December 1985 to 31 Jan 1990 (Source: SWB's weather generator; (Jovanovic et al. 2003))
    - 26 May to 2 June 1997 (Source: SWB's weather generator; (Jovanovic et al. 2003))
    - 7 April to 21 May 1997 (Source: SWB's weather generator; (Jovanovic et al. 2003))
    - 29 to 31 August 2003 (Source: Agricultural Research Council Institute for Soil, Climate and Water (ARC ISCW data) for Deodar weather station)
    - 1 to 13 January 2010 (Source: ARC ISCW data for Deodar weather station)
- SWB generated data (Jovanovic et al. 2003) was used to complete maximum temperature data gaps for 12 to 13 October 1990 and minimum temperature data gaps for 13 to 14 October 1990.
- Deodar data sourced from the ARC ISCW was used to complete minimum and maximum temperature data gaps for 1 to 4 January 2004 and to complete minimum temperature for 5 January 2004.
- Monthly averages from the entire dataset were used to complete maximum temperature for 12 January 2004 and minimum and maximum temperature data gaps for 13 to 26 January 2004.
- Monthly averages were assumed for minimum and maximum temperature data gaps for 9 June 2006 to 27 August 2006. Outstanding rainfall data during this period was assumed to be zero because it was in the winter season.
- Single day data gaps in minimum temperatures existed in some places in the database and these were completed using the average between the day before and the day after.

As a result, a representative weather dataset for the region was compiled from 1 January 1950 to 15 May 2014, without any gaps in the daily rainfall, minimum and maximum temperature data (Figure 3-2). Total annual precipitation data from 1950 that was used in SWB modelling is shown in Figure 3-3.

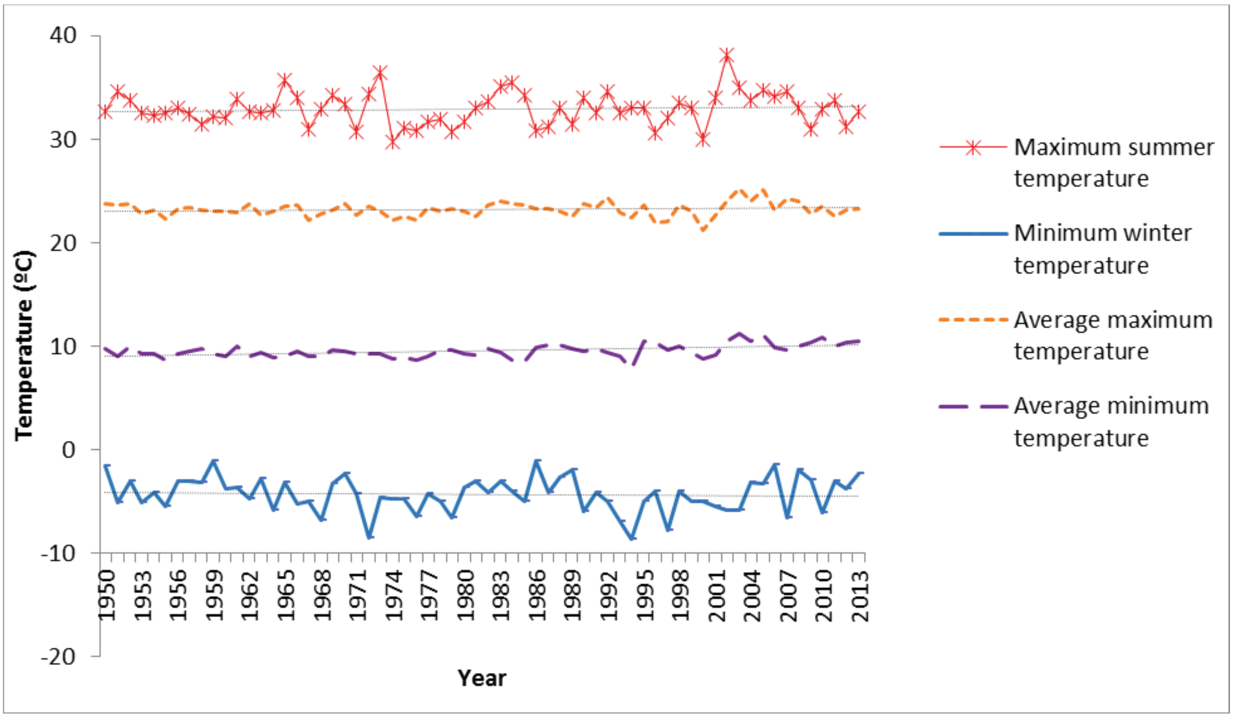

Figure 3-2 Temperature results from compiled dataset used for crop modelling summarised as the maximum summer temperatures, minimum winter temperatures, as well as average annual maximum and minimum temperatures for each year. The gradients of the linear trendlines indicate insignificant change in annual temperature trends.

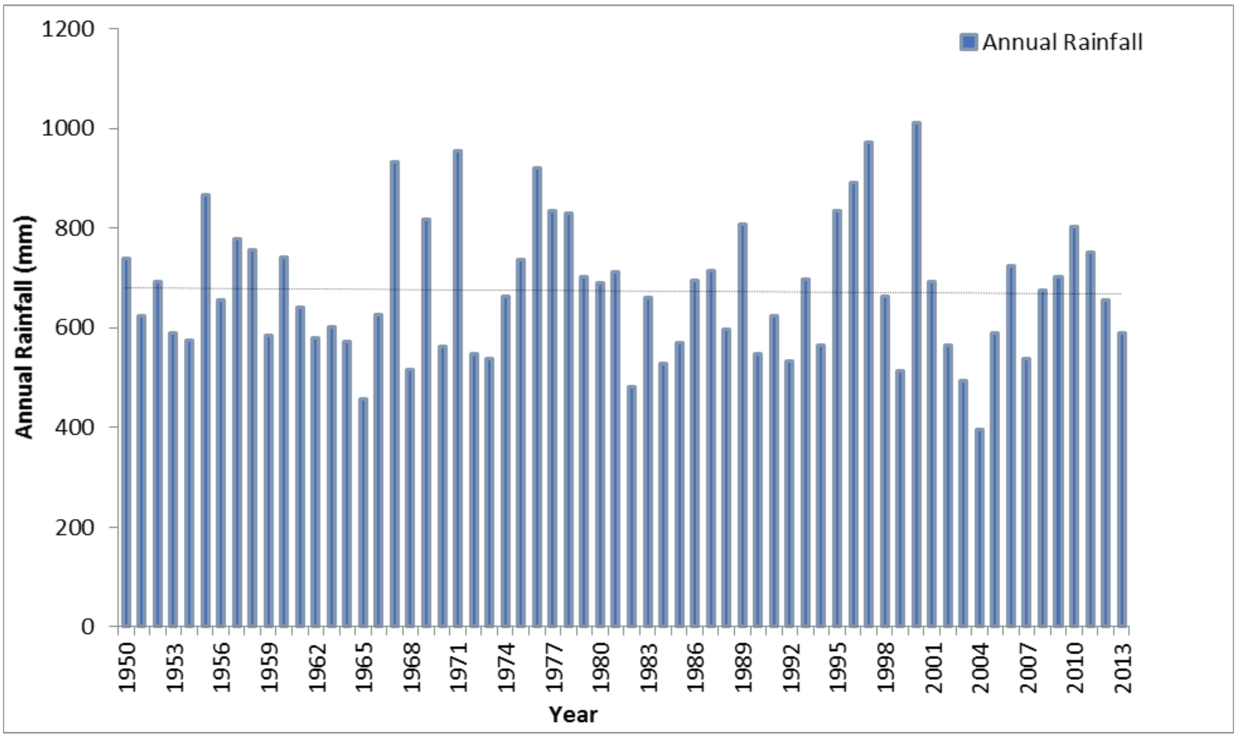

Figure 3-3 Total annual precipitation results from compiled datasets used for crop modelling

3.2.1.2 *Soil data*

Soil data sampled from the study area has been used to parameterise the SWB model (Table 3-2, Table 3-3). Soil input data used to parameterise and calibrate the SWB model for the whole profile included a drainage factor (0 to 1), drainage rate (mm day^{-1}) and maximum rooting depth (m) (Annandale et al. 1999). For each of the eleven soil layers the following data was parameterised: depth of layer (m), volumetric water content (m^3 m^{-3}) at field capacity and permanent wilting point, initial water content (m^3 m^{-3}) and bulk density (Mg m^{-3}).

Table 3-2 General soil profile data parameterised in SWB based on sampling in the Steenkoppies Aquifer

Soil profile data	
Texture	Sandy Loam
Runoff no	250
Field capacity (kPa)	-10
Permanent Wilting Point (kPa)	-1000
Drainage factor	0.8
Drain rate (mm day^{-1})	70
Root depth limit (m)	1
Profile water content at full capacity (m^3 m^{-3})	190*
Profile water content at saturation (m^3 m^{-3})	440*
Profile water content at Permanent Wilting Point (m^3 m^{-3})	72*

* Estimated by the model from individual layer parameters

Table 3-3: Detailed data for each soil layer of a sampling point on the Steenkoppies Aquifer

Soil Layer	**Depth (m)**	**Field capacity (m^3 m^{-3})**	**Initial water content (m^3 m^{-3})**	**Permanent wilting point (m^3 m^{-3})**	**Bulk density (Mg m^{-3})**
1	0.05	0.140	0.147	0.067	1.42
2	0.15	0.147	0.140	0.067	1.42
3	0.2	0.151	0.151	0.082	1.54
4	0.3	0.151	0.151	0.082	1.54
5	0.4	0.187	0.187	0.088	1.54
6	0.5	0.187	0.187	0.088	1.54
7	0.6	0.215	0.215	0.086	1.46
8	0.7	0.215	0.215	0.086	1.46
9	0.8	0.215	0.215	0.086	1.46
10	0.9	0.215	0.215	0.086	1.46
11	1	0.215	0.215	0.086	1.46

3.2.1.3 Crop parameters

New crop parameters for carrots, cabbage, beetroot, broccoli and lettuce (Table 3-4) were recently calibrated for the region based on intensive growth analyses data by Vahrmeijer (2016). Trials were conducted on commercial farms on the Steenkoppies Aquifer under commercial management practices. Cultivars used most commonly by farmers on the Steenkoppies Aquifer for each season were selected for parameterisation. Cabbage cultivars 'Tenacity' and 'Grandslam', carrots cultivars 'Star 3006' and 'Dordogne', and broccoli cultivars 'Star 2204' and ' Parthenon' were used for summer and winter, respectively. The beetroot cultivar 'Red Ace' and lettuce cultivar 'Robbenson' was used for all seasons. Parameters that were developed for summer were also applied for spring, except for beetroot which required slightly different parameters in spring, and the parameters developed for winter were also applied for autumn. Crop parameters for maize and wheat were sourced from Annandale et al. (1999). .

3.2.1.4 Verification of SWB results

SWB results were verified by comparing simulated yield and irrigation data (with standard deviations), to independent actual measurements made on ten farms on the Steenkoppies Aquifer (Vahrmeijer, 2016). Four replications of 1 m^2 plots were demarcated on cropped areas of each farm. Rain gauges were installed within the cropped area to measure irrigation and rainfall and outside the fields to measure rainfall only. The crops were harvested at the commercial harvesting date and the harvestable portion was weighed to determine yield in terms of both fresh mass and dry matter. The grain crops data were validated by Jovanovic et al. (2004), and were included for comparative purposes. Table 3-5 summarises irrigation and yield data that was available for verification of the simulation results of the vegetables.

Table 3-4. Locally produced crop parameters used in the Soil Water Balance model to simulated the data required for WF calculations (Vahrmeijer, 2016)

Parameters	Carrots		Cabbage		Beetroot			Broccoli		Lettuce	Maize	Wheat
	Summer & spring	Autumn & winter	Summer & spring	Autumn & winter	Summer	Spring	Autumn & winter	Summer & spring	Autumn & winter	All seasons	Summer	Winter
Extinction coefficient	0.76	0.76	0.78	0.62	0.64	0.64	0.64	0.77	0.81	0.92	0.56	0.55
Dry-matter-water ratio (Pa)	8	8	9	6	7	7	7	6	7	9	4	4
Conversion Efficiency (kg MJ^{-1})	0.00087	0.00087	0.00094	0.00094	0.0012	0.0012	0.0012	0.001	0.001	0.0009	0.0012	0.0017
Base temperature (°C)	7.2	7.2	4.4	2	4.4	4.4	4.4	0	0	7.2	10	4
Temperature optimal light (°C)	15	15	15	10	15	15	15	15	10	15	25	15
Cut off temperature (°C)	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	23.9	30	25
Emergence day degrees (°C)	103	103	130	50	64	64	64	123	95	71	50	50
Flowering day degrees (°C)	200	200	800	750	200	200	500	1100	650	175	900	750
Maturity day degrees (°C)	1450	1300	1300	1445	1300	1000	1356	1700	1200	529	1700	1500
Transition day degrees (°C)	1238	1238	400	500	700	700	700	500	1200	475	10	400
Maximum leaf age	1450	1300	1300	1445	1300	1000	1356	1700	1200	529	900	900
Max height (m)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.4	0.3	2.2	1
Maximum root depth (m)	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.4
Stem to grain translation	0.5	0.5	0.05	0.05	0.5	0.5	0.5	0.5	0.5	0.01	0.05	0.01
Canopy storage (mm)	1	1	1	1	1	1	1	1	1	1	1	1
Minimum leaf water potential (kPa)	-1500	-1500	-1500	-1500	-1500	-1500	-1500	-1500	-1500	-1500	-2000	-1500
Maximum transpiration (mm day^{-1})	9	9	9	9	9	9	9	9	9	9	9	9
Specific leaf area (m^2 kg^{-1})	17.9	17.9	11	9.5	13	13	13	10.5	9.5	20	15	12
Leaf stem partition (m^2 kg^{-1})	3.08	3.08	1.55	0.56	3.02	3.02	3.02	1.54	1.54	6.33	0.8	1.2
Total Dry Mass at emergence or transplanting (kg m^{-2})	0.0005	0.0005	0.005	0.01	0.003	0.003	0.003	0.001	0.007	0.0008	0.0019	0.0019
Root fraction	0.1	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.1	0.2	0.01	0.02
Root growth rate	2	2	2	2	4	4	4	2	2	2	4	7
Stress index	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95

Table 3-5 Summary of irrigation and yield data obtained for carrots, cabbage, broccoli, beetroot and lettuce from selected farms on the Steenkoppies Aquifer (Vahrmeijer, 2016)

Farm	Carrots	Cabbage	Broccoli	Beetroot	Lettuce
A	**Irrigation and yield** (summer and spring, 2008)				
B	**Irrigation and yield** (autumn and winter 2008 and 2009)	**Irrigation and yield** (spring 2008 and autumn 2009)	**Irrigation and yield** (spring 2008 and autumn 2009)	**Irrigation and yield** (summer 2009 and autumn 2009)	**Irrigation and yield** (summer 2008 and winter 2008 and 2009)
C	**Irrigation** (all seasons 2011-2013)	**Irrigation** (all seasons 2011-2013)		**Irrigation** (summer and autumn 2012-2013)	**Irrigation** (summer, winter and spring 2012 – 2013)
D	-	**Irrigation and yield** (autumn 2009)		**Irrigation and yield** (autumn 2009)	**Irrigation and yield** (summer and spring 2008 and winter 2009)
E		**Irrigation and yield** (winter 2008 summer 2008 autumn 2009)		**Irrigation and yield** (autumn 2009)	**Irrigation and yield** (spring 2008 and winter 2009)
F			**Irrigation and yield** (autumn 2009)		**Irrigation and yield** (winter 2009)
G	**Irrigation and yield** (autumn 2009)		**Irrigation and yield** (autumn 2009)		**Irrigation and yield** (winter 2009)
H		**Irrigation and yield** (winter and spring 2008 and autumn 2009)			**Irrigation and yield** (winter 2009)
I		**Irrigation and yield** (spring 2008, summer 2009 and autumn 2009)			**Irrigation and yield** (spring 2008 and winter 2009)
J		**Irrigation and yield** (spring 2008, summer 2009 and autumn 2009)			**Irrigation and yield** (spring 2008)

3.2.2 Water Footprint Network methodology calculations

Using the verified modelled data and long-term simulations from 2004 to 2013, blue and green WFs were calculated according to the WFN methodology (Hoekstra et al. 2011) as given in Equation 2-3 and Equation 2-4, respectively (**Chapter 2**). As per Hoekstra et al. (2011), yield in fresh mass was used. Water footprints were also calculated using yield in dry matter as an alternative (kg m^{-2}).

Nitrogen (N) and phosphorus (P) pollution from agriculture has received much attention because of the well-known role these nutrients play in eutrophication of surface water resources (Conley et al. 2009, Nagar et al. 1974, Schindler and Fee 1974, Schindler 2006). While eutrophication might not become a problem if either N or P are limiting, it is important to minimise the amount of N and P entering our surface and groundwater resources. In an aquatic ecosystem where only P levels are controlled, excess N can still result in eutrophication of water resources further downstream including estuaries and coastal marine ecosystems (Conley et al. 2009). Both N and P should therefore be taken into account when calculating grey WFs. Nitrogen is of additional concern because of the health risks it poses to infants younger than six months (blue baby syndrome) (Walton 1951). Inorganic N is usually more mobile than P in soil, because P is adsorbed to clay particles (Conley et al. 2009, Sims et al. 1998, Smolders et al. 2010). Nitrogen pollution can also indirectly mobilise P by oxidising geological pyrite deposits and increasing sulphate levels, which react with iron compounds, causing adsorbed P to be released and mobilised, potentially causing eutrophication (Smolders et al. 2010). Gleeson et al. (2012) also highlighted the need to set groundwater sustainability targets that meet drinking water standards, and this highlights the importance of including N in grey WFs for groundwater. Nitrogen is also the most common agricultural pollutant that has been used for calculating grey WFs (Chapagain and Hoekstra 2011, Mekonnen and Hoekstra 2010, Mekonnen and Hoekstra 2011, Mekonnen and Hoekstra 2012), which enables comparisons with a wide range of other WF studies reported in the literature. We have therefore used N as the critical pollutant during the cultivation phase to determine grey WFs of the vegetables selected for this study. We also recognise that other pollutants, including P and pesticides, might be more appropriate in other studies. Grey WFs were determined according to Equation 2-5.

The general standard for N in wastewater of 15 mg ℓ^{-1} (Department of Water Affairs and Forestry 1999) was taken as C_{max}. C_{nat} is the N concentration of the water if no human influences are present. The aquifer has very low N concentrations, with an average of 0.3 mg ℓ^{-1} (Department of Water Affairs 2014), and therefore does not yet reflect the expected impacts of intensive agricultural activities. Thus, the low average natural N concentration of the aquifer was considered to represent natural concentrations and was taken as C_{nat}.

The N load that leaches into the aquifer was determined by estimating the surplus N applied to the crops together with a leaching-runoff factor, according to the method provided by Franke et al. (2013). To determine the surplus N, the N content of the harvested product (which represents the portion of N that is taken up by the plant and removed from the field) was subtracted from the N application per crop. Typical N fertiliser application rates for carrots, cabbage, beetroot and lettuce were provided by farmers on the Steenkoppies Aquifer, and N application to broccoli was assumed to be the same as for cabbage. N application given by the Fertiliser Society of South Africa (Misstofvereniging van Suid Afrika 2007) was used for beetroot, maize and wheat. For maize and wheat, the application rates were also linked to expected irrigated yields for the aquifer. The N contents of the crops was taken from the literature. Nitrogen fertiliser application rates and crop N content used in the calculations are summarised in Table 3-6.

Table 3-6: Nitrogen application rates and crop N contents of selected crops used to determine surplus N applied

	Application (kg N ha^{-1})	N content of fresh mass (%)
Beetroot	140	0.2% [1]
Carrots	190	0.1% [2]
Cabbage	190	0.2% [2]
Broccoli	190	0.4% [2]
Lettuce	130	0.2% [3]
Maize	220	0.9% [4]
Wheat	240	1.5% [5]

References: [1]Petek et al. (2012), [2]Sorensen (1998), [3]ANZECC and ARMCANZ (2000), [4]Alexandrova and Donov (2003), [5]Mossé et al. (1985).

The surplus N applied is multiplied by a leaching-runoff fraction to estimate the amount of N that leaches into the aquifer, with the assumption that all runoff that does occur does end up recharging the aquifer due to the flat terrain of the area. The first step in determining the leaching-runoff fraction is to complete the score card given in Table 3-7. The weighted scores are then used to calculate the leaching-runoff fraction in terms of surplus N applied (β) using Equation 3-1 (Franke et al. 2013).

$$\beta = \beta_{min} \left(\frac{\sum_i S_i \times W_i}{\sum_i W_i} \right) \times (\beta_{max} - \beta_{min})$$

Equation 3-1

where *S* is the score(s) in Row *x* and W is the weight(s) in Column *y* of Table 3-7, β_{min} and β_{max} are the minimum and maximum leaching-runoff fractions. For N a β_{min} value of 0.08 was used and a β_{max} value of 0.8 was used as given by Franke et al. (2013). Management practices in Table 3-7 was considered average, because some farmers use old methods to determine when irrigation is required, and farmers mostly irrigate with pivots, which are not considered as efficient as drip irrigation.

Table 3-7: Determination of the leaching runoff potential of nitrogen (N) for the Steenkoppies Aquifer (Franke et al. 2013)

Category	Factor		Leaching-runoff potential	Very low	Low	High	Very high	Weighted Score *
			Row *x* Score (s)	0	0.33	0.67	1	
			Column *y* Weight					
Environmental factors	Atmospheric input	N-deposition (g N m^{-2} yr^{-1})	10	<0.5	>0.5	<1.5	>1.5	**0**
	Soil	Texture (relevant for leaching)	15	Clay	Silt	Loam	Sand	**10.05**
		Texture (relevant for runoff)	10	Sand	Loam	Silt	Clay	**3.3**
		Natural drainage (relevant for leaching)	15	Poorly to very poorly drained	Moderately to imperfectly drained	Well drained	Excessively to extremely drained	**15**
		Natural drainage (relevant for runoff)	10	Excessively to extremely drained	Well drained	Moderately to imperfectly drained	Poorly to very poorly drained	**0**
	Climate	Precipitation (mm)	15	0-600	600-1200	1200-1800	>1800	**5**
Agricultural practice	N-fixation (kg h^{-1})		10	0	>0	<60	>60	**3.3**
	Management practice		15	Best	Good	Average	Worst	**10.05**

*The weighted score is calculated by multiplying the score in Row *x* with the weight in Column *y*

3.2.3 Hydrological water footprint methodology calculation

Verified SWB model estimates also provided the data used to calculate WFs according to the hydrological methodology. The hydrological methodology has not proposed a water quality impact metric, and uses the grey WF methodology proposed by the WFN. Blue WFs are based on the change in groundwater storage and are calculated as per Equation 2-16 (**Chapter 2**) (Deurer et al. 2011)**.** In the original study Deurer et al. (2011) assumed that all runoff became drainage, because of the flat topography of their study area. This is why runoff in this formula reduces the blue WF on the aquifer. For this study runoff was also assumed to be zero, due to the absence of surface runoff on the Steenkoppies Aquifer. Rain-fed conditions cannot be modelled for the vegetables on the Steenkoppies Aquifer, because some crops fail due to low rainfall conditions in winter. Thus, for blue WF calculations total drainage under irrigated conditions was used instead of D^r plus D^{ir}. This however presented a problem with calculating green WFs, which is based on the change in soil moisture originating from rainfall Equation 2-17 (**Chapter 2**), where ET under rainfed conditions are required (Deurer et al. 2011). Total drainage and ET under irrigated conditions were used to determine green WFs, because D^r or ET^r could not be calculated.

The hydrological methodology, which considers the water balance over an entire calendar year, is not compatible with estimating the WFs of a single short season vegetable crop such as those cultivated on the Steenkoppies Aquifer. Therefore, the annual WF was calculated for typical cropping sequences within a twelve-month period. Fresh weight then equals the combined weight of all crops produced in the sequence. The WF will thus represent a combination of crops, instead of one single crop. A crop rotation of carrots and cabbage is typical on the Steenkoppies Aquifer (Table 3-1). A two-crop sequence of winter cabbage planted on 1 May each year and summer carrots planted on 7 November each year was therefore selected. Due to the intensive farming activities on the aquifer, a three-crop sequence was also selected, with winter broccoli planted on 1 May each year, spring cabbage planted on 25 August each year, and summer beetroot planted on 13 December each year. The crops selected for the three crop sequence was based on the length of the growing seasons, so that the sequence can be completed in one calendar year for comparison with WFN results. Broccoli, which had a high WF according to the WFN results, was specifically included for comparison with WFN results.

In order to compare the hydrological WF results of the two-crop sequence with the WFN results the average WF, according to WFN, of carrots planted in summer and cabbage planted in winter was taken. Likewise, the average WFs according to the WFN for winter broccoli, spring cabbage and summer beetroot was taken to compare the hydrological WFs results of the three crop sequence.

3.2.4 LCA water footprint methodology calculations

Pfister et al. (2009) suggested a WF calculation method based on the LCA methodology. According to this methodology, the volume of water used per functional unit is multiplied by a regional WS Index, which is calculated to better characterise local water use impacts. The methodology therefore attempts to show the context-specific effects of water consumption. Green WFs are excluded, because the methodology argues that green water resources cannot be separated from the land and the use of green water is not considered to have any direct impacts on water availability (Ridoutt and Pfister 2010). The functional unit was defined as 1 tonne of harvested product in fresh mass during the cultivation phase. The literature review in **Chapter 2** gives more information on how this calculation is done.

A WS Index of 0.78, as calculated by Pfister et al. (2009), was used to convert the WFs of the crops on the Steenkoppies Aquifer. The blue WFs according to the WFN methodology were used to calculate LCA WFs, because these WFs quantify the volume of blue water used to produce a product. Site specific WS Indices for the Steenkoppies Aquifer were also calculated for five distinct periods classified in terms of the intensity of irrigated agriculture (**Chapter 6)** according to the methodology proposed by Pfister et al. (2009). The withdrawal to availability ratio (WTA) for regulated catchments were calculated according to Equation 2-10 (**Chapter 2**) given by Pfister et al. (2009) The catchment scale agricultural blue WFs estimated in **Chapter 6** for the five periods were taken as the WU and average outflows from the Maloney's Eye from 1950 to 2012 were taken as WA. Long term monthly and annual precipitation data from 1950 to 2012 was used to calculate the VF according to the formula given by Pfister et al. (2009) (Equation 2-12 of **Chapter 2**). The WS indices for each of the five periods were compared to determine if it produces a relatively constant result that can be applied to a catchment over the long term. The WS Indices that were calculated for the five periods were also compared to the WS Index of 0.78 calculated for the region by Pfister et al. (2009) (Figure 3-4).

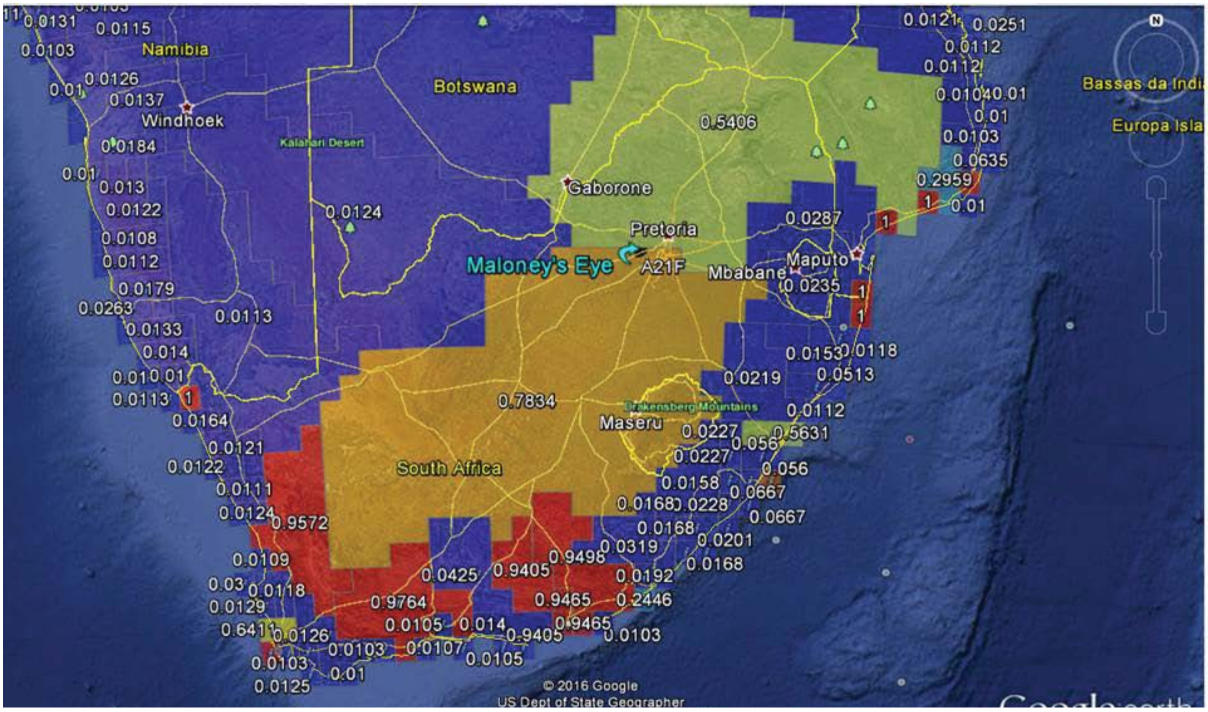

Figure 3-4: The WS Index for South Africa as calculated according to the Life Cycle Assessment methodology by Pfister et al. (2009)

3.2.5 Screening assessment of the packhouse

Initially three packhouses were visited and selected for monitoring, but due to a lack of willingness to cooperate, two of these packhouses were excluded from further monitoring. The selected packhouse on the Steenkoppies Aquifer was visited to do an initial screening (Figure 3-5). A qualitative assessment on the packhouse was done to determine what equipment was used for the different crops that were cleaned and packed and to better understand the flow of water through the packhouse. During this screening exercise a suitable place were identified where a flow meter could be installed, which included all packhouse activities, but excluded washrooms and toilets and other facilities used by the staff but not appropriate for inclusion in the WFs of vegetable crops. The selected packhouse currently processes only carrots (*Daucus carota*), cabbage (*Brassica oleracea*) and lettuce (*Lactuca sativa*). The other selected crops are not currently packed or cleaned on the Steenkoppies Aquifer.

During the screening assessment, it was observed that cabbage and lettuce heads do not require extensive cleaning and therefore use very little water, apart from a bucket or two that is used to clean the work station at the end of each day. Carrots, however, require an extensive process of getting rid of sand, cleaning, polishing and hydrocooling, which uses both water and electricity.

Figure 3-5: Cabbage and carrots packed and cleaned in a packhouse on the Steenkoppies Aquifer

A schematic representation of the process of cleaning carrots is illustrated in **Figure 3-6**. A more recent development in the packhouse is a series of ponds for treatment after which water is recycled back into the packhouse. Sludge from the pond system is discharged into an artificial wetland. Water inputs through boreholes are still required by the polisher on a daily basis and by the hydrocooler every second week. The flow meter was installed to measure these water inputs. There are, therefore, three different water flows, including water recycled within the system, borehole water inputs and sludge outputs. A flow meter was installed at the main inlet where groundwater enters the packhouse.

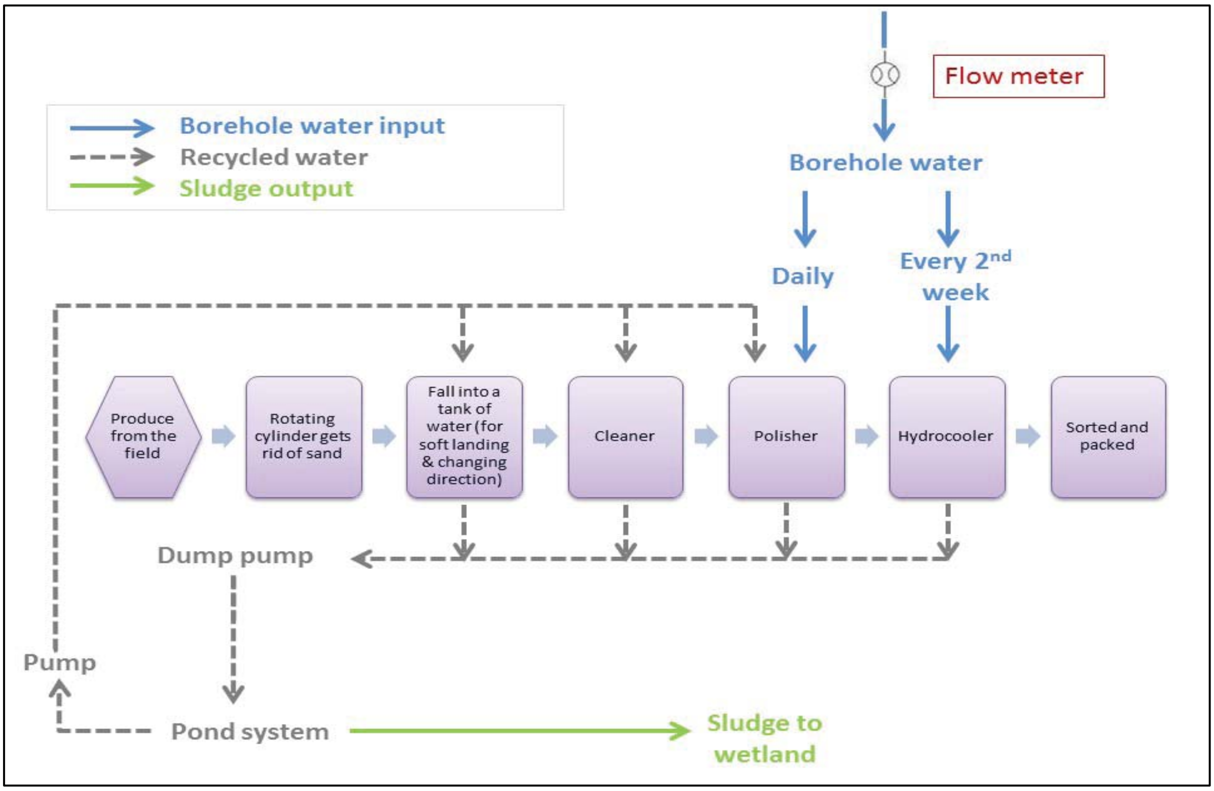

Figure 3-6: Schematic representation of the process of cleaning and cooling carrots in a packhouse on the Steenkoppies Aquifer.

3.2.6 Blue water footprint of processing crops in the packhouse

Packhouse blue WFs for carrots, cabbage and lettuce were calculated according to the WFN methodology, which were then multiplied by the WS Index of 0.78 given by (Pfister et al. 2009) to determine the WF according to the LCA methodology as well. The blue WF in the packhouse includes direct water used for cleaning and cooling as well as water used indirectly through electricity use. A '40 MS' multi-jet magnetic water meter (Arad, Israel) was installed at the main inflow to the packhouse in June 2016. Flow measurements were taken daily before operations start. The total water flowing into the packhouse had to be apportioned to each vegetable that was cleaned and packed as well as to general cleaning of the packhouse. Data is not available to do this and it was thus based on estimates given by the packhouse managers. According to the packhouse manager, 70% of water used in the packhouse is used for carrots, because of the polisher and hydrocooler used for cleaning carrots, while 5% is used for cabbage and 5% for lettuce. The remaining 20% is used for general packhouse maintenance and cleaning. General cleaning and maintenance of the packhouse cannot be ascribed directly to any specific crop, and therefore the percentage water used for cleaning the packhouse was equally apportioned to carrots, cabbage and lettuce. Thus, 76.6%, 11.6% and 11.6% of the total inflows into the packhouse were apportioned to carrots, cabbage and lettuce respectively.

Daily production reports were obtained for the full period that the flow meter was monitored. The production reports indicated the quantities of the different vegetables that were packed in the packhouse (Production Report 2016). These reports indicated both quantities of crops received by the packhouse and quantities packed by the packhouse. The difference was assumed to be wastage. To determine water used per crop production, the quantities received by the packhouse were used as opposed to the quantities packed. The difference in packhouse level water use between vegetables that were received and vegetables that were packed is considered wasted water.

3.2.7 Grey water footprint of processing crops in the packhouse

Grey WFs of cleaning and packing vegetables in the packhouse were determined using Equation 2-5 given in **Chapter 2**. Grab samples of effluent were taken from two packhouses on the Steenkoppies Aquifer for water quality analyses (Table 3-8). Chemical Oxygen Demand (COD) exceeded wastewater discharge limits, indicating high concentrations of organic material in the effluent. The exceptionally high concentrations of COD in the effluent water, indicates that COD is actually the most critical pollutant. However, a methodology has not been developed to understand the fate of COD concentrations and how it impacts the water quality of the aquifer, which should be addressed in future research. The results indicated that both inorganic nitrogen (N) and phosphorus (P) concentrations are within wastewater discharge limits. When considering the limits for N and P to maintain ecosystems and prevent eutrophication (Department of Water Affairs and Forestry 1996), P concentrations were of greater concern. Ortho-phosphates (OP) are the only form of soluble inorganic P that can directly be utilised by organisms and is extremely reactive (Wetzel 2001). Therefore, OP was selected for grey WF calculations at the packhouse level.

Table 3-8: Water quality analyses for effluent grab samples taken at two packhouses on the Steenkoppies Aquifer

Analyses	**Sample Identification**		**Wastewater Discharge Limits (Department of Water Affairs and Forestry 1999)**		**Aquatic Ecosystems Limits (Department of Water Affairs and Forestry 1996)**
	Farm A sample	**Farm B sample**	**General Limit**	**Special Limit**	**Eutrophic conditions**
pH – Value at 25°C	6.9	6.3	**5.5-9.5**	**5.5-7.5**	
Nitrate as N (mg ℓ^{-1})	<0.2	<0.2	**<15**	**<1.5**	**2.5-10**
Nitrite as N (mg ℓ^{-1})	<0.1	<0.1			
Total Phosphate as P (mg ℓ^{-1})	5.1	6.9	**---**	**---**	**0.025-0.25**
Ortho Phosphate as P (mg ℓ^{-1})	0.6	1.5	**<10**	**1 (median); 2,5 (maximum)**	
Biochemical Oxygen Demand as O_2 (mg ℓ^{-1})	72	72	**---**	**---**	
Chemical Oxygen Demand as O_2 (Total) (mg ℓ^{-1})	480	1 040	**<75**	**<30**	
Free & Saline Ammonia as N (mg ℓ^{-1})	<0.2	<0.2	**<6**	**<2**	

The general standard for OP in wastewater of 10 mg ℓ^{-1} (Department of Water Affairs and Forestry 1999) was considered too high for the use of C_{max}. Thus, 0.025 mg ℓ^{-1}, which is the lower limit of eutrophic conditions according to Department of Water Affairs and Forestry (1996), was taken as C_{max}. C_{nat} is the P concentration of the water if no human influences are present. In general the aquifer has very low P concentrations, with a median value of 0.007 mg ℓ^{-1} (Department of Water Affairs 2014).

There are, however, some outliers in the dataset with extremely high P concentrations, resulting in an average of 0.014 mg ℓ$^{-1}$, which is much higher than the median. These outliers are most likely caused by agricultural activities and must be excluded from the value used as C_{nat}. Thus, median natural P concentrations of the aquifer were considered to represent the natural conditions and were taken as C_{nat}. Total P concentrations in the effluent were used in the load, and not the surplus, because the surplus only applies to the cultivation phase.

It was assumed that the average volume of effluent discharged equals the average volume of water flowing into the packhouse. The P concentration was multiplied by the average volume of water used per crop (determined according to methodology described in **Section 3.2.6**) to determine the load of P released in effluent outflows. It was assumed that carrots, cabbage and lettuce contribute equally to the total P concentration in the effluent. The first step in determining the leaching-runoff potential was to complete the score card given in Table 3-9. The weighted scores were used to calculate the leaching-runoff potential in terms of P applied (β) using Equation 3-2 (Franke et al. 2013).

$$\boldsymbol{\beta} = \boldsymbol{\beta}_{min} \left(\frac{\sum_i \boldsymbol{S}_i \ \boldsymbol{x} \ \boldsymbol{W}_i}{\sum_i \boldsymbol{W}_i} \right) \boldsymbol{x} \ (\boldsymbol{\beta}_{max} - \boldsymbol{\beta}_{min})$$

Equation 3-2

Where β is the leaching-runoff potential of P discharged, *S* is the scores in Row *x* of **Table 3-9**, W is the weights in Column *y* of Table 3-9. β_{min} and β_{max} are the minimum and maximum leaching-runoff potential. For P β_{min} value of 0.0001 was used and β_{max} value of 0.1 was used as given by Franke et al. (2013). The fraction of P leaching to the aquifer was divided by total production, taken from the daily production reports of July 2016 to obtain total P load per tonne of crop.

Table 3-9: Determination of the leaching-runoff potential of phosphates (Franke et al. 2013)

Category	Factor		Leaching-runoff potential	Very low	Low	High	Very high	Weighted score*
			Score (s)	**0**	**0.33**	**0.67**	**1**	
			Weight					
Environmental factors	Soil	Texture (relevant for runoff) **	25	Sand	Loam	Silt	Clay	8.25
		Erosion **	25	Low	Moderate	High	Very high	8.25
		P content (g P m^{-2}) **	20	<200	200-400	400-700	>700	13.4
	Climate	Rain intensity	15	Light	Moderate	Strong	Heavy	4.95
Agricultural factors	Management practice		15	Best	Good	Average	Worst	10.05
Total Score								**0.45**

*The weighted score is calculated by multiplying the score in Row *x* with the weight in Column *y*. **Data taken from Franke et al. (2013)

3.2.8 Assessment of indirect water use in the packhouse

Generating electricity is a water intensive process and this indirectly contributes to the WF of processing vegetables in the packhouse. This water use is part of the WF of crops, although the water that is used does not originate from the aquifer, and can also be referred to as an indirect WF. Data on electricity use in the packhouse was obtained from electricity bills over 13 months from November 2014 to October 2015. The electricity measurements, however, also include two borehole pumps and the farm house together with the packhouse electricity use. The accountant indicated that the packhouse use of electricity represents 85% of the total electricity use. Eskom uses an average of 1.32 liters of water to generate 1 kilowatt hour of electricity (Eskom 2016). This average value was used to convert the electricity use to an indirect water use. The total electricity use in the packhouse was apportioned to individual vegetables packed according to the percentages 76.6%, 11.6% and 11.6% for carrots, cabbage and lettuce respectively as detailed in **Section 3.2.6**. Carrots are expected to use a higher proportion of electricity, because of the extensive process required for cleaning and packing carrots which includes the running of a polisher and hydrocooler. Input volumes from daily production reports for the same period (November 2014 to October 2015) were obtained and used for the WF calculations.

3.3 Results

3.3.1 SWB results

The verification of SWB irrigation and yield results are given in Figure 3-7 and Figure 3-8, respectively. Irrigation is higher during winter even though atmospheric evaporative demand is lower, because the area receives little or no rainfall in winter and cooler temperatures lead to longer growing seasons. Irrigation and yield for lettuce is low because lettuce has a short growing season, while yields for broccoli are low, because of a low harvest index.

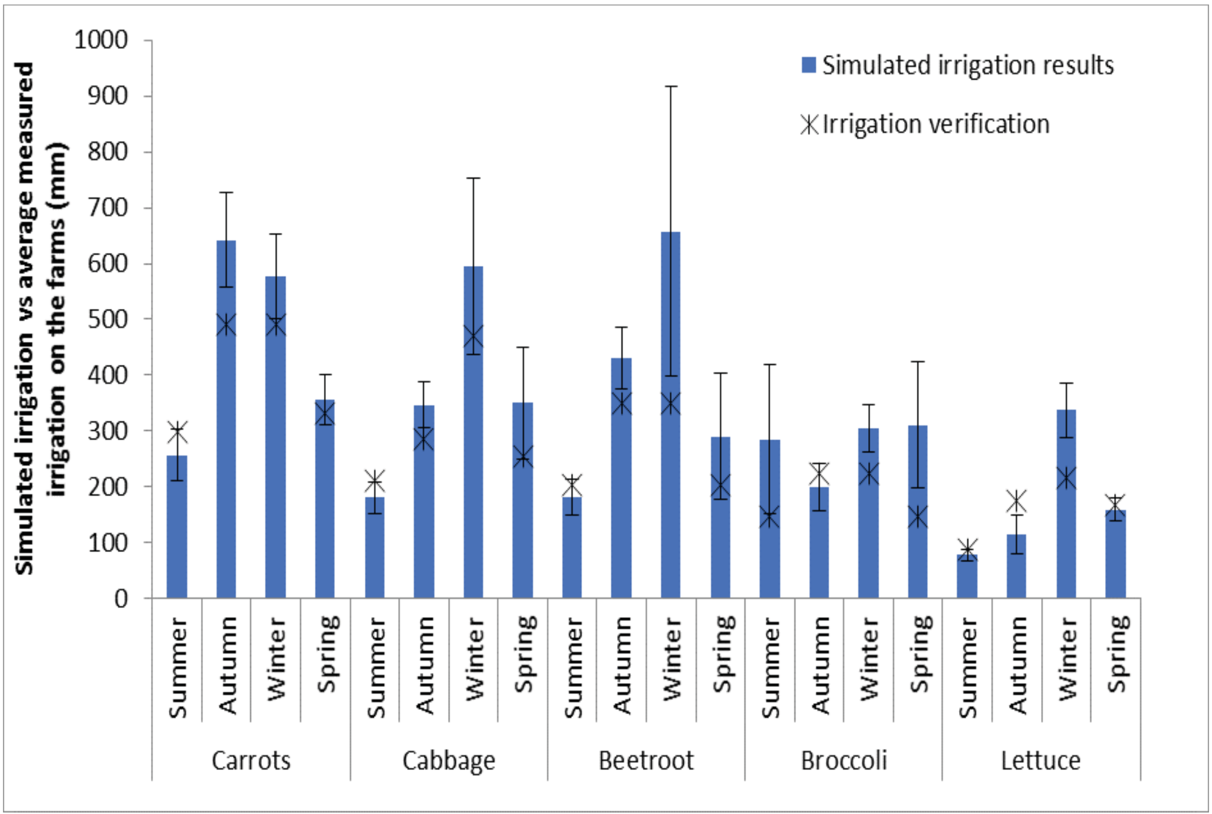

Figure 3-7: Average of 10 year's (2004–2013) simulated seasonal irrigation with standard deviations (shown as error bars) of vegetable crops in the different growing seasons compared to measured irrigation verification data from farms on the Steenkoppies Aquifer.

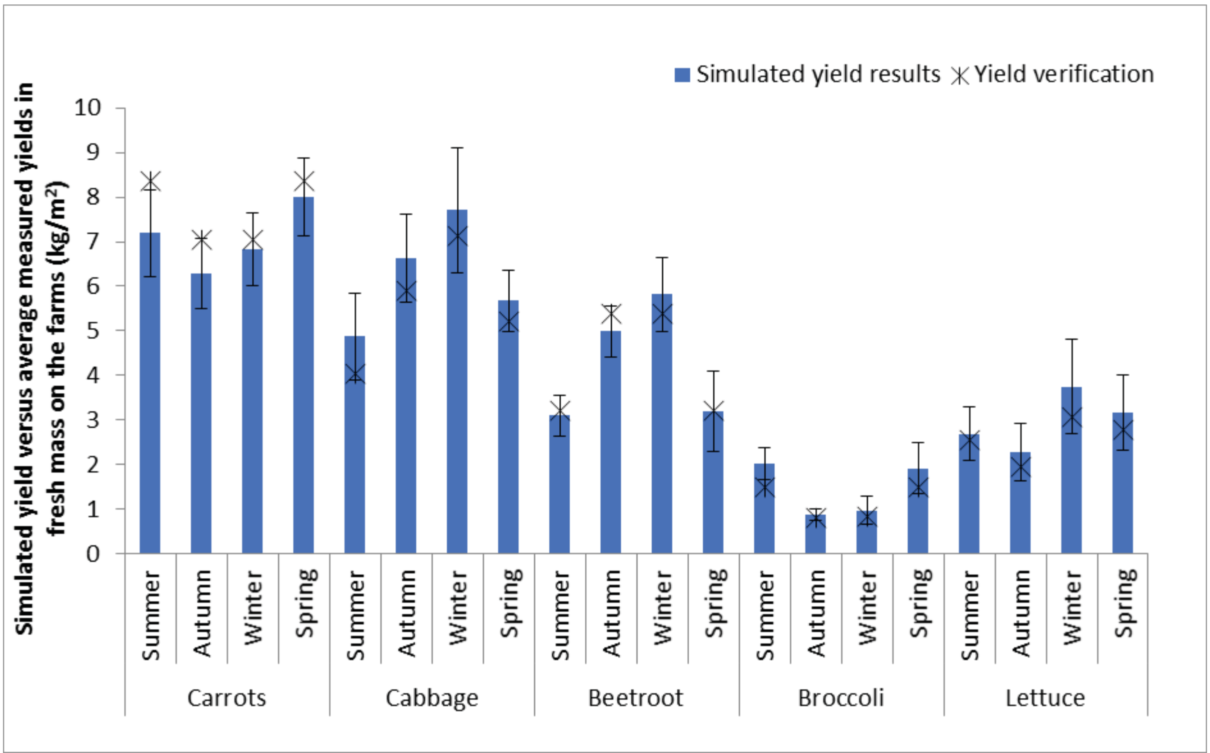

Figure 3-8: Average of 10 year's (2004–2013) simulated seasonal yields with standard deviations (shown as error bars) of vegetable crops for the different growing seasons compared to measured fresh mass yield data from the farms on the Steenkoppies Aquifer.

3.3.2 Cultivation water footprints according to the WFN

The WFN blue, green and grey WFs with fresh mass as the functional unit for the cultivation phase of each of the crops in each of the four growing seasons, and a single season in the case of maize and wheat, are given in Table 3-10. Compared to the other vegetables, broccoli has a high blue, green and grey WF because the crop has a small harvestable portion, resulting in relatively low yields. The WFs of maize and wheat are notably higher than for the vegetables.

Table 3-10: Blue, green and grey water footprints (WFs) using fresh mass as a functional unit for cultivating the main vegetable and grain crops grown on the Steenkoppies Aquifer

Crop	Month	Average seasonal WFs of crops ($m^3\ t^{-1}$)			
		Blue	Green	Blue + Green	Grey
Carrots	Summer	36	25	61	48
	Autumn	104	12	116	60
	Winter	88	7	95	52
	Spring	45	17	62	39
Cabbage	Summer	38	29	66	66
	Autumn	53	11	64	31
	Winter	77	1	79	18
	Spring	63	16	79	46

Beetroot	Summer	60	40	100	92
	Autumn	87	14	101	33
	Winter	121	3	124	20
	Spring	104	15	118	96
Broccoli	Summer	142	120	262	183
	Autumn	225	76	301	575
	Winter	322	5	327	540
	Spring	170	44	214	214
Lettuce	Summer	31	24	56	100
	Autumn	51	20	71	131
	Winter	93	1	93	56
	Spring	56	6	62	80
Maize	Summer	452	253	707	377
Wheat	Winter	732	30	762	443

3.3.3 Cultivation blue and green water footprints according to the hydrological methodology

The blue and green WF results of the two- and three-crop rotations according to the hydrological methodology compared to the WFN methodology are displayed in Figure 3-9. The hydrological blue WFs of the three-crop rotation are higher than the two-crop rotation per tonne of crops produced. Average blue WFs according to the hydrological method are lower than average blue WFs according to the WFN method. This is because the WFN accounts for total ET, while the hydrological methodology considers rainfall to reduce the WF. The hydrological green WFs for both the two- and the three-crop rotations are negligible, because the WF is based on changes in soil moistures under irrigation, which reduces the variability in soil moisture.

Hydrological studies typically work in hydrological years, which include wet and dry seasons. For this reason it was proposed by Deurer et al. (2011) that WFs must also work according to the hydrological year. However, total annual water budgets over a hydrological year concealed seasonal green water scarcities and high WFs of certain crops, such as broccoli, which were clearly revealed by the WFN results.

Positive blue WFs according to the hydrological methodology indicate a net reduction in water in the aquifer under the two- and three- crop rotation fields. There are, however, areas on the aquifer with natural vegetation and other land uses where water is not abstracted from the aquifer, where a net recharge is expected. For example, as shown in Figure 3-10, 122 mm average drainage was estimated to occur under natural vegetation. Upscaling to aquifer level is therefore required to fully understand the long-term sustainability of all land uses combined, and specifically the agricultural activities, on the aquifer. Doing the WF of the entire hydrological year required that crop sequences be used for the short season vegetable crops in this study and this complicated upscaling to a catchment level. Upscaling would require that typical crops sequences be used, instead of simply using total yields. Although there are only a few crops on the aquifer, there are numerous combinations of crops planted in different sequences over a year, which requires more assumptions and generalisations to be made to upscale hydrological WFs to a catchment level.

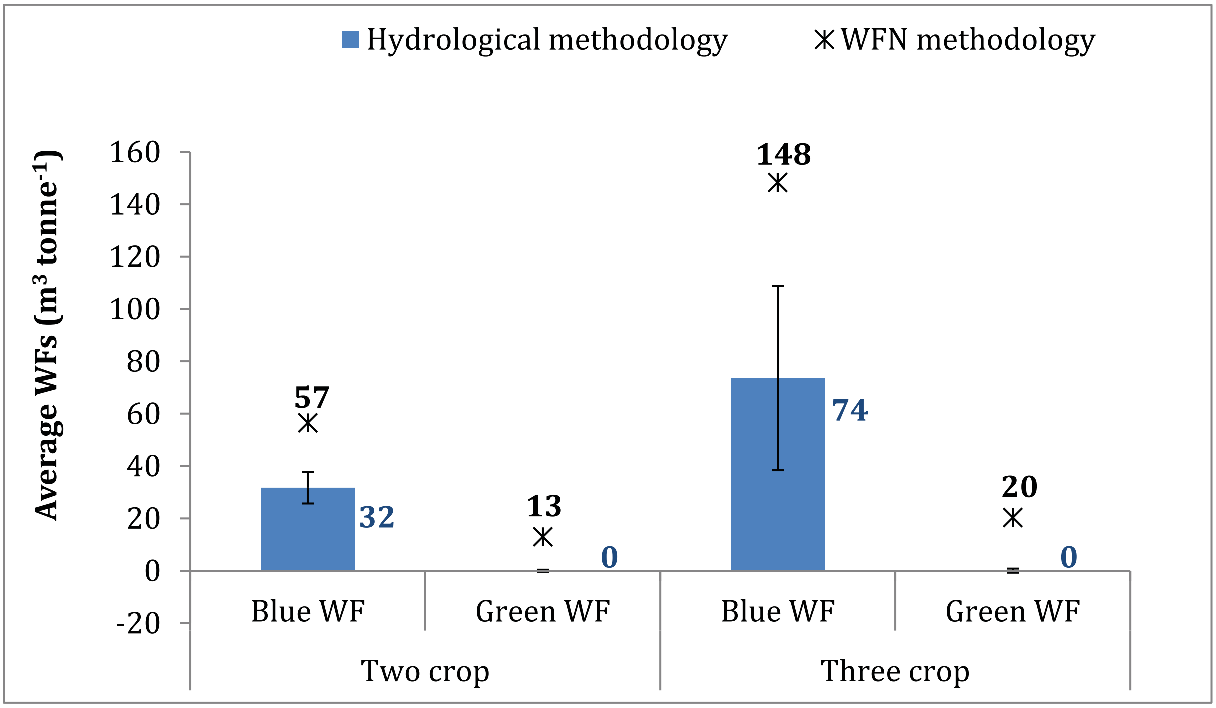

Figure 3-9: Average hydrological blue and green WFs of an annual two crop rotation sequence (carrots summer and cabbage winter) and an annual three crop rotation sequence (broccoli winter, cabbage spring and beetroot summer) compared to average WFs according to the WFN methodology

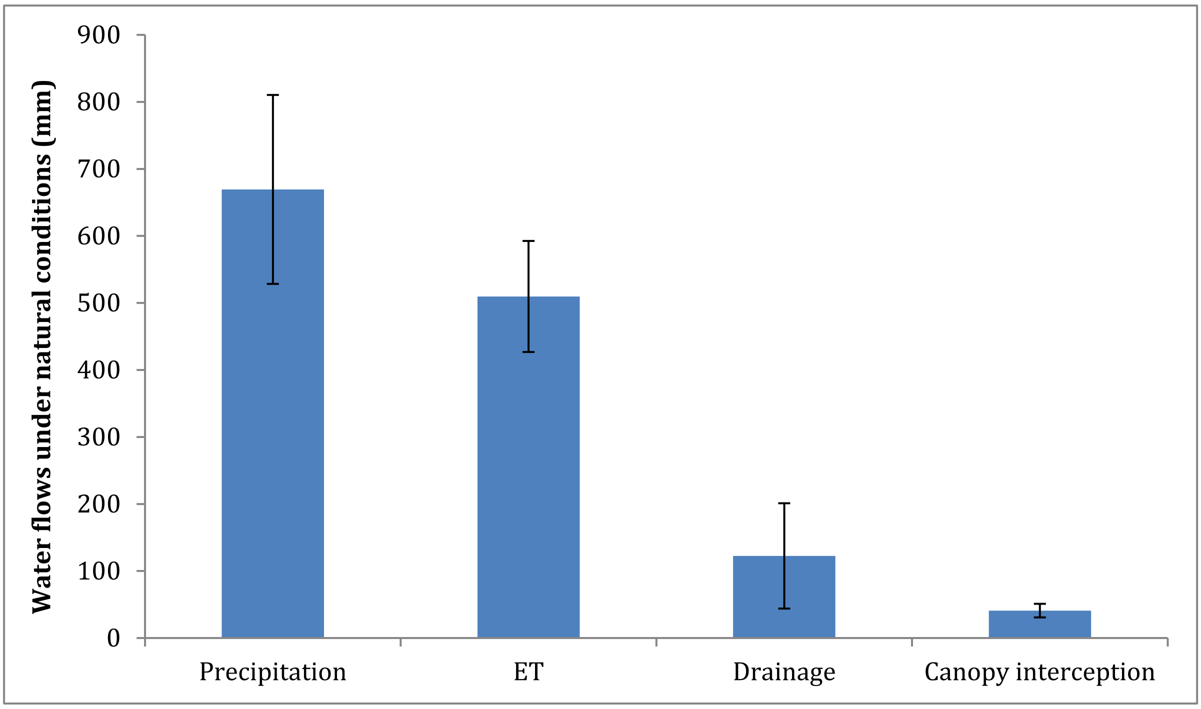

Figure 3-10: Precipitation, evapotranspiration (ET), drainage and canopy interception estimated for natural vegetation on the Steenkoppies Aquifer.

For South African fruit or vegetable crops for which drainage plus runoff is higher than irrigation, a negtaive blue WF is possible for this method. For example, based on data collected over a year, we can estimate that for a 12 year old apple orchard in the Koue Bokkeveld (rainfall = 1198 mm, ET = 952 mm, runoff = 291 mm, irrigation = 845 mm, drainage = 800 mm, yield = 60 t ha^{-1}) the blue WF will be -41 m^3 t^{-1}. Dreur et al. (2011) and Herath et al. (2013) recommend the calculation of the green WF using what the ET, runoff, drainage and yield would be under rainfed conditions (no irrigation). For apples (a summer crop) growing in a winter rainfall region there will most likely not be a yield with which to do this calculation, so this approach is not feasible in this scenario. If we make a simple assumption that the WF is determined only by green water use, the green WF (ET/yield) will be 159 m^3 $tonne^{-1}$. The attained result is largely because irrigation is applied during the dry summer season, which more than compensates for the water used by the orchard over this period, while rainfall during the wet winter months (when the orchard is dormant) results in recharge and runoff. While it may be useful to know that under this land use recharge of water resources is greater than irrigation, is confusing or even misleading to obtain a negative blue water footprint for a crop that is so heavily reliant on irrigation. While it was acknowledged that this approach can lead to further understanding of the hydrology of the system using the WF value alone, this method does not appear to be more effective in creating a WF that is useful for consumer awareness. This matter is further addressed in **Section 8.1**.

3.3.4 Cultivation blue water footprints according to the Life Cycle Assessment (LCA) methodology

WS indices for South Africa, as calculated by Pfister et al. (2009) are shown in Figure 3-4. The Maloney's Eye Catchment is at the northern border of an extremely large inland area of 452 765 km^2 with a WS Index of 0.78 (orange area in Figure 3-4). WS indices calculated with more local data for five periods from 1950 to 2012 is given in Table 3-11. The relatively high VF of 30 was calculated for the Maloney's Eye Catchment, compared to the median VF of 1.8 that was used by Pfister et al. (2009) in a global case study. This high VF resulted in high WS indices, even though it is reduced to 5.5 (square root) for regulated catchments such as the Maloney's Eye Catchment. For example, the WS index for 1950 to 1980 where the WU is only 2 Mm^3 still exceeds the threshold (0.5) between moderate and severe water stress as specified by Pfister et al. (2009). There is, however, a notable difference between the WS index of the first period and that of the later periods, due to differences in blue water use for agriculture on the Steenkoppies Aquifer. The WS index given by Pfister et al. (2009) is also different from WS indices calculated with local data.

Table 3-11: Summary of Water Stress (WS) Indices for the Maloney's Eye Catchment and data used in the calculation for five periods from 1950 to 2012

Period	Average water use (Mm^3 yr^{1-})	Average water availability (Mm^3 yr^{1-})	Withdrawal to availability ratio	WS Index
1950 to 1979	2	14	0.1	0.6
1980 to 1986	4	14	0.3	1.0
1987 to 1995	13	14	1.0	1.0
1996 to 2004	20	14	1.5	1.0
2005 to 2012	25	14	1.9	1.0
Average 1950 to 2012	10	14	0.7	1.0

WFs according to the LCA methodology are lower than WFs according to the WFN methodology (Table 3-12). Looking at the comparison between WF results according to the WFN methodology and the LCA methodology, it appears as if the LCA methodology does not add much value since LCA WFs reduce the WFN WFs of all crops by the same proportions. However, the results are potentially useful to compare water use in one part of the country with similar water uses in other areas around the world. This method will therefore not be very useful to water resource managers working in one hydrologically linked catchment or aquifer where the water stress in one area will impact the entire system. Catchment managers may also require more quantitative data which gives them the option of interpreting data within their own information systems.

Table 3-12: Water Footprints according to the Life Cycle Assessment (LCA) methodology

Crop	Season	Blue WF according to the Water Footprint Network (m^3 tonne $^{-1}$)	Water Stress Index	LCA Water footprint of the functional unit (m^3 H_2O e)
Carrots	Summer	36	0.78	28
	Autumn	104	0.78	82
	Winter	88	0.78	69
	Spring	45	0.78	35
Cabbage	Summer	38	0.78	30
	Autumn	53	0.78	42
	Winter	77	0.78	61
	Spring	63	0.78	50
Beetroot	Summer	60	0.78	47
	Autumn	87	0.78	68
	Winter	121	0.78	95
	Spring	104	0.78	81
Broccoli	Summer	142	0.78	112
	Autumn	225	0.78	176
	Winter	322	0.78	252
	Spring	170	0.78	133
Lettuce	Summer	31.3	0.78	24
	Autumn	51.2	0.78	40
	Winter	92.6	0.78	73
	Spring	56.2	0.78	44
Maize	Summer	453	0.78	355
Wheat	Winter	732	0.78	573

3.3.5 Blue water footprint in the packhouse

The WFs of packing and cleaning carrots, cabbage and lettuce in a packhouse on the Steenkoppies Aquifer are 1.3 m^3 t^{-1}, 0.3 m^3 t^{-1} and 0.9 m^3 t^{-1}, respectively (Table 3-13 and Figure 3-11). These packhouse WFs are notably much lower compared to average blue WFs of cultivation in all growing seasons, which were 68 m^3 t^{-1}, 58 m^3 t^{-1} and 58 m^3 t^{-1} for carrots, cabbage and lettuce respectively. Thus, the packhouse WFs for carrots, cabbage and lettuce were, respectively, 1.9%, 0.5% and 1.6% of the average cultivation WFs taken over all seasons. Figure 3-12 to Figure 3-14 shows the proportions of packhouse WFs in relation to the blue plus green and grey WFs during cultivation of carrots, cabbage and lettuce, respectively.

More than 76% of the water used in the packhouse was attributed to carrot processing, because of the extensive requirements for cleaning and cooling, which explains the relatively high WF of carrots during this stage. The WF of lettuce in the packhouse is higher than cabbage, even though it was assumed that both use 11.6% of the total water supplied to the packhouse (**Section 3.2.6**). This is because the weight of lettuce heads (average of 0.6 kg) is much lower than that of cabbage (average of 3.5 kg), which resulted in a lower yield in terms of mass. If water used per crop head was determined, the WF of lettuce would have been lower than that of cabbage during this stage, because the input volumes of lettuce are higher than cabbage in terms of crop head counts.

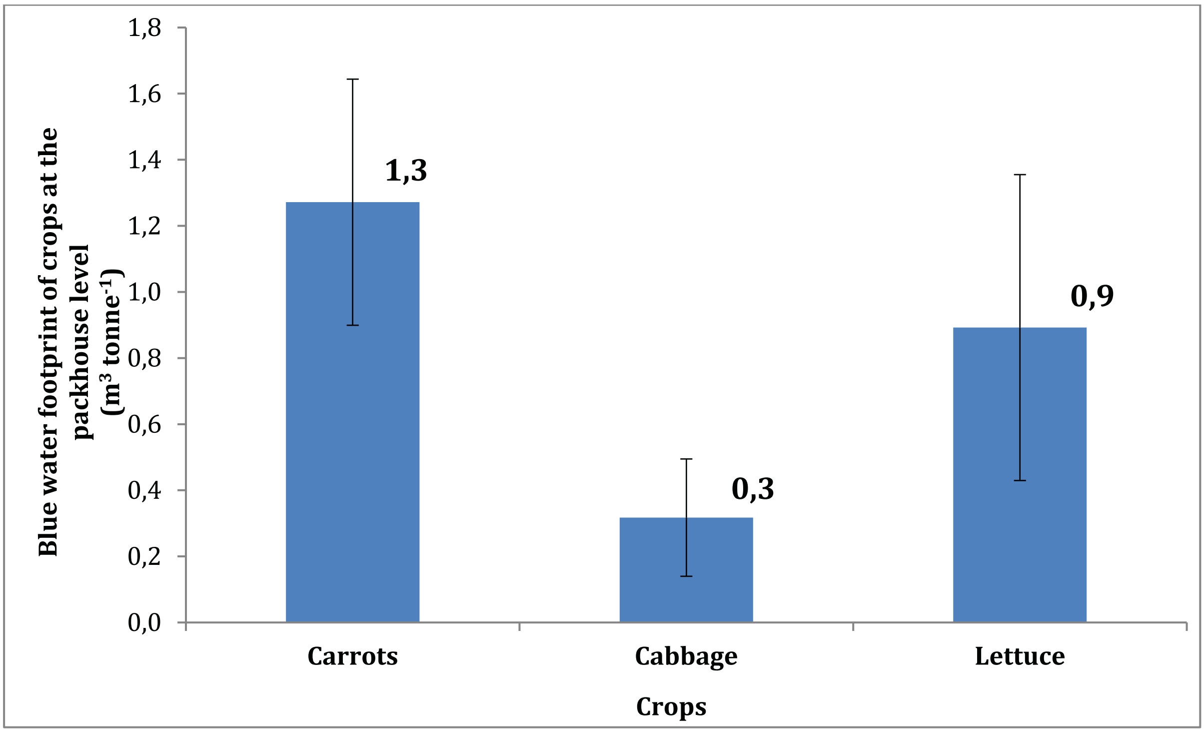

Figure 3-11: Blue water footprints of carrots, cabbage and lettuce for cleaning and packing in a packhouse on the Steenkoppies Aquifer

Table 3-13: Blue WFs for cleaning and packing carrots, cabbage and lettuce in the packhouse

Date	Flow meter (m^3 day^{-1})	Water used attributed to crop (m^3)			Production (tonnes)			Blue water footprint (m^3 $tonne^{-1}$)		
		Carrots	Cabbage	Lettuce	Carrots	Cabbage	Lettuce	Carrots	Cabbage	Lettuce
24-Jun-16	93	72	11	11	79	24	11	0.9	0.4	1.0
25-Jun-16	57	44	7	7	76	19	13	0.6	0.4	0.5
26-Jun-16	57	44	7	7	0	40	6	-	0.2	1.1
27-Jun-16	108	83	13	13	87	85	13	1.0	0.1	1.0
28-Jun-16	116	89	14	14	0	61	13	-	0.2	1.0
29-Jun-16	115	88	13	13	63	68	19	1.4	0.2	0.7
30-Jun-16	100	77	12	12	63	60	16	1.2	0.2	0.7
1-Jul-16	103	79	12	12	50	22	8	1.6	0.5	1.5
2-Jul-16	103	79	12	12	0	13	8	-	0.9	1.5

Date	Flow meter (m^3 day^{-1})	Water used attributed to crop (m^3)			Production (tonnes)			Blue water footprint (m^3 tonne^{-1})		
		Carrots	Cabbage	Lettuce	Carrots	Cabbage	Lettuce	Carrots	Cabbage	Lettuce
3-Jul-16	0	0	0	0	0	0	0	-	-	-
4-Jul-16	85	65	10	10	0	75	9	-	0.1	1.0
5-Jul-16	91	70	11	11	0	79	12	-	0.1	0.9
6-Jul-16	92	71	11	11	69	75	12	1.0	0.1	0.9
7-Jul-16	93	72	11	11	63	55	13	1.1	0.2	0.8
8-Jul-16	99	76	12	12	60	39	5	1.3	0.3	2.4
9-Jul-16	55	42	6	6	38	0	0	1.1	-	-
10-Jul-16	55	42	6	6	0	45	10	-	0.1	0.7
11-Jul-16	92	71	11	11	63	93	6	1.1	0.1	1.8
12-Jul-16	93	72	11	11	54	61	13	1.3	0.2	0.8
13-Jul-16	92	71	11	11	63	63	12	1.1	0.2	0.9
14-Jul-16	93	72	11	11	63	50	8	1.1	0.2	1.4
15-Jul-16	72	55	8	8	50	23	11	1.1	0.4	0.8
16-Jul-16	37	28	4	4	0	16	7	-	0.3	0.6
17-Jul-16	37	28	4	4	0	35	10	-	0.1	0.4
18-Jul-16	93	72	11	11	57	53	16	1.3	0.2	0.7
19-Jul-16	96	74	11	11	50	48	14	1.5	0.2	0.8
20-Jul-16	93	72	11	11	54	48	12	1.3	0.2	0.9
15-Aug-16	105	81	12	12	48	49	17	1.7	0.2	0.7
16-Aug-16	106	82	12	12	59	22	16	1.4	0.6	0.8
17-Aug-16	104	80	12	12	63	30	18	1.3	0.4	0.7
18-Aug-16	105	81	12	12	62	25	24	1.3	0.5	0.5
19-Aug-16	89	69	10	10	72	13	20	1.0	0.8	0.5
20-Aug-16	89	69	10	10	54	25	18	1.3	0.4	0.6
21-Aug-16	89	69	10	10	0	35	15	-	0.3	0.7
22-Aug-16	104	80	12	12	68	39	12	1.2	0.3	1.0
23-Aug-16	104	80	12	12	52	0	0	1.5	-	-
24-Aug-16	106	82	12	12	63	0	0	1.3	-	-
25-Aug-16	102	78	12	12	58	22	16	1.4	0.5	0.7
26-Aug-16	146	112	17	17	46	21	18	2.4	0.8	1.0
27-Aug-16	74	56	9	9	0	14	14	-	0.6	0.6
28-Aug-16	74	56	9	9	0	20	18	-	0.4	0.5
29-Aug-16	103	79	12	12	62	39	16	1.3	0.3	0.8
30-Aug-16	103	79	12	12	49	34	28	1.6	0.4	0.4
31-Aug-16	102	78	12	12	53	40	22	1.5	0.3	0.5
1-Sep-16	106	82	12	12	56	43	18	1.5	0.3	0.7
2-Sep-16	61	47	7	7	73	15	16	0.6	0.5	0.4
3-Sep-16	61	47	7	7	62	17	9	0.8	0.4	0.7
4-Sep-16	61	47	7	7	27	21	10	1.8	0.3	0.7
5-Sep-16	107	82	12	12	66	48	5	1.3	0.3	2.7
6-Sep-16	106	82	12	12	68	45	10	1.2	0.3	1.3
7-Sep-16	104	80	12	12	57	51	10	1.4	0.2	1.3
8-Sep-16	105	81	12	12	60	53	11	1.3	0.2	1.1
9-Sep-16	98	75	11	11	0	22	6	-	0.5	2.0
10-Sep-16	98	75	11	11	0	15	12	-	0.8	0.9

Date	Flow meter (m^3 day^{-1})	Water used attributed to crop (m^3)			Production (tonnes)			Blue water footprint (m^3 $tonne^{-1}$)		
		Carrots	Cabbage	Lettuce	Carrots	Cabbage	Lettuce	Carrots	Cabbage	Lettuce
11-Sep-16	98	75	11	11	0	31	8	-	0.4	1.5
12-Sep-16	104	80	12	12	59	38	9	1.4	0.3	1.3
13-Sep-16	103	79	12	12	54	44	8	1.5	0.3	1.5
14-Sep-16	102	78	12	12	50	57	14	1.6	0.2	0.9
15-Sep-16	103	79	12	12	0	52	15	-	0.2	0.8
16-Sep-16	108	83	13	13	62	40	18	1.3	0.3	0.7
17-Sep-16	55	42	6	6	24	21	11	1.7	0.3	0.6
18-Sep-16	55	42	6	6	0	36	12	-	0.2	0.5
19-Sep-16	104	80	12	12	52	68	20	1.5	0.2	0.6
20-Sep-16	104	80	12	12	61	75	22	1.3	0.2	0.6
21-Sep-16	106	82	12	12	76	59	24	1.1	0.2	0.5
22-Sep-16	104	80	12	12	79	0	0	1.0	-	-
23-Sep-16	66	51	8	8	68	45	14	0.7	0.2	0.5
24-Sep-16	34	26	4	4	16	9	9	1.6	0.4	0.4
25-Sep-16	34	26	4	4	0	42	15	-	0.1	0.3
26-Sep-16	108	83	13	13	64	65	29	1.3	0.2	0.4
27-Sep-16	99	76	12	12	71	0	0	1.1	-	-
28-Sep-16	0	69	10	10	46	28	9	-	-	-
Average	**95**	**69**	**10**	**10**	**46**	**28**	**9**	**1.3**	**0.3**	**0.9**

3.3.6 Grey water footprint at the packhouse level

The data used to calculate P loads discharged per tonne of crop is summarized in Table 3-14. The leaching-runoff potential fraction was determined to be 0.045. The packhouse level grey WFs are higher than the packhouse level blue WFs. Grey WFs at the packhouse level are negligible compared to grey WFs during the cultivation phase. The grey WFs of cabbage at the packhouse level is notably lower than that of carrots and lettuce, because cabbage requires relatively low volumes of water if compared to carrots and, in terms of fresh mass, more cabbage crops are packed on an average day compared to lettuce.

Table 3-14: Grey WFs and data used to calculate grey WF of processing and packing each crop in the packhouse

Crops	Carrots	Cabbage	Lettuce
Average Ortho Phosphate (as P) in effluent (kg m^{-3})	0.00105	0.00105	0.00105
Average water use per crop in packhouse (m^3 day^{-1})	69	10.5	10.5
Average crop production in packhouse (t day^{-1})	46	28	9
Phosphate load leaching to the aquifer per crop produced (kg P t^{-1})	7 e^{-5}	0.00002	5 e^{-5}

Packhouse grey WFs (m^3 t^{-1})	**4**	**1**	**3**
Grey WFs of cultivation average over all seasons (m^3 t^{-1})	50	40	92
Percentage of grey water footprints in the packhouse in terms of grey WFs during cultivation (%)	8%	2%	3%

3.3.7 Indirect water used in packhouse

The WF of electricity used in the packhouse to clean and pack carrots, cabbage and lettuce is indicated in Table 3-153-15. This WF is low compared to the blue WF for cleaning and packing the crops. This volume is not added to the blue WF of the packhouse, because it is sources from another catchment and does not impact the Steenkoppies Aquifer.

Table 3-15: Water footprints (WFs) of electricity used in the packhouse for cleaning and packing carrots, cabbage and lettuce

Date	Packhouse electricity use (kwh)	WF of electricity use (m^3)	Water used attributed to crop (m^3)			Production (tonnes)			WF (m^3 $tonne^{-1}$)		
			Carrots	Cabbage	Lettuce	Carrots	Cabbage	Lettuce	Carrots	Cabbage	Lettuce
November 2014	114110	151	115	17	17	1929	6751	4051	0.060	0.003	0.004
December 2014	95635	126	97	15	15	1882	6586	3951	0.051	0.002	0.004
January 2015	127070	168	128	19	19	2245	7858	4715	0.057	0.002	0.004
February 2015	123268	163	125	19	19	1750	6126	3675	0.071	0.003	0.005
March 2015	129156	170	131	20	20	1669	5840	3504	0.078	0.003	0.006
April 2015	110389	146	112	17	17	1141	3994	2396	0.098	0.004	0.007
May 2015	91023	120	92	14	14	1310	4584	2750	0.070	0.003	0.005
June 2015	88602	117	90	14	14	1494	5228	3137	0.060	0.003	0.004
July 2015	93285	123	94	14	14	1802	6307	3784	0.052	0.002	0.004
August 2015	89681	118	91	14	14	1923	6730	4038	0.047	0.002	0.003
September 2015	106270	140	107	16	16	1474	5161	3096	0.073	0.003	0.005
October 2015	131504	174	133	20	20	1646	5763	3458	0.081	0.003	0.006
Average	**108333**	**142999**	**110**	**17**	**17**	**1689**	**5911**	**3546**	**0.067**	**0.003**	**0.005**

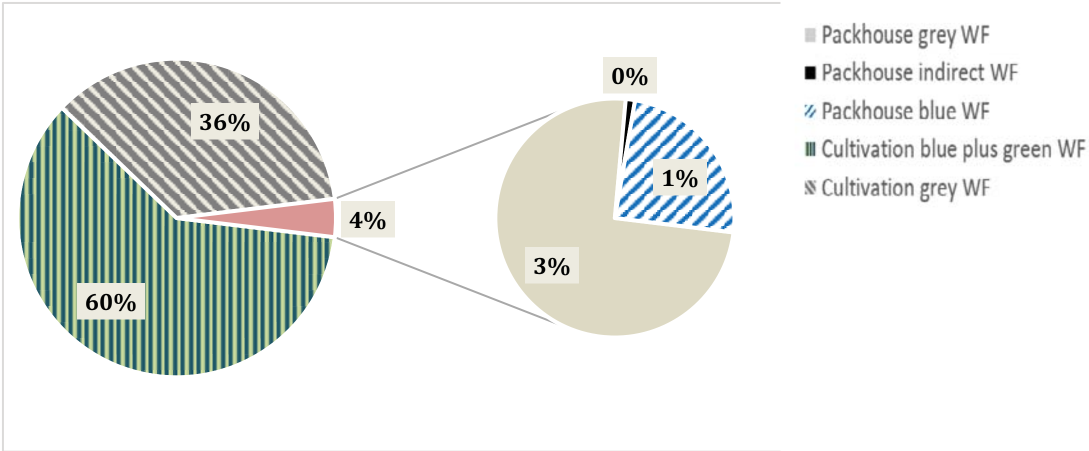

Figure 3-12: Comparing the blue plus green and grey WF of carrots during cultivation with the blue, grey and indirect WFs at the packhouse level.

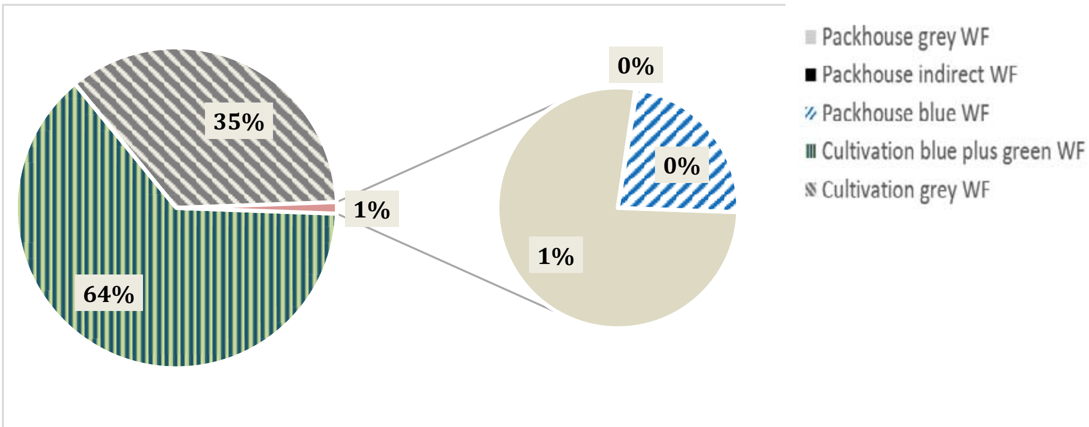

Figure 3-13: Comparing the blue plus green and grey WF of cabbage during cultivation with the blue, grey and indirect WFs at the packhouse level.

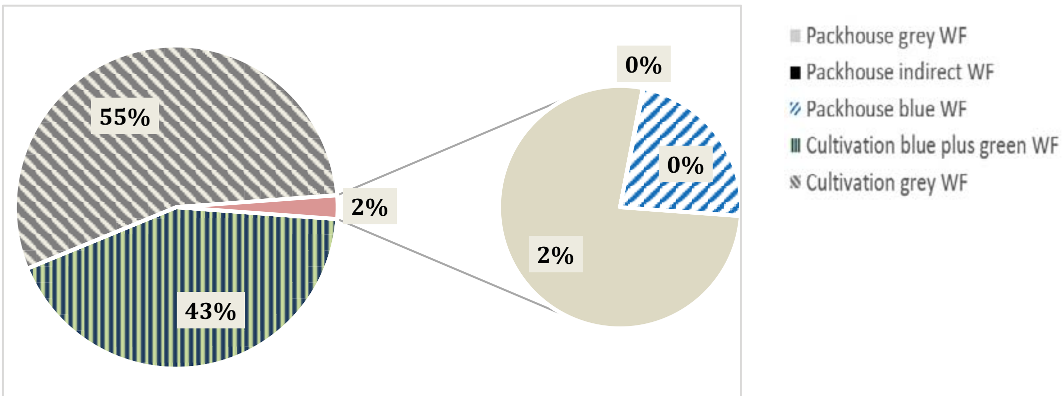

Figure 3-14: Comparing the blue plus green and grey WF of lettuce during cultivation with the blue, grey and indirect WFs at the packhouse level.

3.4 Discussion

Water footprints according to the WFN can be useful in various ways. They can, for example, indicate high water uses per yield in certain seasons and by certain crops. However, a crop WFs according to the WFN, which is a volume of water used per yield of crop, can be misleading if communicated outside the context of the local circumstances and without the sustainability assessment step for the WF in a particular area. This raised concern from the LCA and hydrology communities who indicated that a volume of water used must be interpreted within the local context. Although this is true, there are a number of challenges involved in producing a standard method that can cover all the complexities involved in understanding the impact of a water use on local resources.

The hydrological method takes all water flows into account, as opposed to the WFN that considers crop ET only. Although the hydrological method seems more comprehensive than the WFN method, the following issues were encountered in the assessment of the methodology:

- According to the hydrological methodology (Deurer et al. 2011), blue WFs are the difference between volumes abstracted through irrigation and volumes recharged due to deep drainage and runoff. In the original method by Deurer et al. (2011), runoff is considered to recharge the blue water source, which was groundwater in their case, because of the flat topography of their study area. However, in different circumstances runoff will more likely flow out from a catchment and will not replenish the aquifer. In this case, therefore, the method will overestimate aquifer replenishing rates and underestimate blue WFs.
- Green WF calculations are based on the change in soil moisture originating from rainfall. It was, however, not possible to calculate green WFs in the same way as the methodology suggests, because modelling under rain-fed conditions is required and some of the crops will fail due to low rainfall, particularly in the dry winter season. Green WFs were therefore calculated using the change in soil moisture with irrigation included, resulting in negligible green WFs. The methodology for green WFs is therefore not considered suitable for an irrigation system, like the Steenkoppies Aquifer, and is more applicable to rain-fed systems.
- WFs according to the hydrological approach are calculated over a year. To determine the WFs for the short season vegetable crops in this study, crop sequences over a year were used. This, however, concealed the high WFs of certain crops, like broccoli, and the impact on water resources in dry seasons.
- The methodology does not include guidelines on the water requirements on downsteam users or specify the volumes of water that is required to flow from a particular catchment.
- Finally, the method was also not considered useful for the Steenkoppies Aquifer case study, because the WFs for the crop sequences presented many complexities if one wished to upscale the crop WF results to a catchment level.

The LCA methodology has some important strengths, most notably the more advanced calculation of water quality impacts in terms of eutrophication, freshwater ecotoxicity and human health (Pfister et al. 2009). The method takes multiple environmental impacts into account, such as water consumption and carbon footprints. Considering the unique geohydrological characteristics and water issues of the Steenkoppies Aquifer, more local WS indices are required. However, although spatial variations may impact the WS index, the WS index should also be sensitive to temporal variations. The LCA method attempts to address such temporal variation by including a VF as a measure of variation in climatic conditions. The

VF increases the WS Index of the catchment and will result in increased WFs. The VF is lower for catchments with dams or aquifers that regulate flows and reduce variations in water availability (Pfister et al. 2009). The aquifer will reduce variations in water availability, which will reduce the WS index. The intensive use of the Steenkoppies Aquifer has caused severe reductions in groundwater levels and outflows from Maloney's Eye, and the aquifer has become more water-stressed as a result. Therefore, the WS index determined for 1950 cannot be applied to the later years when commercial agriculture expanded and impacted on the aquifer, despite the inclusion of the VF. Thus, in the case of the Maloney's Eye Catchment a different WS index would have been more appropriate in later years when the aquifer became more stressed.

The aim of a WF assessment is to address sustainable water use. This must be done on national, regional and local levels and ultimately it must aim to change the behaviour of water consumers. The so-called knowledge hierarchy (Ackoff 1989) provides a useful way to better understand the difference between WF methodologies and the complexities involved in developing and using them. As indicated in Figure 3-15 (taken from Rowley (2007)), data is at the bottom of the knowledge hierarchy. Data that is interpreted becomes information, knowledge is the know-how or experience of what to do with information and wisdom is the judgement as to whether our actions are right or wrong. In a WF context, the volume of water that is used to produce a product is data. This data only becomes informative when interpreted in a local context of water availability and environmental demand. Somehow the information should be communicated to consumers, producers and water resource managers in order for them to make wise decisions that will ensure the sustainability of the water used to produce a product. In Figure 3-15, Rowley (2007) also indicates that data can be programmed, while wisdom cannot be programmed or generated by a computer. This is why it is really difficult to develop a WF method of which the outcome is an undisputed number that can be used on labels and will indicate 'right' or 'wrong' to a consumer.

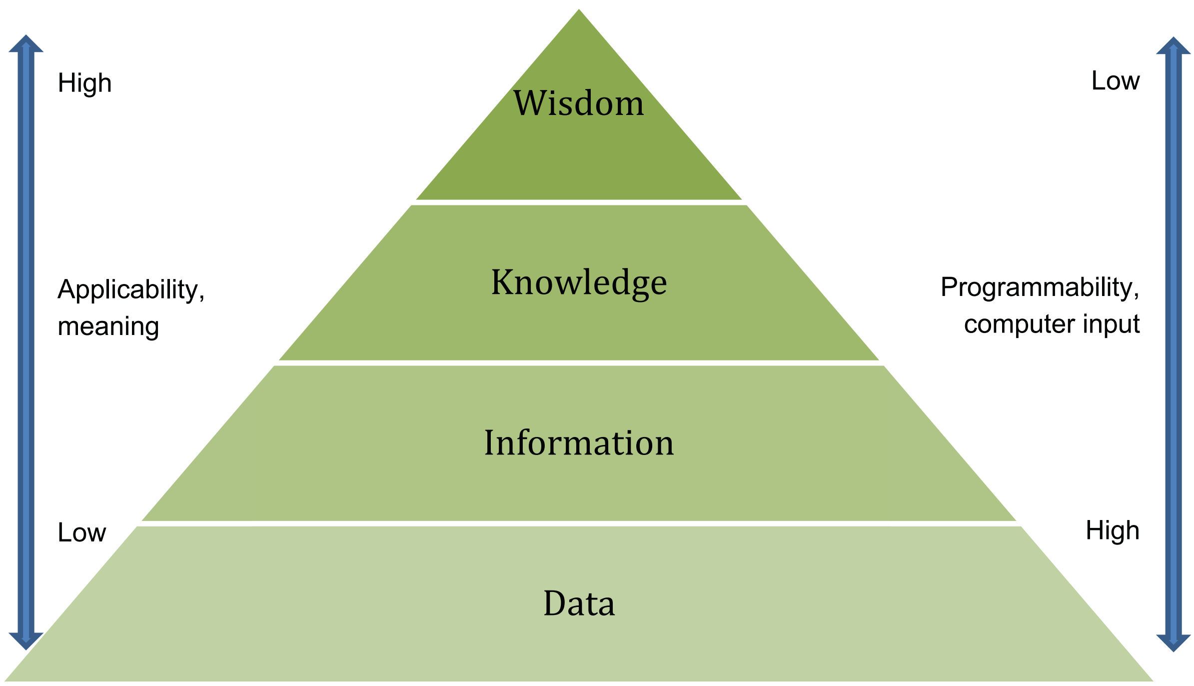

Figure 3-15: The knowledge hierarchy (Rowley 2007)

Volumetric WFs according to the WFN methodology, are at the level of data, defining the WF as a volume of water used to produce a product or provide a service. Data is often most valuable when a water resource manager can interpret it within his specific location to get the necessary information for decision making. However, care must be taken not to communicate a WF defined as a volume of water used, which is mere data, as information or wisdom implying that a volume used is ‘good’ or ‘bad’. For this reason, the LCA and hydrological communities developed modified methodologies seeking to interpret the data to obtain information (a better understanding of the water use in terms of water availability and the hydrology) and wisdom (the LCA methodology potentially providing consumers with a label that will indicate the degree of impact).

Although it is very important to get from data to wisdom, there are many complexities involved in standardising a method on these higher levels of the knowledge hierarchy. Figure 3-15 (Rowley 2007) indicates this, by showing that the higher levels of the knowledge hierarchy cannot be programmed and calculated by computers. For example, the WS index calculated using the LCA methodology considers the availability of water within a certain area. Although it is important to consider water availability in relation to water use, it is not the only consideration in terms of sustainability. Water demands by the ecosystem, people or for economic use must all be considered. This can become very complex, taking ecological water requirements as an example. It is commonly recognised that flow reductions in rivers are not desirable (Lake, 2003) and that floods are important ecological events that flush alien vegetation and sediments from a river (Rountree 2014). However, changes in the seasonality of flows such as increasing dry season flows and decreasing wet season flows, which is common in irrigation schemes, also have an impact on river ecosystems (Lake 2003, Pattie et al. 1985, Rountree 2014). Aquatic species are adapted to certain flow regimes which support connectivity in the aquatic ecosystem and habitats (Bunn and Arthington 2002). Changes to geohydrological characteristics, such as groundwater converted to surface water, are undesirable (Rountree 2014). Managing water uses to ensure the sustainability of a river ecosystem is further complicated by differences in river sensitivities. Maintaining the natural flows of rivers is more important if the aquatic and riparian biodiversity is sensitive with, for example, red data species (Rountree 2014). Often a water resource manager has to decide whether to allocate water to people or ecosystems, which involves trade-offs of various impacts. These are only some of the complexities associated with the water demand of an ecosystem, and the WFs according to the LCA methodology do not address these.

One of the drawbacks of water becoming a global resource is that water users become disconnected from and unaware of the impacts of their water uses. It is therefore very important to consider ways of influencing consumer behaviour. How this should be done has been debated by scientists that are involved in WF assessments. The volumetric WF of the WFN is not a suitable metric for communication to consumers or for product labelling, because it cannot be used outside the environmental context of the water use. The ISO standards (ISO 14046 2014) did not specify ways of reporting WFs to consumers for awareness raising, indicating that they too struggled with the complexity of standardising such a method. The other methods have attempted to interpret and modify the WFN data, most notably the LCA method that aimed to produce product labels. This study on WFs has indicated that calculating WF labels still requires much refinement and debate and will most likely result in a symbol indicating responsible water use or stewardship, as opposed to a quantitative or even stress-weighted volumetric WF label. Consumers need all levels of the knowledge hierarchy (data, information, knowledge and wisdom) to make educated decisions about the products they buy. However, influencing consumers through education may have unpredictable outcomes. Some consumers may choose products based on potential impacts on people, others could make decisions based on ecological sustainability. Advertising and marketing is another way of influencing market demands and the interpretation of information. Crops with a sustainable WF, according to local assessments, could be promoted above crops with unsustainable WFs. Governments can subsidise crops with sustainable WFs to reduce their retail price. Future studies must pay attention to the various ways in which consumer behaviour can be influenced to change market demands.

The results confirmed published literature indicating that the WFs of cleaning and packing vegetables are relatively low compared to the WFs resulting from cultivation (Dominguez-Faus et al. 2009, Hoekstra et al. 2011, Hoekstra and Chapagain 2011, Ridoutt and Pfister 2010). The Grey WFs of carrots, cabbage and lettuce in the packhouse are also relatively small, being 8%, 2% and 3% respectively compared to the grey WFs of cultivation. The indirect WF of electricity use in the packhouse are also relatively small, being 5%, 1% and 0.5% of the physical blue WF at the packhouse level for carrots, cabbage and lettuce, respectively.

The blue WFs in the packhouse vary notably between crops, with carrots having a higher blue WF than cabbage and lettuce. The functional unit used for these WF calculations for the packhouse also had an impact on the outcomes. If lettuce and cabbage fresh mass are used, the WFs of lettuce in the packhouse are higher than those of cabbage, but if yield in heads is used, the WFs of cabbage would be higher than the WFs of lettuce.

3.5 Conclusions

Through a case study on the Steenkoppies Aquifer, three WF methodologies were assessed and compared in terms of their usefulness to water resource managers and consumers. It is concluded that blue and green WFs calculated according to the WFN methodology are most useful for a catchment or aquifer manager, because the WFs are quantitative and can therefore do the following:

- They potentially indicate the high WFs of certain vegetables, such as broccoli;
- They reveal WFs in the dry winter season;
- They a relatively simple to calculate and understand;
- They can be used within different information systems, such as water use licencing or water allocation decisions.

The concern over the way in which WFs of the WFN are communicated outside the context of the environment in which the water is used, is however, legitimate and these results should not be used for awareness raising. The other two methodologies attempt to develop a single value that will indicate the sustainability of a water use, but due to the vast number of variables, complexities and trade-offs involved in sustainable water use, such a number seems to be an unrealistic goal. Product labels will more likely be in the form of a symbol that indicates good water stewardship.

The WFN methodology was therefore selected to be applied in further assessments on the Steenkoppies Aquifer. For the remainder of this study,, the term WFs quoted refer to the WFN results given in Table 3-10.

Water footprints, calculated according to the WFN methodology provided the necessary data to quantify the volume of water used per yield of carrots, cabbage and lettuce in the packhouse. The WFs of beetroot, broccoli, maize and wheat at the packhouse level could not be calculated, because these crops were not being packed when the study was undertaken. Grey WFs are more relevant than blue WFs at the packhouse level, but these outcomes could be lower when the more recently introduced waste water treatment facilities are in operation.

From the calculations in this chapter it is seen that water used at the packhouse level is relatively small, between 0.5% and 2% of the blue WF resulting from cultivation. In the packhouse that was investigated, there are also limited possibilities for further reducing the blue WF at the packhouse level, as water recycling has already been implemented as far as possible. In terms of management priorities, further reductions in packhouse water use are less important, compared to the major reductions in blue WFs resulting from cultivation that are necessary to achieve sustainable blue water use.

Although the WFN methodology was considered to be the simplest method to apply and to interpret, some complexities were encountered in the calculations of WFs of vegetable crops. **Chapter 4** discusses these complexities and possible ways in which they can be dealt with.

4 UNDERSTANDING COMPLEXITIES IN ESTIMATING WATER FOOTPRINTS OF VEGETABLE CROPS

by

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4.1 Introduction

Chapter 3 compared different methodologies that have been proposed to calculate a water footprint (WF) of a product. It was concluded that the Water Footprint Network (WFN) methodology is most useful to a water resource manager, because of its quantitative nature. Apart from the fact that WFs according to the WFN is not suitable for awareness raising and labelling, there are other complexities when applying this methodology in a crop production context.

This chapter explores the potential intricacies involved in calculating WFs of vegetable crops according to the WFN method using a case study on the water stressed Steenkoppies Aquifer. Factors influencing WF outcomes, including natural variations in weather conditions between growing seasons and between different years are discussed. Water footprints are also directly dependent on crop simulation model outputs, which are in turn affected by the quality of parameterisation and input data used, including weather data. Variations in water content between different crops can impact the WFs, which are most commonly expressed as a volume of water used per yield in fresh mass, and we explore the impact of functional units on the results. Finally, some complexities in using the grey WF method are discussed, and aquifer water quality measurements used to challenge the calculation of grey WFs.

In addition to WFs for the crops mentioned above, the WFs for tomatoes and potatoes are also estimated for South Africa based on historical data from previous research commissioned by the WRC. These crops are included due to their importance in South Africa, but could not be included in the Steenkoppies Aquifer work as they are either not grown there in significant quantities (tomatoes) or the farmers were not willing to allow on-farm monitoring (potatoes) by the research team.

4.2 Materials and Methods

4.2.1 Inter-seasonal and inter-annual variation in WFs

In **Chapter 3** WFs were determined for carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) in different seasons. Variations between WFs based on the seasonality of the vegetable crops were estimated and compared to more generic results published in the literature. Long term simulations were also considered necessary to better understand inter-annual variation in WFs of all crops, including the vegetables, maize and wheat, due to changes in prevailing weather patterns. Thus, WFs of each crop in all the relevant seasons were calculated from 2004 to 2013.

4.2.2 The importance of standardised weather datasets

A weather dataset from 1983 to 2013, which included rainfall, minimum and maximum temperature, wind speed and humidity data was obtained from the Deodar Weather station (AgroClimatology Staff 2014). Solar radiation data was available from 2004 onwards, when a pyranometer was added to the weather station. If solar radiation data is unavailable, SWB estimates these values according to FAO 56 recommendations (Allen et al. 1998). Simulation results, and the effect it had on WFs, when using estimated datasets were compared to results when measured datasets are used.

4.2.3 Using different functional units for WF assessments

Rebitzer et al. (2004) defined a functional unit as 'a quantitative description of the service performance (the needs fulfilled) of the investigated product system'. The functional unit of crops, for example, can therefore be the crop yield, or a function of the crop, such as nutritional value. Despite the common use of fresh mass yield as a functional unit, it has been criticised for not being the most appropriate, because crops have different moisture contents and can provide a consumer with a certain nutritional benefit, which is not necessarily correlated with fresh mass (Ingwersen 2012, Schau and Fet 2008). Due to differences in water content some crops have a disproportionately high WF if yield in fresh mass is used, but if yield in dry matter is used these crops' WFs become relatively low. Yield results in SWB are estimated in dry matter (0% moisture), which was converted to fresh mass. The water contents of beetroot, lettuce, maize and wheat were taken from the United States Department of Agriculture (USDA) (United States Department of Agriculture 2015). A constant percentage dry matter was assumed for the other crops. The harvestable dry matter results from SWB were converted to fresh mass by dividing it by the dry matter percentages, as summarised in **Table 4-1.**

Table 4-1: Percentage crop dry matter used to convert Soil Water Balance model dry matter results to fresh mass

Crops	Percentage dry matter
Carrots	10%[1]
Cabbage	7%[1]
Beetroot	13%[2]
Broccoli	13%[1]
Lettuce	4%[2]
Maize	90%[2]
Wheat	87%[2]

[1]Assumed constant percentage; [2] obtained from United States Department of Agriculture (2015)

Using the nutritional value of the crops as a functional unit can be useful because water use is directly connected to a certain benefit derived from the crop. Water footprints were therefore also reported in terms of selected nutrients required by a person per day according to Mahan and Escott-Stump (2004). Required nutrients as a functional unit is complex, because there are a large number of variables involved, such as:

- The different WFs for each growing season.
- The differences in Recommended Dietary Allowances (RDA) depending on gender and age (Mahan and Escott-Stump 2004).
- The different nutrients that a crop provides (United States Department of Agriculture 2015).

The WFs of summer carrots, cabbage, beetroot, broccoli, lettuce and maize were selected to determine the volume of total blue plus green water required to theoretically meet the RDA of men between age 31 to 50 in terms of proteins, carbohydrates, iron, zinc and manganese. Winter WFs were used for wheat, because in the study area it is only planted in winter. The nutrient content of each crop were obtained from the National Nutrient Database for Standard Reference (United States Department of Agriculture 2015). Recommended Dietary Allowance values obtained from Mahan and Escott-Stump (2004) are given in **Table 4-2**.

Table 4-2: Recommended Dietary Allowance (RDA) of selected nutrients required daily by a man aged 31 to 50 years (Mahan and Escott-Stump 2004).

Nutrient	RDA of a man aged 31 to 50
Proteins	56 g
Carbohydrates	130 g
Iron	8 mg
Magnesium	420 mg
Zinc	11 mg

Finally, prices used to calculate the Consumer Price Index (CPI) were obtained for each crop and was used as a functional unit (Statistics South Africa 2016). Monthly prices for CPI calculations from 2008 to 2015 were categorised into the four seasons and divided into WFs of each season to obtain a volume of water used per prices used for CPI calculation. Maize and wheat was excluded from this assessment, because there is not a single value for these grains in CPI, but different values for the various products derived from them.

4.3 Results

4.3.1 Inter-seasonal and inter-annual variation in water footprints

The blue, green and grey WFs with fresh mass as the functional unit for the cultivation phase of each of the crops in each of the four growing seasons, and one season in the case of maize and wheat (shown in **Figure 4-6**), are compared to values published by the WFN (Mekonnen and Hoekstra 2011) in **Table 4-3**.

Table 4-3: Blue, green and grey water footprints using fresh mass as a functional unit for cultivating vegetable crops, maize and wheat on the Steenkoppies Aquifer compared to outcomes from the literature

Crop	Month	Average seasonal WF of crop (m^3 $tonne^{-1}$)				WFs (m^3 $tonne^{-1}$) reported in the literature (Mekonnen and Hoekstra 2011)				Percentage difference between local and published blue + green WFs
		Blue	Green	Blue + Green	Grey	Blue	Green	Blue + Green	Grey	
Carrots	Summer	36	25	61	48	28	106	134	61	120%
	Autumn	104	12	116	60	28	106	134	61	15%
	Winter	88	7	95	52	28	106	134	61	41%
	Spring	45	17	62	39	28	106	134	61	116%
Cabbage	Summer	38	29	66	66	26	181	207	73	212%
	Autumn	53	11	64	31	26	181	207	73	224%
	Winter	77	1	79	18	26	181	207	73	163%
	Spring	63	16	79	46	26	181	207	73	162%
Beetroot	Summer	60	40	100	92	26	82	108	25	8%
	Autumn	87	14	101	33	26	82	108	25	7%
	Winter	121	3	124	20	26	82	108	25	-13%
	Spring	104	15	118	96	26	82	108	25	-9%
Broccoli	Summer	142	120	262	183	21	189	210	75	-20%
	Autumn	225	76	301	575	21	189	210	75	-30%
	Winter	322	5	327	540	21	189	210	75	-36%
	Spring	170	44	214	214	21	189	210	75	-2%
Lettuce	Summer	31	24	56	100	28	133	161	77	256%
	Autumn	51	20	71	131	28	133	161	77	169%
	Winter	93	1	93	56	28	133	161	77	108%
	Spring	56	6	62	80	28	133	161	77	212%
Maize	Summer	452	253	707	377	81	947	1028	194	45%
Wheat	Winter	732	30	762	443	342	1277	1619	207	120%

The WFs of the five vegetable crops included in this study vary significantly depending on the growing season of the crops. Not only does the total blue plus green WF vary between growing seasons, but the blue WFs calculated for the vegetable crops on the Steenkoppies Aquifer are also much higher in winter. The high blue WF of broccoli in winter is due to a very low relative yield of the harvestable portion that is produced by the crop during this season. Some WFs are similar for different seasons, for example the small variation in blue plus green WFs for cabbage over all four seasons. Some WFs have high standard deviations, like wheat in winter and broccoli in summer and spring (**Figure 4-6** and **Figure 4-7**). These high standard deviations highlight the need to do long term simulations to capture the inter-annual variation in WFs due to the variation in weather conditions.

The WFs of the vegetable crops corresponded to the WFs reported by Mekonnen and Hoekstra (2011) in some seasons. There was a 15% difference between total blue plus green WFs of carrots given by Mekonnen and Hoekstra (2011) and local blue plus green WFs of carrots in autumn. Total blue plus green WFs of beetroot given by Mekonnen and Hoekstra (2011) corresponded to local blue plus green WFs of beetroot in summer, autumn and spring with a percentage difference of 8%, 7%, and -9% respectively. The local WF of broccoli was higher than previously reported values, but corresponded well to blue plus green WFs of Mekonnen and Hoekstra (2011) in spring with a -2% difference. Other seasons did not correspond well with WF results given by Mekonnen and Hoekstra (2011), for example the 120% difference in WF of summer carrots, 224% difference in WF for autumn cabbage and the 256% difference in WF of summer lettuce. Percentage differences between local WFs of cabbage and lettuce and those reported in the literature is very high for all seasons. Blue plus green WFs of wheat are much lower than the WFs given by Mekonnen and Hoekstra (2011), with a 112% difference.

4.3.2 The importance of standardised weather datasets

Compared to measured solar radiation, values from 1983 to 2003, which were estimated according to FAO 56 (Allen et al. 1998), were observed to result in noticeably different daily summer and spring ET_o and yield estimates, in turn impacting the WF estimates (which use cumulative crop ET values and yield in their calculation). **Figure 4-1** and **Figure 4-3** shows the effect of using estimated solar radiation on simulated yields of carrots, cabbage, beetroot, broccoli and lettuce planted during summer, as compared to yield results that were obtained with measured solar radiation data post 2004. The square of the correlation coefficient (R^2) between verification yields and yields simulated with measured solar radiation of the five vegetables was 0.94, indicating strong correlation (**Figure 4-4**). The R^2 for verification yields and yields simulated with estimated solar radiation for the five vegetables was 0.6, indicating poorer correlation. This effect was much more insignificant for crops planted in autumn and winter, and in some cases yields were slightly over-estimated in these colder seasons (**Figure 4-2**). The reason why this effect is more prominent in summer and spring is possibly because the study area is a summer rainfall region and solar radiation is more accurately estimated in the absence of cloud cover.

Sensitivity to the quality of weather data and which variables are measured versus estimated should be carefully considered during parameterisation and application of crop parameters in models such as SWB. If crop parameterisation is based on weather datasets which includes estimates and afterwards used with completely measured datasets, the results may be inaccurate. Instead it is recommended that the weather data that is used for parameterisation, whether specific variables are estimated or measured, must be used consistently over the simulation period. In this study, volumetric green and blue WFs were calculated using only 2004 to 2013 weather data, because these data included measured values (including solar radiation, wind speed and humidity) for which crop parameterization was done, and provided the most accurate results when compared to the verification data.

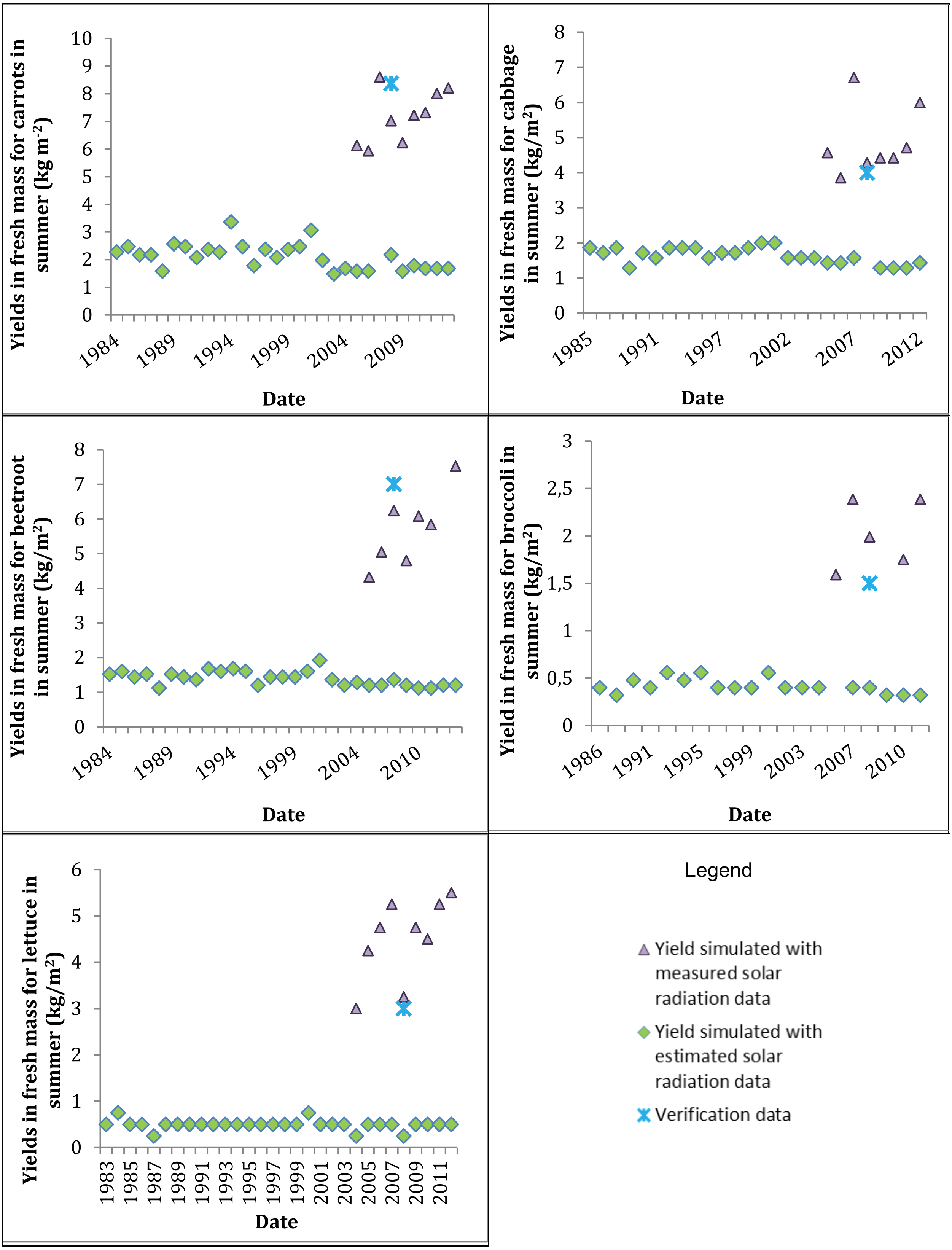

Figure 4-1: Soil Water Balance model simulated yields versus actual yields of vegetable crop grown in summer indicating the influence in using estimated solar radiation data on simulated yield outcomes.

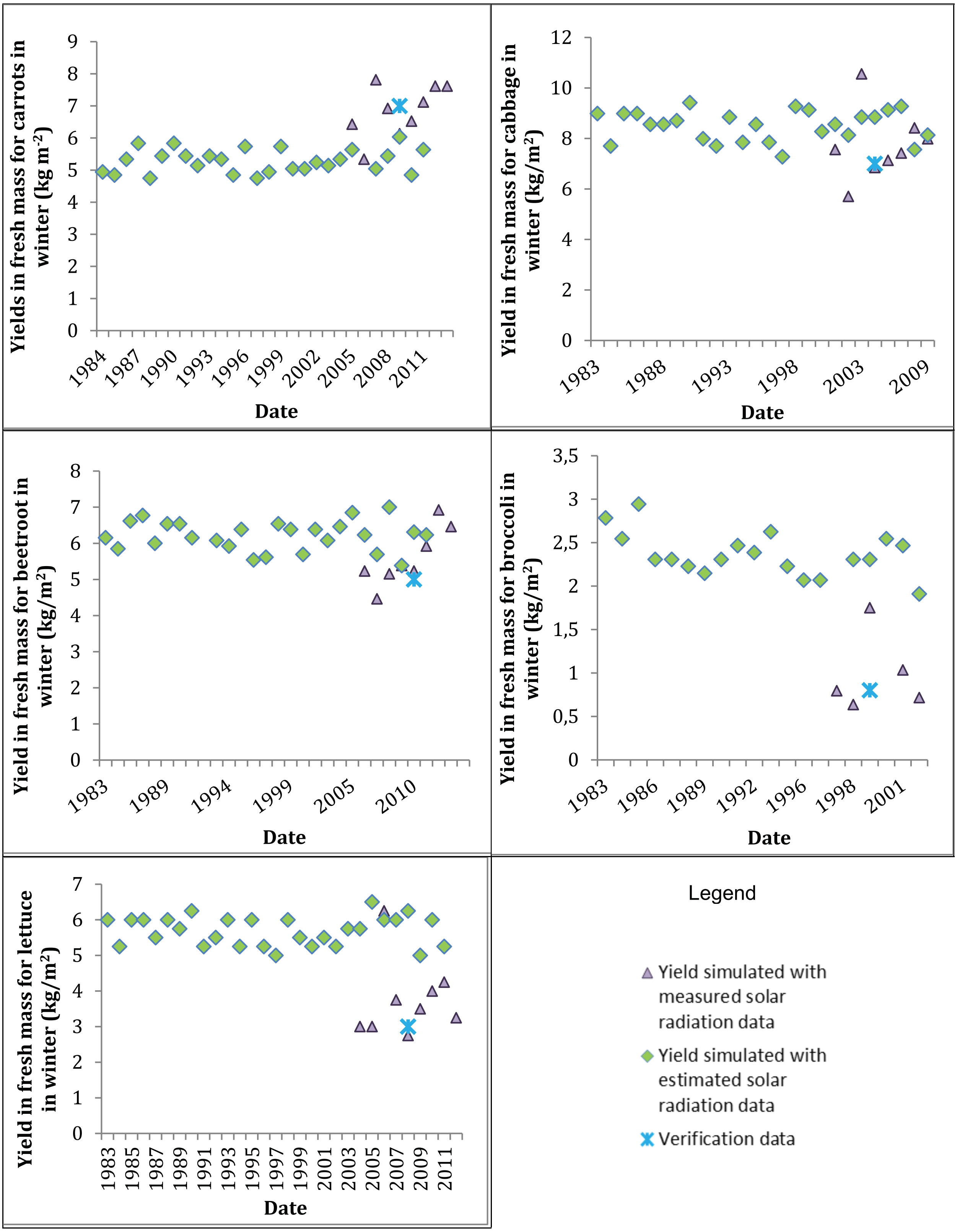

Figure 4-2: Soil Water Balance model simulated yields versus actual yields of vegetable crop grown in winter indicating the influence in using estimated solar radiation data on simulated yield outcomes.

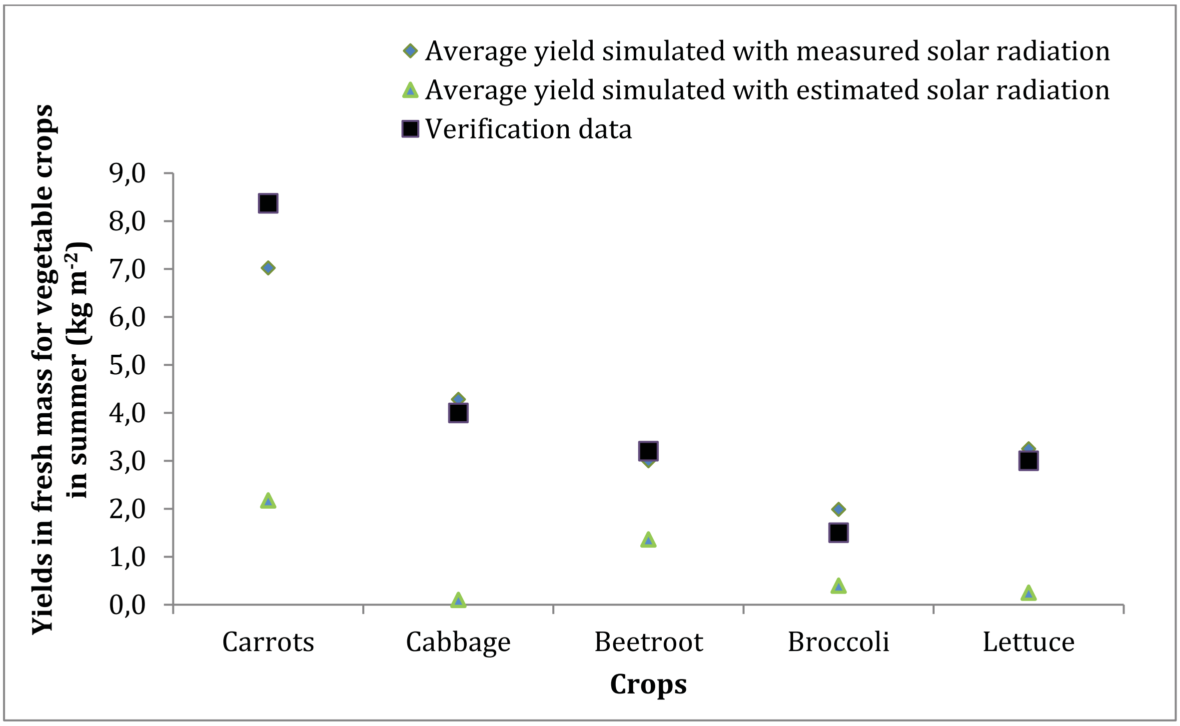

Figure 4-3: Soil Water Balance model results for simulated and measured yield of carrots, cabbage, beetroot, broccoli and lettuce with measured and estimated solar radiation data compared to verification data.

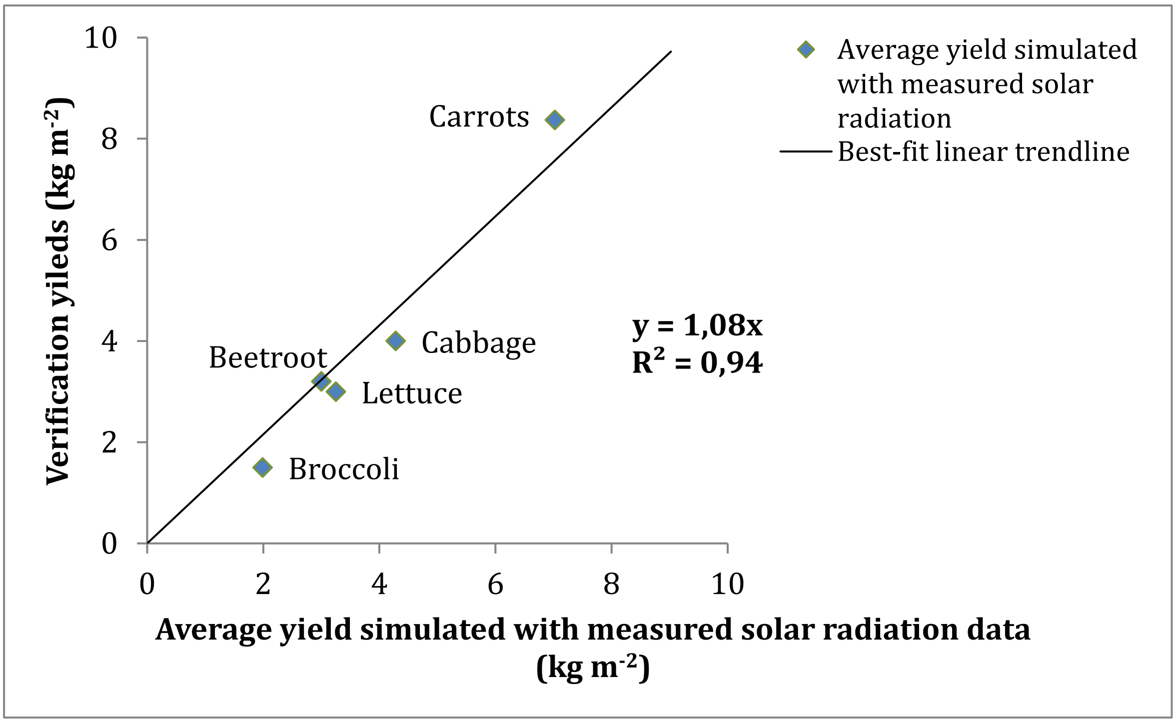

Figure 4-4: Correlation between verification yield data and yields simulated with the Soil Water Balance model using measured solar radiation data for carrots, cabbage, beetroot, broccoli and lettuce

A method was developed to correct ET_o values from simulations done with solar radiation data that was estimated according to FAO 56 (Allen et al. 1998). ET_o results simulated with estimated solar radiation data (from 1983) was compared to ET_o values estimated with measured solar radiation data (from 2004) in a regression analysis to obtain ET_o correction factors for each month separately. Two sets of statistics, which included minimum, maximum, median, 25th and 75th percentiles of ET_o values, for simulations with estimated and measured solar radiation were calculated for each month. The statistics of ET_o with estimated solar radiation were plotted against the statistics of ET_o with measured solar radiation on a regression line, which had a linear distribution for all months. Regression equations were obtained for each month (**Table 4-4**) and applied as correction factors to monthly ET_o values simulated with estimated solar radiation data. The corrected monthly ET_o values simulated with estimated solar radiation data had a long-term average similar to average ET_o values simulated with measured solar radiation data (**Figure 4-5**). This approach was not used here, because the complete set of weather data from the Deodar weather station from 2004 onwards was sufficient for the purposes of this study. However, the approach is recommended for situations where complete weather data is not available.

Table 4-4: Regression equations to obtain corrected monthly ET_o values for datasets without solar radiation data

Month	Equation to obtain corrected monthly ET_o values (y) from ET_o values (x) calculated without solar radiation data
January	y = 0.8x + 40.1
February	y = 1.1x + 19.9
March	y = 0.8x + 35.0
April	y = 0.5x + 55.9
May	y = 0.6x + 29.6
June	y = 1.0x – 28.0
July	y = 1.1x - 35.2
August	y = 1.8x - 133.0
September	y = 0.6x + 62.2
October	y = 0.6x + 67.9
November	y = 0.7x + 62.7
December	y = 0.3x + 102.8

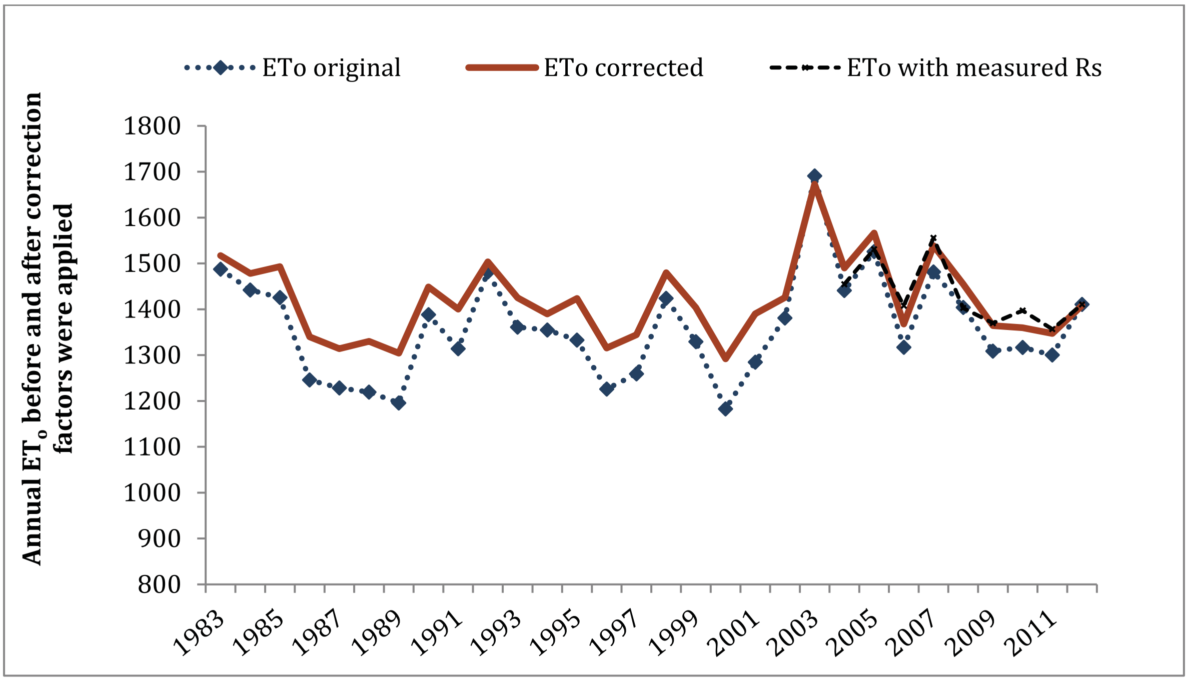

Figure 4-5: Original ET_o results from SWB versus corrected ET_o results

4.3.3 Using different functional units for water footprint assessments

The WF results expressed in terms of dry matter are illustrated in **Figure 4-7**. Water footprints of maize and wheat are much higher than the vegetable crops if expressed in terms of fresh mass, however, if WFs are expressed in terms of dry matter, the WFs of maize and wheat are much more similar to the vegetable crops. This is because the water content of maize and wheat is much lower (10% and 13% respectively) compared to the vegetable crops (between 87% and 96%). The WF of lettuce expressed in terms of dry matter yield is relatively much higher than when expressed in terms of fresh mass. This is because of the high physical water content of lettuce (95%).

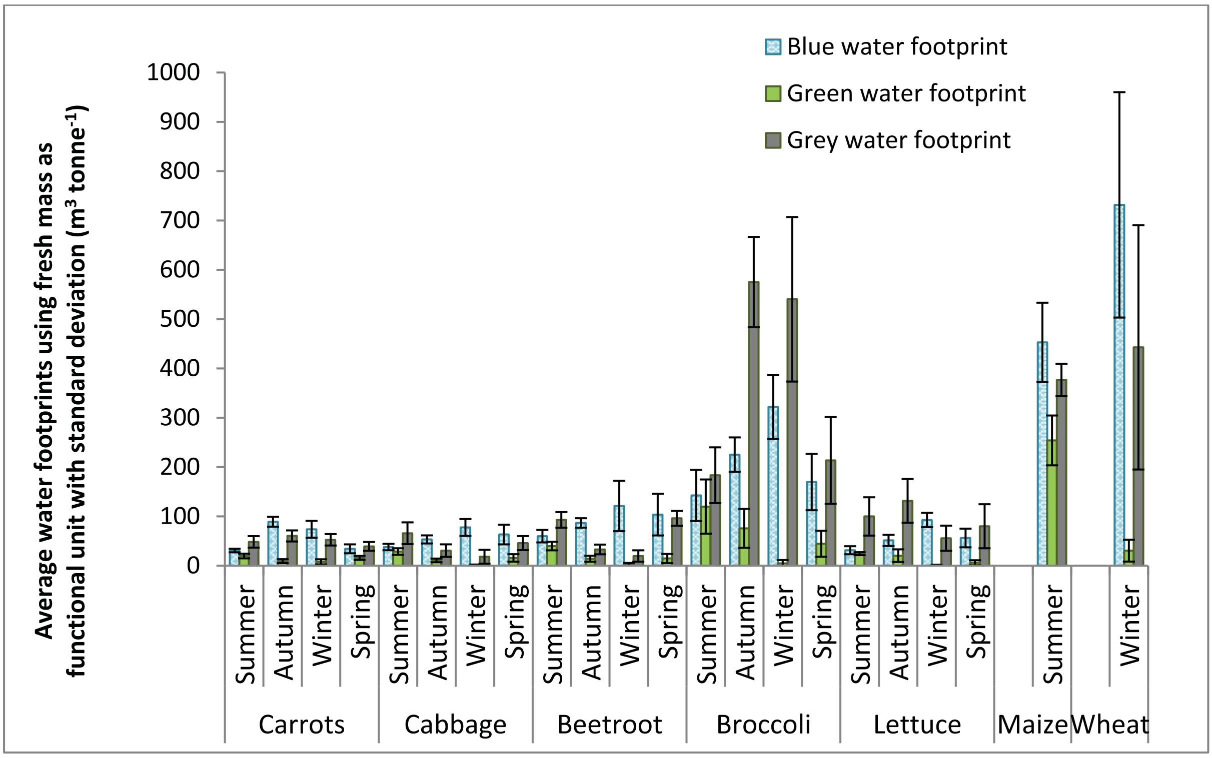

Figure 4-6: Average of 10 year's blue and green water footprints (2004–2013) with standard deviations (shown as error bars) of vegetable and grain crops in the different growing seasons on the Steenkoppies Aquifer using fresh mass as a functional unit

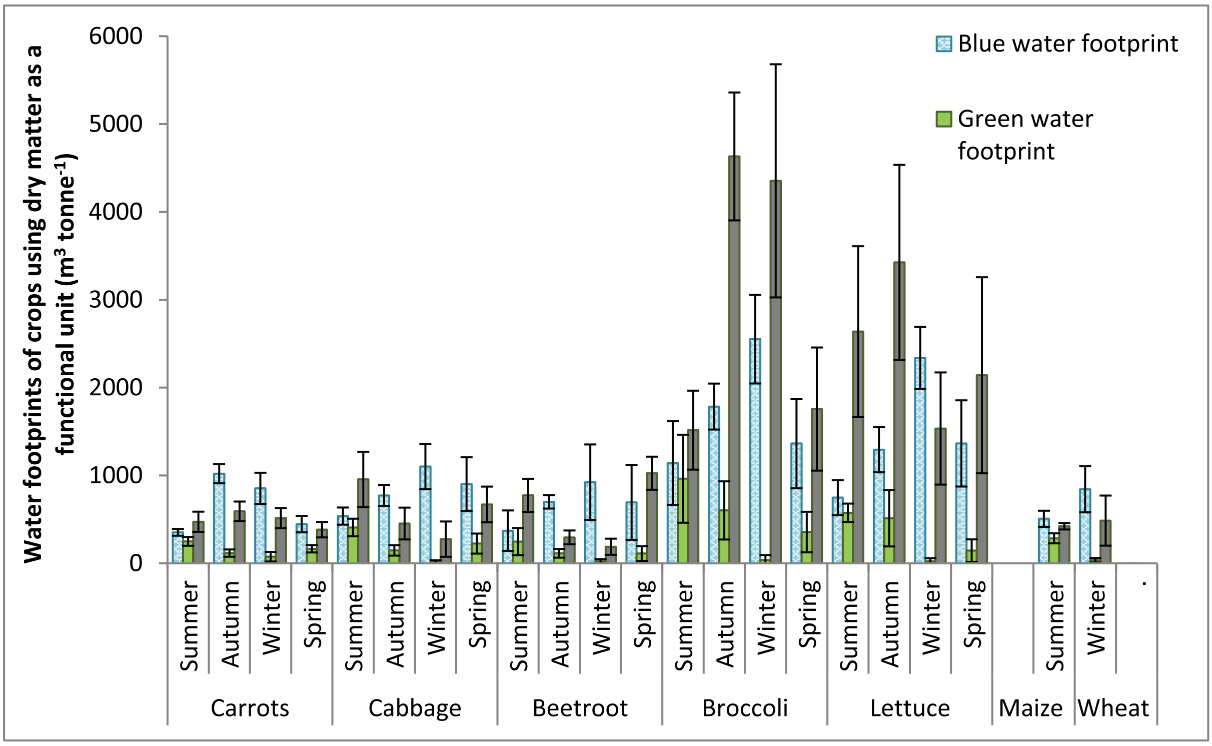

Figure 4-7: Average of 10 year's blue and green water footprints (2004–2013) with standard deviations (shown as error bars) of vegetable and grain crops in the different growing seasons on the Steenkoppies Aquifer using dry matter as a functional unit

The WF of summer crops using selected nutrients required to supply a man aged 31 - 50 with their RDA as a functional unit is illustrated in **Figure 4-8**. The high WF of broccoli, as expressed in terms of nutrient yield, now becomes comparable to the WFs of similar crops as a result of its high nutritional value. The WF of the nutrient with the highest WF can indicate the final WF of the crop, because the other nutrients are also produced. It is also important that local measurement of crop nutrient composition be used in future research, because the micro-nutrient uptake of crops is influenced by soil characteristics and fertilization. If WFs are expressed in terms of prices used to calculate the CPI (**Figure 4-9**), broccoli has a much more comparable WF, which is even lower than the WF of beetroot for all seasons.

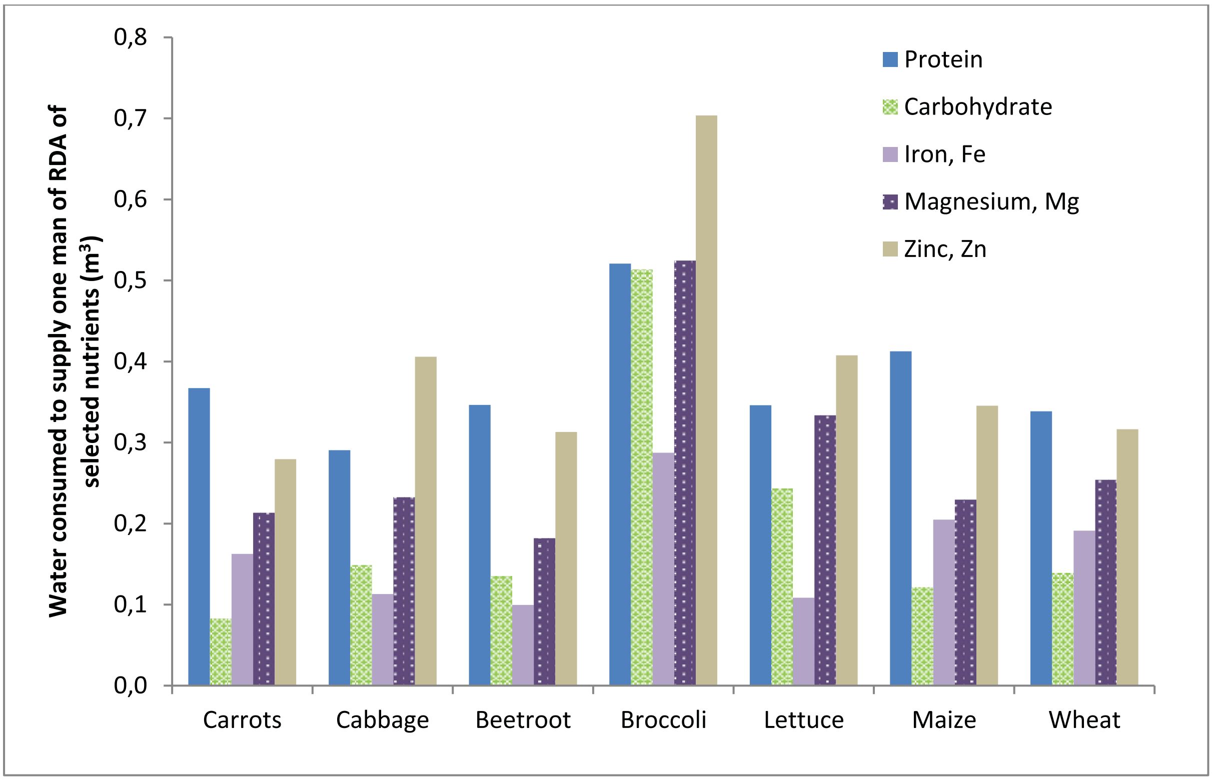

Figure 4-8: Blue plus green water footprint to supply a man (aged 31 to 50) with their Recommended Dietary Allowance (RDA) (Mahan and Escott-Stump 2004) in terms of selected nutrients.

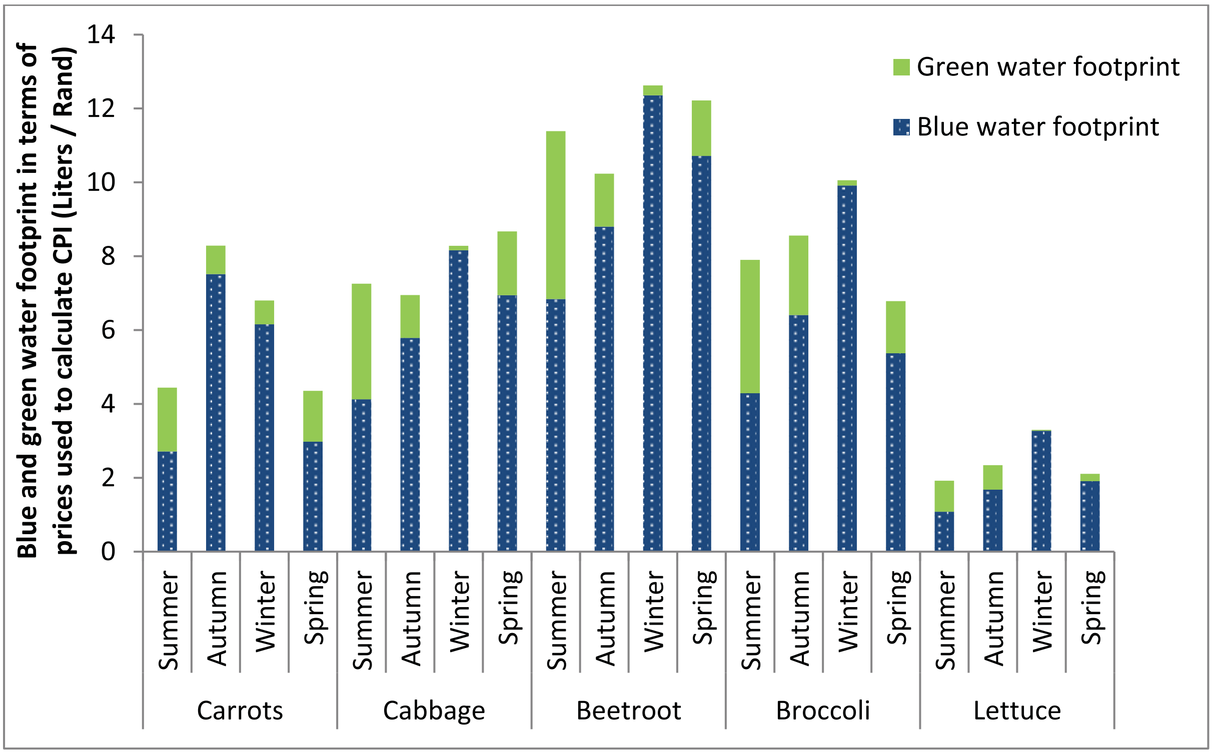

Figure 4-9: Blue and green water footprint of crops in terms of prices used to calculate the Consumer Price Index (CPI)

4.3.4 Complexities in grey water footprints

Grey WFs of carrots, cabbage and beetroot given by (Mekonnen and Hoekstra 2011) were similar to local grey WFs, especially for carrots in autumn, and cabbage and beetroot in winter (**Table 4-3**). Local grey WFs for lettuce in spring also compared well with the grey WFs given by Mekonnen and Hoekstra (2011). Grey WFs of broccoli in all seasons, maize and wheat were much higher than the grey WFs given by Mekonnen and Hoekstra (2011). High grey WFs of broccoli are also due to the low harvestable index of the plant.

Analyses of the groundwater in the Steenkoppies Aquifer indicated that nitrate concentrations are within the limits of domestic water standards, with no sign of the impact of intensive crop production. This phenomenon is contradictory to the grey WFs of the crops, but could be explained to some extent by high rainfall water influx through the aquifer which can dilute the N reaching the aquifer. However, due to the intensive agriculture on the aquifer a significant water quality impact is expected at some stage. The annual cropped area on the Steenkoppies Aquifer is approximately 5300 ha. It is reasonable to expect that 50 kg ha^{-1} of applied N (265 000 kg) leaches to the aquifer. The volume of rainfall that falls on the Steenkoppies Aquifer and the catchment above it is approximately 150 Mm^3 per year. If 10% of rainfall recharges the aquifer (Wiegmans et al. 2013), this will dilute the N that reaches the aquifer to 18 mg N $liter^{-1}$, a high concentration that should have altered the water quality of the aquifer by now. This emphasizes the uncertainties regarding the fate of N after application to the field and requires further study.

4.3.5 Water footprint of potatoes grown in Pretoria

Blue + green water footprints for potatoes grown in Pretoria ranged from 62-599 m^3 $tonne^{-1}$ (**Table 4-5** and **Table 4-6**). Water footprints were generally lower for the treatments receiving slightly below 'optimal' irrigation for which any depleted soil water was replaced (W2, W3). There were also clear genotype differences. For example, during the spring 1994 growing season, the WF of '84-304-4' was nearly 50% lower than that of '81-163-40'. Water footprints were generally lower in autumn than in spring, most likely due to lower evaporation and higher transpiration water use efficiency in autumn (Steyn et al. 1998). The lowest WFs were generally observed in autumn for the intermediate water regimes. The average WF for the intermediate water regimes for autumn was 72 m^3 $tonne^{-1}$, while for spring it was 97 m^3 $tonne^{-1}$.

Mekonnen and Hoekstra (2011) estimated the global average water footprint of potatoes at 224 m^3 $tonne^{-1}$ (33 blue WF, 191 green WF). The authors attribute potato production to 1% of the total water footprint of crop production. For the Pampean region in Argentina, Rodriguez et al. (2015) estimated a potato water footprint of 182 m^3 $tonne^{-1}$ (78 blue WF, 104 green WF).

Table 4-5: Water use efficiency and blue + green water footprints for potatoes planted in spring and subjected to different water regimes (Steyn et al., 1998)

			WUE (kg ha^{-1} mm^{-1})					WF blue + green (m^3 tonne^{-1})				
Season	Rain shelter #	Genotype	W1	W2	W3	W4	W5	W1	W2	W3	W4	W5
Spring 1992	1	Vanderplank	107.7	108.9	102.3	78	47.9	93	92	98	128	209
	1	Up-to-date	89.4	96.7	97.7	89.1	40.8	112	103	102	112	245
	1	Late Harvest	100	102.3	104.4	55	17.1	100	98	96	182	585
	2	Vanderplank	73.3	80	88.2	91.7	59	136	125	113	109	169
	2	Up-to-date	79.5	81.8	81.2	76.9	41.1	126	122	123	130	243
	2	Late Harvest	91.4	99.7	95.3	73.1	32.9	109	100	105	137	304
Spring 1993	1	Late Harvest	86.2	85.4	104.2	91.3	57	116	117	96	110	175
	1	Hoevelder	101.4	110.2	109.8	96.4	49.7	99	91	91	104	201
	1	Mnandi	110.6	132.5	135.4	122.1	74.1	90	75	74	82	135
	2	Up-to-date	116.8	140.6	140	63.4	45.4	86	71	71	158	220
	2	82-252-5	93.9	99	94.6	88.5	49.5	106	101	106	113	202
	2	83-252-1	98.1	108.3	98.1	81.4	52.7	102	92	102	123	190
Spring 1994	1	Late Harvest	64.4	86	102.4	99.7	59.7	155	116	98	100	168
	1	81-163-40	73.8	82.7	106.8	86.2	16.7	136	121	94	116	599
	1	83-363-67	81.4	102	109.2	99.2	49.2	123	98	92	101	203
	2	Up-to-date	99.4	103.8	100.2	82.4	41.3	101	96	100	121	242
	2	Mondial	90.5	100.4	97.6	70.6	37.6	110	100	102	142	266
	2	84-304-4	136.3	160.9	162.4	120.1	67.3	73	62	62	83	149

Table 4-6 Water use efficiency and blue + green water footprints for potatoes planted in autumn and subjected to different water regimes (Steyn et al., 1998)

			WUE (kg ha^{-1} mm^{-1})					WF blue + green (m^{3} tonne^{-1})				
Season	Rain shelter #	Genotpye	W1	W2	W3	W4	W5	W1	W2	W3	W4	W5
Autumn 1992	1&2	Vanderplank	118.6	206.8	156.3	117.1	96.6	84	48	64	85	104
	1&2	Buff'elspoort	140.4	161.8	167.4	123.9	95.8	71	62	60	81	104
	1&2	Up-to-date	135	171	193.2	160.4	145.1	74	58	52	62	69
	1&2	BPI	138.7	179.8	171.1	163.2	131.9	72	56	58	61	76
	1&2	Kimberley Choice	107.4	126.3	148	112	83.3	93	79	68	89	120
	1&2	Late Harvest	115.9	139.5	128.4	131.8	111.5	86	72	78	76	90
Autumn 1993	1	Vanderplank	150.3	159.5	117.1	105.3	37.8	67	63	85	95	265
	1	Up-to-date	198.2	206.7	221.6	212.1	156.1	50	48	45	47	64
	1	Late Harvest	206.6	206	217.8	218.3	163.3	48	49	46	46	61
	2	Vanderplank	62.2	69	92.5	102.7	93.2	161	145	108	97	107
	2	Up-to-date	105.9	112.9	127.2	122.4	115.1	94	89	79	82	87
	2	Late Harvest	121.1	133.4	136.7	146.5	134.7	83	75	73	68	74
Autumn 1994	1	Late Harvest	105.2	121.9	146.1	125.7	114.9	95	82	68	80	87
	1	Hoevelder	104.2	119.2	127.1	120.9	110.3	96	84	79	83	91
	1	Mnandi	115.8	128.2	149.6	134.6	113.1	86	78	67	74	88
	2	Up-to-date	92.9	110.6	151.8	160.2	144.3	108	90	66	62	69
	2	82-252-5	97.3	114.6	168.9	159	137.3	103	87	59	63	73
	2	83-252-1	87.9	103.1	153.1	159	129.3	114	97	65	63	77

Autumn 1995	1	Late Harvest	114.7	134.1	129.5	125.4	120.7	87	75	77	80	83
	1	81-163-40	180.4	154.5	160.1	148.7	144.3	55	65	62	67	69
	1	83-363-67	146.1	128.5	125	124.7	93.4	68	78	80	80	107
	2	Up-to-date	104.6	108.3	108.8	106.6	127.6	96	92	92	94	78
	2	Mondial	161.9	168.3	158.4	136.5	149	62	59	63	73	67
	2	84-304-4	115.5	126.5	139.5	127.5	151.7	87	79	72	78	66

4.3.6 Water footprints of tomatoes grown in Marble Hall, Pretoria, Vredendal, Platskraal, Messina

For the trials considered, WFs for tomatoes grown in South Africa ranged from 38-123 m^3 $tonne^{-1}$, with the lowest WF being for the crop grown in Pretoria, and the highest WF for the crop grown in Messina. Higher levels of water stressed generally led to higher WFs (**Table 4-7**).

The global average water footprint for tomatoes was estimated by Mekonnen and Hoekstra (2011) at 171 m^3 $tonne^{-1}$ (108 green, 63 blue). Chapagain and Orr (2009) estimated the average tomato water footprint for Spain at 73.8 m^3 $tonne^{-1}$ (60.5 blue, 13.6 green). For Italy, the water footprint of industrial tomatoes was estimated to be 95 m^3 $tonne^{-1}$ (60 blue, 35 green) (Aldaya and Hoekstra 2010).

Table 4-7: Water use efficiency and blue + green water footprints for tomatoes

Trial	Treatment	CumETD	Fresh yield	WUE	WF
		(mm)	(tonnes ha^{-1})	(kg m^3)	(m^3 $tonne^{-1}$)
Marble Hall 1992/93	-	621	81.1	13.1	77
Pretoria 1992/93	T20R01	398	66	16.6	60
	T20R20	466	71	15.2	66
	T20R100	536	73	13.6	73
	T50R100	437	64	14.6	68
	T75R100	399	53	13.3	75
Pretoria 1994/95	WetWet	242	64.3	26.6	38
	WetStress	193	38.6	20	50
	StressWet	156	23.4	15	67
	StressStress	122	17	13.8	72
Vredendal 1994/95	-	502	109	21.7	46
Platskraal 1994/95	-	444	98.8	22.3	45
Messina 1995	-	992	80.6	8.1	123

4.4 Discussion

Although WFs can provide very useful information in an agricultural context, there are still challenges involved in calculating WFs, interpreting the information and understanding the limitations of the information that need to be addressed. The aim of this study was to better understand the complexities involved in calculating WFs for vegetable crops.

A number of studies in the literature have reported different WFs due to spatial and annual variation in climatic conditions (Mekonnen and Hoekstra 2011, Multsch et al. 2016, Sun et al. 2013). Inter-annual variation in blue, green and grey WFs of maize production in Beijing was found to be related to changing climate and agricultural management practices (Sun et al. 2013). Blue WFs increased and green WFs decreased as a result of both drier climates and intensifying agricultural inputs. Grey WFs were correlated to an increase in chemical inputs during more recent years (Sun et al. 2013). Multsch et al. (2016) reported increased green WFs in high rainfall parts of the High Plains Aquifer (HPA) and increased blue WFs in parts of the HPA with low rainfall and higher temperatures. By calculating average WFs for crops from 1996 to 2005, Mekonnen and Hoekstra (2011), recognised the inter-annual variation in WFs of crops. Our results show that it is also important to interpret WFs with specific reference to the growing season, especially for short season crops with a range of planting date options. High inter-annual variation for this case study was illustrated by the high standard deviations of some crops during certain growing seasons, for example broccoli in summer with an average blue plus green WF of 262 m^3 $tonne^{-1}$ and a standard deviation of 105 m^3 $tonne^{-1}$.

It should be widely recognised that WF estimates can be significantly influenced by the quality of data used to parameterise and run crop models. We observed that daily ET_o estimates can differ significantly when either measured or estimated solar radiation data is used, so recommend that consistent weather data be used from parameterisation to model application. This was observed particularly for solar radiation during summer and spring for our study region. Using estimated solar radiation data for crops planted in autumn and winter, however, resulted in smaller differences in ET_o and yield estimates. Therefore the consistency in weather data that is used could potentially have a significant impact on WF results. Zhuo et al. (2014) obtained similar results with a sensitivity analysis of WFs of maize, soybeans, rice and wheat to errors in input variables. They found that WFs of these crops are particularly sensitive to variations in ET_o, which resulted in an increase in crop water use and a decrease in yield estimates. The comparison between WFs calculated using more generic data from Mekonnen and Hoekstra (2011) as given in **Table 4-3** not only highlights the importance of reporting WFs for a specific season, it also highlights the need to use local data, for example to parameterise a specific crop. All WFs reported by Mekonnen and Hoekstra (2011) had a high green and low blue WF, while locally produced WFs had a high blue and low green WF. This is due to the study area being located in the dry summer rainfall high central plateau of South Africa. The study area is considered to represent other areas in South Africa with similar climatic conditions.

The functional unit used to calculate WFs has a significant impact on WF metrics. Grains with low moisture content, such as maize and wheat, will have a disproportionately high WF compared to vegetables when using fresh mass yields. Depending on the objective of the study, different functional units for various crops can be used to reveal which crops will be more efficient, for example in producing important nutrients or generating most economic gain per volume of water. Assessing WFs in terms of other functional units such job creation is recommended for future research, because such alternative assessments can provide important information on how to allocate limited water supplies to achieve various objectives.

The high WF of broccoli due to the low relative yield of the harvestable portion that is produced by the crop presents a complexity and potential drawback in the application of the WF information, because the rest of the plant is often used for composting or animal feed. It can be argued that the beneficial use of the rest of the plant increases the total yield, and should be reflected in the WF. This could also be the case for many other crops. Compost will be incorporated into and increase the yield of the next crop and benefit soil health and the long-term sustainability of the system. Therefore, composting the non-edible part of the previous crop will potentially reduce the WF of the next crop. It can also be argued from a different point of view if one uses compost to reduce the need for fertilisers. Production of fertilisers will have a certain WF and the compost will reduce the WF of the crop by reducing the need for fertiliser and the water required to produce the fertiliser. The blue, green and grey WF of fertilisers has not yet been addressed. Composting can also reduce the grey water footprint, because the use of organic N will potentially reduce the need for inorganic N and create N use efficiency.

Initial soil water content at planting will theoretically impact the blue versus green WF outcomes, because it will determine the amount of irrigation required. This impact, however, was assumed to be relatively small, because it was assumed that most farmers irrigate the land to field capacity in order to prepare for planting and data modelling also assumed a relatively wet soil profile. It was also assumed that the soil water content was the same before planting and after harvesting.

The grey WF is a way of reporting impacts on water quality, which is a very important aspect of water resource management. The concept has, however, often been criticized for being too simplistic (Perry 2014, Ridoutt and Pfister 2013, Wichelns 2011). In a crop production context, water pollution is an especially complex issue. Phosphates, salts, sediments and pesticides are also pollutants associated with agriculture, and need to be taken into account when addressing water quality. Therefore, it is not completely effective to assess the water quality impacts based on one pollutant. Similar to the WFs based on different nutrients, the grey water footprint can be calculated for various pollutants and the highest WF can be used as the total. There are uncertainties in the determination of the N load leaching into the aquifer, because the fate of N is not well understood. The intensive use of fertilisers and the vulnerability of the aquifer to pollutants, as indicated by Witthueser et al. (2009), suggested that some impact could be expected on the water quality due to cultivation of crops. However, water quality analyses of the underlying groundwater indicated very good quality water, despite the intensive farming that has occurred over the past few decades. It is clear that the process of water pollution and pollutants leaching into the groundwater in the Steenkoppies Aquifer is still difficult to quantify. Nitrates can be removed from the soil through denitrification, which is dependent on a number of factors. Being a strong oxidising agent, nitrates are often denitrified by dissolved organic carbon (DOC) or iron (Katz et al. 2014, Song et al. 2016, Xu et al. 2015). Redox conditions and depth of the groundwater, which in turns affects the availability of DOC, also play a role in denitrification (Katz et al. 2014, Starr and Gillham 1993). A simplified method such as the grey WF does not provide the necessary information to improve water quality management of an aquifer. The use of grey WFs also becomes complex in a crop production context in cases where compost is used. Future research needs to address the potential benefits of composting crop residues in terms of the grey WF.

4.5 Conclusions

If water becomes scarce, farmers and water resource managers will have to ask the question of what they want to achieve with the available water. WF information can inform farmers to plant less water intensive crops or water resource managers to restrict certain crops during dry years or months. However, the method becomes complicated in a crop production context, because of inter-seasonal and inter-annual variations in WFs, the importance of local crop parameters and the requirement for comprehensive weather data. Crops, such as broccoli, with a low harvestable index will have a high WF, not representing how the residues of the plant are potentially used for other beneficial uses such as composting and animal feed. Water footprints that are calculated using fresh mass as a functional unit results in high WFs of crops with low water contents, such as maize and wheat, as compared to crops with high water contents, such as the vegetable crops. If WFs are calculated using dry matter, the high WFs of maize and wheat become more similar to the WFs of the vegetables. Using alternative functional units, such as nutritional content, potentially provides more meaningful information, which allows managers to make more informed decisions about water management and allocation. The current grey WF did not explain why the N concentration of the groundwater is within domestic standards, despite decades of agricultural activities on the Steenkoppies Aquifer. This could be due to an overestimation of the N load that reaches the aquifer or a big lag in the system.

In this chapter the WFs of selected vegetable crops have been calculated for the different growing seasons. In the next chapter these calculated WFs will be used to determine catchment scale WFs for the Steenkoppies Aquifer, to determine the sustainability of the catchment WFs of agriculture and to better understand how WF information can improve water resource management.

5 WATER FOOTPRINTS OF SELECTED FRUIT TREE CROPS

by

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5.1 Introduction

Past studies (Midgley and Lötze, 2008) have shown that a water risk hot spot lies in the Western Cape Province of South Africa. Citrus and deciduous fruit industries are particularly at risk as they utilize large volumes of water per unit weight of fruit produced (Dzikiti and Schachtschneider 2015). The Irrigation Strategy for South Africa has set a target to increase the area under irrigation in South Africa by more than 50% (DAFF 2010). However, with only limited new agricultural water supply developments planned, an increase in the area under irrigation will consequently necessitate significant improvements in the water productivity of currently irrigated land to enable this expansion.

As a result of generally low and erratic rainfall, the seasonality of that rainfall, and the high value of fruit and vegetable crops, it is estimated that 90% of fruit and vegetables produced in South Africa are grown under irrigation (Nieuwoudt et al. 2004). Under the compulsory registration, authorisation and licensing of water-use, which is being driven by the National Water Resource Strategy (Department of Water Affairs 2013), implementation of measures to improve water productivity (WP) is at the core of the strategy. However, implementation of WP improvements in this sector firstly requires accurate data on the water requirements of crops. In addition, tools are needed to better manage the actual water use requirements of these crops so that they use less water without compromising fruit quality, yield and profits (Dzikiti et al. 2011, Fernández and Cuevas 2010). WF accounting (Hoekstra 2003, Hoekstra et al. 2011) is a means of conducting comparative water use assessments across various land-uses at wider scales. It indicates the water-use summed over the various steps of the entire production chain. When linked to yield, it has potential to identify existing levels of water productivity and where those may potentially be improved.

As an international water resource management concept the WF approach has come under some sharp criticism (Perry 2014, Wichelns 2011). However, when validated with actual field observations it remains a potentially useful tool to raise consumer awareness, identify relative differences in product water requirements, identify hotspots, assist in formulating policy for sustainable local water management decision making, and ultimately help to improve efficiencies in water use across the entire production process (Aldaya et al. 2010). Further advantages of applying the WF concept include that it facilitates in distinguishing between the relative contributions of irrigation and rain water to the crop production process, as well as providing a framework for an assessment of impacts on water quality. On the other hand a WF assessment is only as good as the data on which it is based. The primary objectives of this component of the project were therefore to use data from state-of-the-art measurement and modelling techniques to quantify the actual volumes of blue, green and grey water associated with apple and citrus orchards under current land and water management practices, and use yield data to calculate the resultant Water Footprints (WFs) and Water Productivity (WP) values of these crops.

5.2 Materials and methods

5.2.1 Study Sites

For the purposes of WF determination, apple and citrus orchard water use data was obtained from a previous project (Gush and Taylor 2014). Details of the sites, methods and results are available from that report, but for ease of reference are repeated here in brief.

5.2.1.1 Apple orchard

Apple orchard water use data was from a 12-year old apple orchard (*Malus domestica*) within a commercial farm ("Nooitgedacht") located near the town of Ceres in the Western Cape Province of South Africa (S33° 12' 03.57"; E19° 20' 15.06"; 1089 masl). The orchard was 134 m by 172 m (2.3 ha) in extent (**Figure 5-1**). It was planted to 'Cripps' Pink' apples on M793 rootstock, with every 8^{th} tree in each row being a 'Hillary' crab-apple pollinator. Row orientation was north – south and the trees were spaced at 1.25 m by 4 m, giving a planting density of 2000 trees per ha, with a short grass cover between rows. Average tree height was 5.1 m and average trunk diameter at 0.3 m from the base of the tree was 0.1 m. Irrigation water and fertiliser ('fertigation') were applied by means of short-range micro-sprinklers, with scheduling based on daily soil moisture and weather data. The discharge rate of each micro-sprinkler was 30 ℓ h^{-1}, equivalent to 5 mm per hour for emitters which were positioned every 1.5 m within the tree rows. Soils were gravel, with a high sand and stone content, well drained and with an effective rooting depth of approximately 0.6 m. Annual orchard yields were 54 tonnes ha^{-1} in the 2008/2009 season and 69 tonnes ha^{-1} in the 2009/2010 season, with an average of 61.5 tonnes ha^{-1} over the two seasons (Gush et al. 2014).

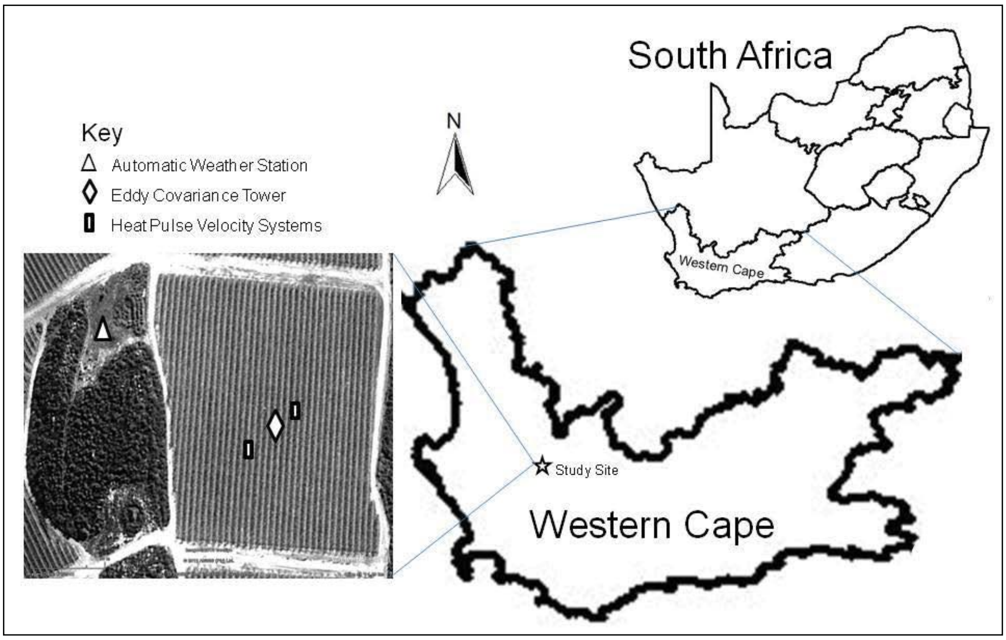

Figure 5-1: Location of the apple study orchard. The Google Earth extract (extreme left) provides the layout of the study site (from Gush et al. 2014).

5.2.1.2 Citrus orchard

Citrus orchard water use data was from Patrysberg Farm in the Western Cape Province (32° 27' 15.43'' S and 18° 58' 3.58'' E, 149 m.a.s.l., orchard area 3.9 ha) near Citrusdal, in the winter rainfall region of South Africa (**Figure 5-2**). Measurements were conducted from August 2010 to August 2012 on 'Rustenburg' Navel orange trees. The area receives an average annual rainfall of 200 mm and has average minimum and maximum temperatures of 10 °C and 24 °C. The trees were grafted on 'Troyer' citrange rootstocks and were planted in 1996. The row orientation was 79° ENE. Tree spacing was 6 x 2.5 m (667 plants ha^{-1}), with trees being pruned shortly after harvest to a height of 3.2 m, with selective limb removal, according to the industry standards of the production area. Average tree height was 3.3 m and average effective orchard canopy cover was 0.88. The area under the trees was clean cultivated, with an active cover in between rows in the winter. The orchard was drip irrigated, with two drip lines per tree row and pressure compensating emitters with a discharge of 1.8 ℓ h^{-1} spaced 0.8 m apart. Irrigation was typically scheduled 2-3 times per day for 2 h. The soil texture was a loam with an average of 5-10 % clay in the top metre (Taylor et al. 2014).

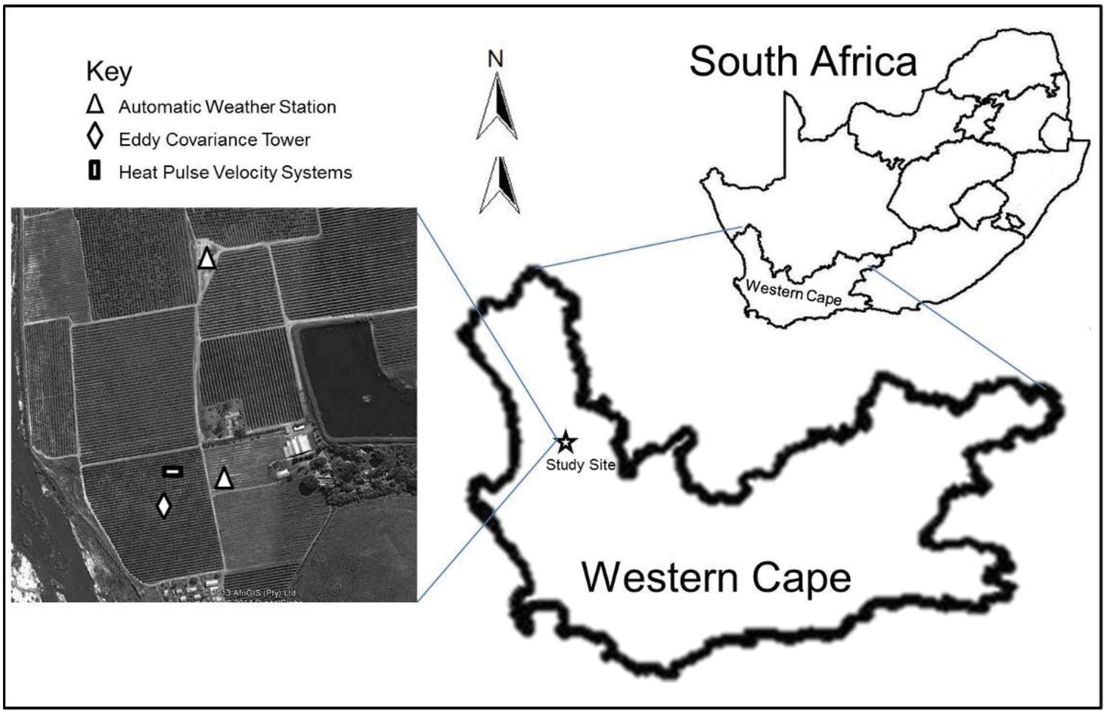

Figure 5-2: Location of the 'Rustenburg' Navel orange orchard (from Taylor et al. 2014).

The study sites fall within the Olifants/Doorn Water Management Area (WMA) in the winter rainfall region of the Western Cape Province.

5.2.2 Field Measurements

5.2.2.1 Meteorological measurements

Automatic weather stations (AWS) were installed in open areas close to both study orchards. According to Gush and Taylor (2014) these were equipped with CR1000 data loggers (Campbell Scientific Inc., Logan, UT, USA), and measured rainfall (TE525-L, Texas Electronics, Dallas, Texas, USA), solar radiation (LI-200SA, LI-COR Inc., Lincoln, NE, USA), temperature and humidity (HMP50, Vaisala, Helsinki, Finland), wind speed and wind direction (Model 03001, RM Young, Traverse city, Michigan, USA). Sensors were mounted 2 m above the ground, and variables were scanned at 10 s intervals and stored in the loggers at hourly intervals over the entire monitoring period. Hourly values were further processed into daily averages or totals, and the data were used to calculate daily reference evaporation (ET_o) for the sites according to the FAO-56 approach (Allen et al. 1998).

5.2.2.2 Sap flow / transpiration

The heat ratio method (HRM) (Burgess et al. 2001) of the heat pulse velocity (HPV) technique was used to measure sap flow in selected trees within the apple and citrus orchards. Six apple trees (4 'Cripps Pink' and 2 'Hillary' crab-apple pollinators) and five 'Rustenburg' Navel trees were instrumented with the HRM / HPV technique. Further details of the theory and application of the HPV equipment utilised in this study are provided by Taylor and Gush (2014). Measurements of tree attributes influencing transpiration, namely stem diameters, tree heights, canopy dimensions, and sapwood characteristics (xylem depth, density and moisture content) were recorded, while Leaf area index (LAI) measurements were taken periodically with a LI-2000 Plant Canopy Analyser (LI-COR Inc., Lincoln, NE, USA).

Measured heat-pulse velocities were corrected for sapwood wounding caused by drilling, using wound correction coefficients described by Burgess et al. (2001). The corrected heat-pulse velocities were then converted to sap-flux densities according to the method described by Marshall (1958). Finally, the sap-flux densities were converted to whole-tree total sap flow volumes by calculating the sum of the products of sap-flux density and cross-sectional area for individual tree stem annuli (ring-shaped areas determined by below-bark individual probe insertion depths and sap-wood depth). Hourly sap-flow volumes were aggregated into daily, monthly and annual totals for each tree, and were assumed to equate to transpiration (T).

5.2.2.3 Total evaporation

An extended open path eddy covariance (OPEC) system was used to measure total evaporation (ET) of the apple and citrus orchards during short-term seasonal measurement campaigns. In the apple orchard measurements took place on four separate occasions, namely autumn (13 – 16 May 2008), summer (3 – 17 December 2008), spring (9 – 12 October 2009) and winter (28 July – 4 August 2010). In the citrus orchard measurements were conducted from 25 April to 2 May 2011, which represented typical autumn / early winter conditions, and from 14 March to 3 April 2012, representing late summer conditions. On each occasion the instruments were positioned at appropriate heights on a lattice mast, installed in the centre of the respective orchards, to enable adequate “fetch”. Details on the sensors comprising the OPEC system deployed for this purpose are provided in Gush and Taylor (2014).

5.2.2.4 Irrigation and soil water content

In the apple orchard, irrigation was monitored by means of a water pressure sensor (IRROMETER Company Inc., Riverside, CA, USA), fixed on the irrigation line and connected to a CR10X data logger (Campbell Scientific Inc., Logan, Utah, USA), which was programmed to record the duration (in minutes) of individual irrigation events. Corresponding irrigation volumes were subsequently calculated based on the delivery rate of the micro-sprinklers. CS616 soil water content probes (Campbell Scientific Inc., Logan, UT, USA) were also installed within the tree rows to monitor soil water content fluctuations associated with irrigation and rainfall events (Gush et al. 2014).

In the citrus orchard two tipping bucket rain gauges were installed underneath two drippers on separate dripper lines to record irrigation volumes using a CR10X logger (Taylor et al. 2014).

5.2.3 Evaporation modelling

Observed orchard ET data captured during seasonal measurement campaigns were extrapolated to the full monitoring period through modelling. Following this approach, ET was calculated as the algebraic sum of separate tree transpiration and soil evaporation sub-models. For the apple orchard a two-layer Shuttleworth-Wallace type model (Shuttleworth and Wallace 1985) as modified for cherry orchards by Li et al. (2010) was applied. For the citrus orchard actual ET was calculated as the sum of measured transpiration and modelled soil evaporation using the FAO-56 model. Further details are available in Gush et al. (2014), Taylor et al. (2014) and Taylor et al. (2015).

The models were run on an hourly time step, and at the completion of the modelling exercise monthly basal/transpiration (K_{cb}) and full crop coefficients (K_c) were derived for the orchards using the FAO-56 approach (Allen et al., 1998), by dividing daily transpiration and ET totals with corresponding daily reference evaporation (ET_o) values, and calculating monthly averages for the orchards.

5.2.4 Water footprint determination

The total WF associated with the fruit production process (i.e. m³ water used per tonne of fruit produced) was calculated according to the method of Hoekstra et al. (2011). This was determined for the study orchards by accounting for all processes using water over a calendar year, which incorporated the full growing season until produce was ready for distribution at the farm gate. The field measurements provided accurate quantification of the different components of crop water use (CWU), particularly CWU_{blue} (m^3 ha^{-1}), which was calculated as orchard ET associated with irrigation applications over the growing season. This constituted the primary water use component; however, information on all other CWU_{blue} uses in the fruit production chain was obtained through additional field measurements and interviews with managers on the farms. These comprised quantities of water used for spraying operations in the orchards (micro-nutrients, fungicides, pesticides, herbicides, chemical fruit thinning agents), packhouse operations (fruit washing, cleaning of equipment), orchard worker water use (5 ℓ person^{-1} day^{-1} for drinking and hand-washing) and evaporative water losses from irrigation storage dams.

CWU_{green} (m^3 ha^{-1}) was determined by subtracting the CWU_{blue} from the total annual ET of the orchards determined from measurements and modelling. This effectively accounted for the fraction of orchard ET associated with the use of rainfall. WF_{blue} and WF_{green} were then calculated by dividing CWU_{blue} and CWU_{green}, respectively by the fruit yield of the orchards (tonnes ha^{-1}).

The Water Footprint Network defines the grey water footprint as "the volume of freshwater that is required to assimilate the load of pollutants, and is calculated as the volume of water that is required to maintain the water quality according to agreed water quality standards" (Hoekstra et al. 2011). Information was requested from each farmer or farm manager pertaining to the pesticides, insecticides and fertilising agents used on each farm (e.g., frequency of spraying / fertilising, volume concentration, active ingredients, etc). Some challenges arising from this component of the study include the fact that certain pollutants such as pesticides do not break down for very long and should not be present in water at all, not even in small concentrations. The Grey water footprint calculations are particularly sensitive to this input, and concentrations have a disproportionately large influence on the final result. Consequently, only nitrogen applications through the processes of fertigation were considered in this assessment. WF_{grey} was calculated using application rates of nitrogen (N) determined from on-farm data and applying that to the Hoekstra et al. (2011) equation (**Equation 5-1**):

$$WF_{grey} = \frac{(\alpha \times AR) \,/\, (C_{max} - C_{nat})}{Y}$$

Equation 5-1

where α is the leaching fraction (fraction of applied chemical reaching freshwater bodies), AR is the application rate (kg ha^{-1}), c_{max} is the maximum acceptable concentration of the applied chemical in water according to guidelines or standards (mg ℓ$^{-1}$), c_{nat} is the natural concentration of the applied chemical in water (mg ℓ$^{-1}$), and Y is the average crop yield (tonnes ha^{-1}). According to Franke and Mathews (2013) and Franke et al. (2013), the maximum concentration (c_{max}) for N is 13 mg. ℓ$^{-1}$, with an ambient N concentration (c_{nat}) of 4.33 mg. ℓ^{-1}. A leaching fraction of 10% was assumed for N, which was applied at 250 kg ha^{-1} in the apple orchard, and at 185 kg ha^{-1} in the citrus orchard.

The system produced only one product (i.e. apples or oranges respectively), and consequently the total WF (m^3 $tonne^{-1}$) could be fully attributed to this crop, and was thus calculated as the sum of the respective components, such that:

$$WF = WF_{blue} + WF_{green} + WF_{grey}$$

Equation 5-2

Yield was also used to calculate the Water Productivity (WP) of the crop (kg m^{-3}), essentially the inverse of its Water Footprint. The water consumed was considered to be Total Evaporation (ET), combining both stand transpiration (T) and soil evaporation (E).

5.3 Results and discussion

5.3.1 Weather

5.3.1.1 Apple orchard

At the apple orchard site monthly variations in mean maximum and minimum temperatures, total rainfall and average daily total solar radiation reflected typical Mediterranean-type climatic conditions with cool wet winters and warm dry summers (**Figure 5-3**). Total annual rainfall differed substantially between the first and second year of study. From July to June, rainfall amounted to 1198 mm in 2008/2009, but just 560 mm in 2009/2010, of which approximately 21% fell during the summer growing season (October to April) of both years. Conversely, ET_o totals calculated using hourly AWS data and the FAO56 method (Allen et al. 1998) were similar for the two years, totaling 1580 mm in 2008/2009 and 1578 mm in 2009/2010. Daily ET_o values ranged from a maximum of 8 – 9 mm in summer, when the atmospheric evaporative demand was at its peak, down to approximately 1 mm in winter in both years (Gush et al. 2014).

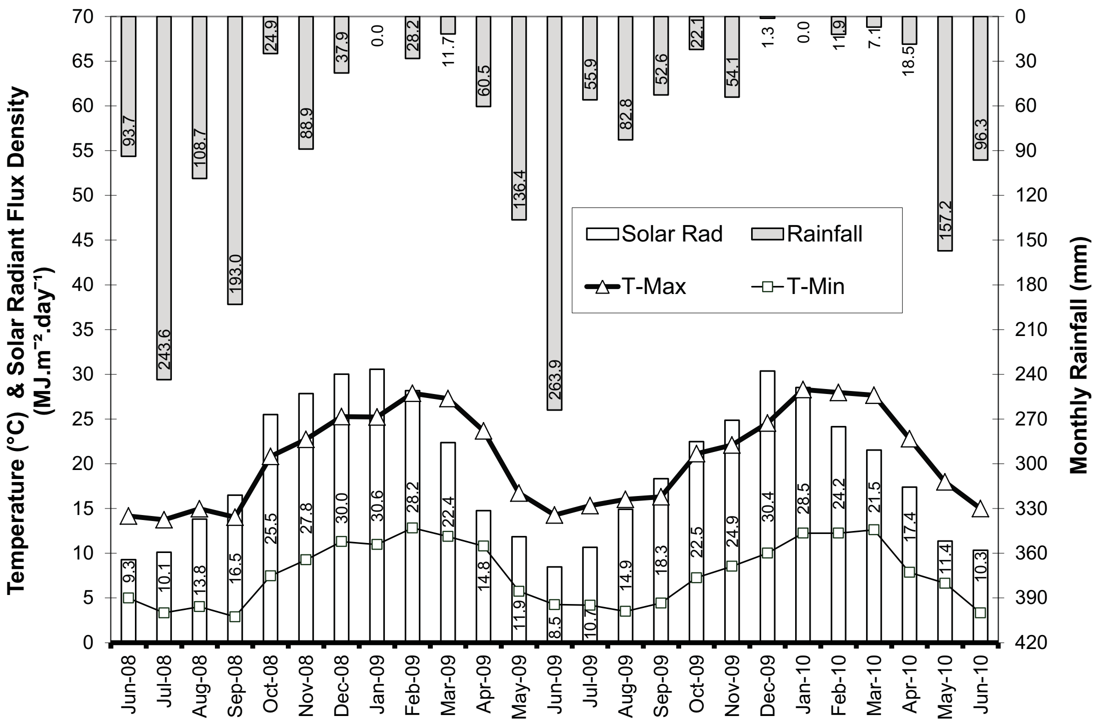

Figure 5-3: Monthly values of rainfall (mm), mean daily maximum and minimum temperatures (°C) and mean daily radiant flux density ($MJ.m^{-2}$ day^{-1}) recorded at the apple orchard between June 2008 and June 2010 (from Gush et al. 2014).

5.3.1.2 Citrus orchard

At the citrus orchard site the weather also reflected Mediterranean-type conditions (**Figure 5-4**). Temperatures ranged from daily minimums of -1.95 °C in winter (August) to a maximum of 43.8 °C in summer (January), with a mean annual temperature of 19 °C. Below zero temperatures were registered for 15 days and above 40°C for 19 days over the two year monitoring period. Daily total solar irradiance ranged from 1.3 to 37.7 $MJ.m^{-2}$ day^{-1}, with average daily totals of 7.9 MJ m^{-2} day^{-1} in winter (June) and 29.6 $MJ.m^{-2}$ day^{-1} in summer (February). Annual rainfall for the first growing season (August 2010 – July 2011) was 183 mm, and for the second season (August 2011 – July 2012) was 201 mm. Daily ET_o values, as calculated using the FAO-56 method (Allen et al., 1998), ranged from approximately 4 - 9 mm in summer, when the atmospheric evaporative demand was at its peak, down to approximately 0.5 - 1 mm in winter (Taylor et al. 2014). Reference evapotranspiration (ET_o) total was 1489 mm in 2010/2011.

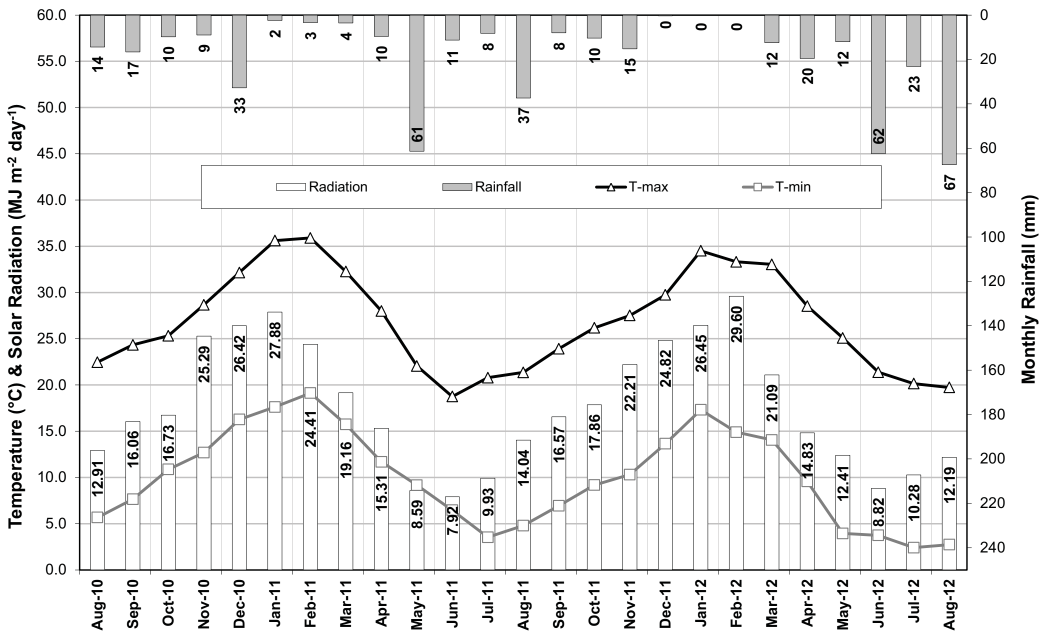

Figure 5-4: Monthly values of meteorological variables recorded in the citrus orchard between August 2010 and August 2012 (from Taylor et al. 2014).

5.3.2 Transpiration

5.3.2.1 Apple orchard

Distinct seasonal trends in transpiration (T) were observed in the apple trees due to the deciduous nature of the species. On an annual time scale (June to July) each 'Cripps' Pink' apple tree transpired approximately 3990 ℓ of water. Converting these T rates into the equivalent water depth for the entire orchard, while accounting for planting density (2000 trees per ha) and the representative proportions of 'Cripps' Pink' and pollinator trees, transpiration equated to 683 mm (6828 m^3 ha^{-1}) in 2008/2009 and 691 mm (6912 m^3 ha^{-1}) in 2009/2010 (Gush, et al. 2014).

5.3.2.2 Citrus orchard

In the citrus orchard seasonal trends were evident but not as pronounced due to the evergreen nature of the species. Daily water use varied from 1.5 to 42.5 ℓ day^{-1} (0.1 – 4.1 mm day^{-1}) with an average of 23.4 ℓ day^{-1} (2.1 mm day^{-1}). After converting these T rates into the equivalent water depth for the entire orchard, while accounting for planting density, transpiration equated to 682 mm (6822 m^3 ha^{-1}) in 2010/2011 (Taylor et al. 2014).

5.3.3 Total evaporation measurements and modelling results

5.3.3.1 Apple orchard

In the apple orchard, ET measurement data from the four eddy covariance campaigns represented the seasonal changes in ET from the orchard. This data was used to calibrate the two layer model described earlier. After subsequent application of the model to scale up the ET data from campaign measurements to the annual scale, the annual ET for the study orchard was found by Gush et al (2014) to be 952 mm (9520 m³ ha^{-1}) in 2008/2009 and 966 mm (9660 m³ ha^{-1}) in 2009/2010. It was found that total annual water application (irrigation plus rainfall) exceeded total annual ET of the apple orchard (**Figure 5-5**), but this was to be expected given that rainfall occurred primarily during the winter when the orchard was leafless and dormant. This winter period represented the bulk of the 'green water' component of the total WF, particularly as 'blue water' irrigation volumes supplied the majority of the water required by the actively growing orchard during the summer months. Growing season water applications were generally well balanced against water losses (particularly T), only deviating somewhat towards the end of the season when trees were dropping leaves and slowing in their T rates, providing opportunity for reduced irrigation applications and potential water savings at this stage.

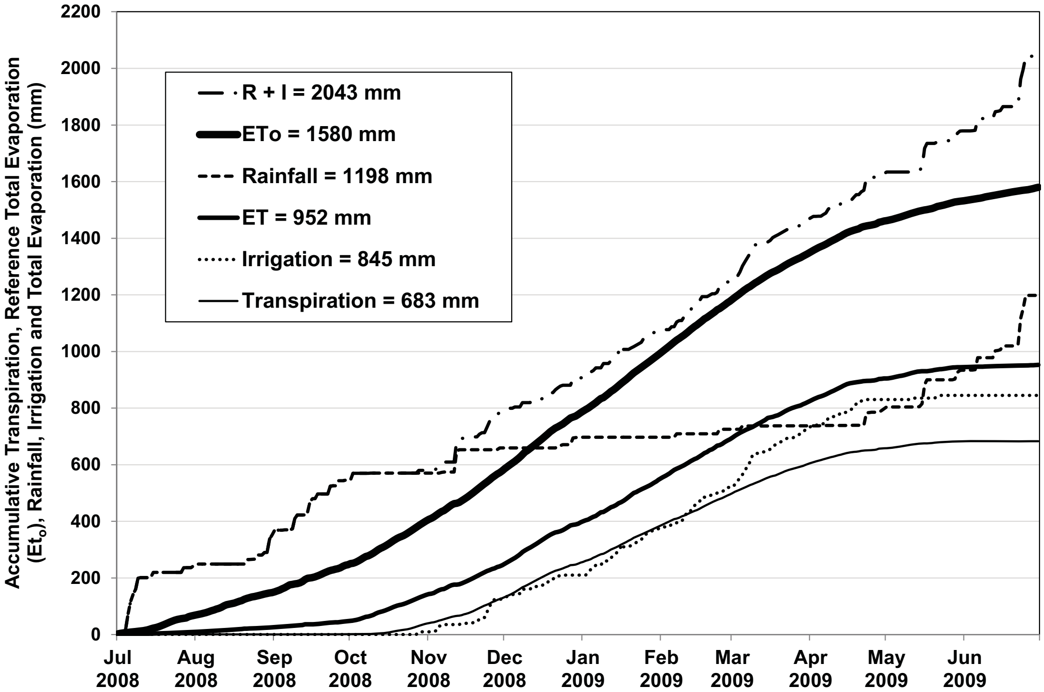

Figure 5-5: Cumulative applied water (irrigation, rainfall, combined), transpiration, total evaporation and reference total evaporation for the 2008/2009 season (July – June 2009) in the apple orchard (Gush et al. 2014).

Crop coefficient results derived by Gush et al (2014) for the orchard over the two years were averaged and illustrate the seasonal variation in ET and T within the orchard (**Figure 5-6**). The significant contribution of inter-row vegetation and wetted soil surface to the overall ET of the orchard is evident from the difference between the K_{cb} and K_c values, particularly in winter (July / August) when trees are leafless (K_{cb} is zero) but there is frequent rainfall and associated evaporation (K_c values of 0.1 – 0.2), as this is a winter rainfall site.

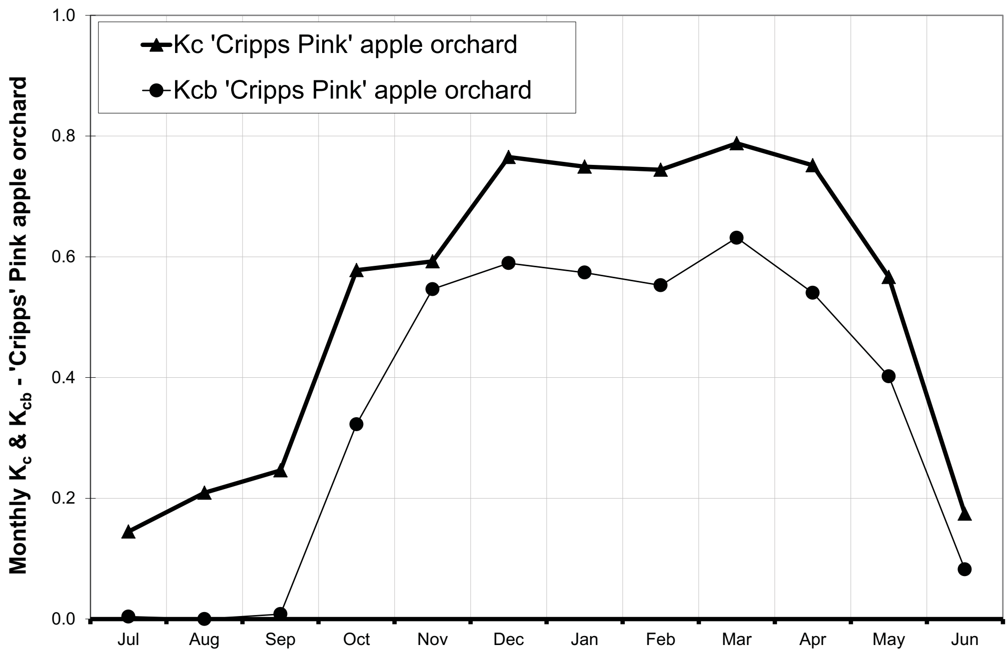

Figure 5-6: Monthly basal (K_{cb}) and full (K_c) crop coefficient values (average of the 2008/2009 and 2009/2010 seasons) determined for the apple orchard (Gush et al. 2014).

5.3.3.2 Citrus orchard

In the citrus orchard observed ET data showed generally low daily ET totals, with values ranging from 0.77 mm to 2.79 mm. Using these estimates and the resultant model to extrapolate to a full year, total ET for the 2010/2011 season was estimated to be 874 mm. The total amount of water applied to the orchard in the 2010/2011 season (rainfall + irrigation = 814 mm) was somewhat less than total evaporation indicating utilisation of residual deeper soil water reserves or groundwater, and reflecting conservative water management in this orchard (**Figure 5-7**).

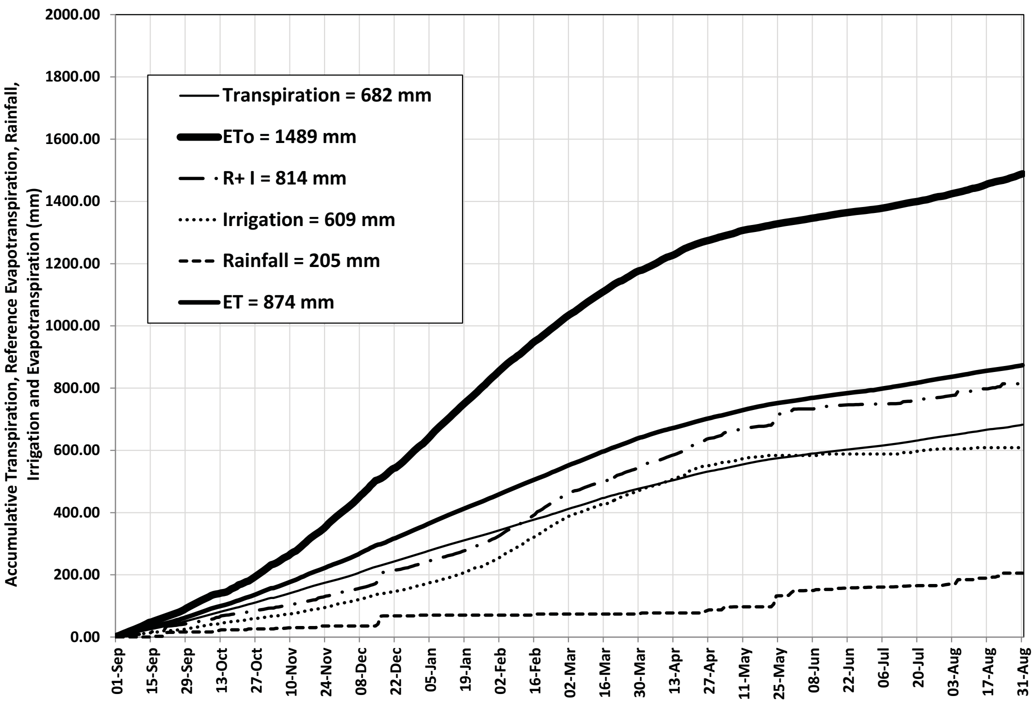

Figure 5-7: Cumulative applied water (irrigation, rainfall, combined), transpiration, total evaporation and reference total evaporation for the 2010/2011 season (September 2010 to August 2011) in the citrus orchard (Taylor et al. 2014).

Crop coefficient results derived by Taylor et al (2014) for the orchard show a trend of lower values in summer and higher values in winter (**Figure 5-8**), which is the opposite of the trend seen for apples. The higher values in winter are attributable to the relatively consistent ET rates throughout the year, combined with lower Reference Total Evaporation (ET_o) values in winter, as $K_c = ET/ET_o$. The comparatively minor contribution of inter-row vegetation and wetted soil surface to the overall ET of the orchard is evident from the relatively small differences between monthly K_{cb} and K_c values.

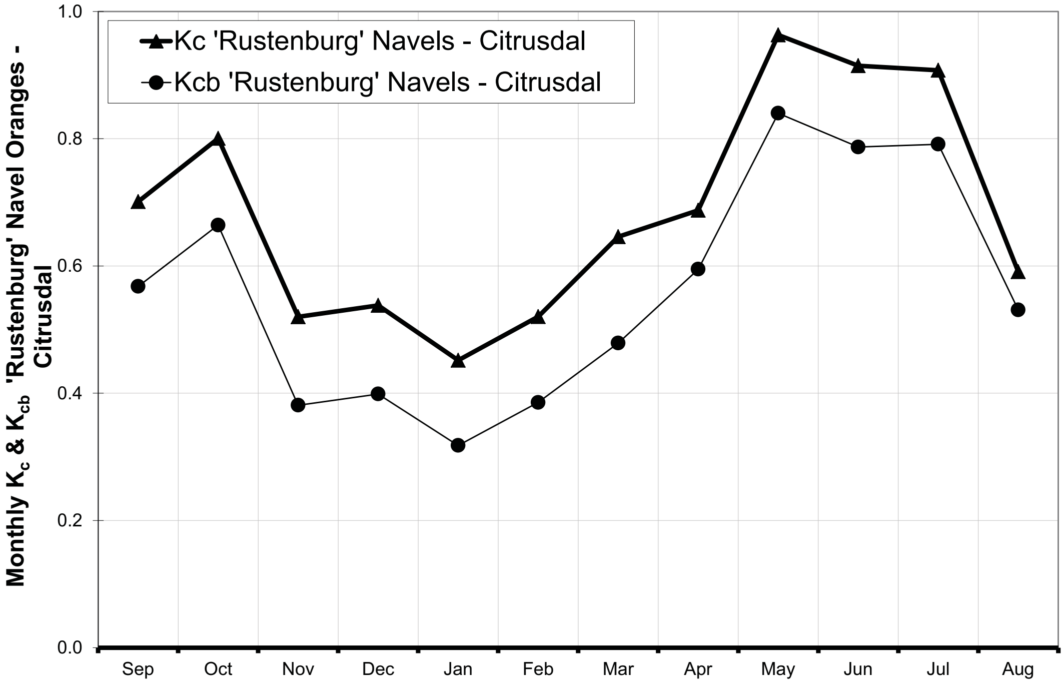

Figure 5-8: Monthly basal (Kcb) and full (Kc) crop coefficient values determined for the citrus orchard (Taylor et al. 2014).

5.3.4 Water footprints at farm scale

5.3.4.1 Apple orchard

Observed data from the field measurements over the full production periods (one year each) indicated that the ET of the apple orchard was 9520 $m^3\ ha^{-1}$ in 2008/2009 and 9660 $m^3\ ha^{-1}$ in 2009/2010. Summing additional water uses associated with orchard and farm management (spraying, pack-house use, evaporation from dams etc.) supplementary water use was calculated to be approximately 380 $m^3\ ha^{-1}$. After assessing the volumes of daily orchard ET that could be directly attributed to irrigation applications over the two growing seasons, and adding these to the supplementary water uses, it was found that CWU_{blue} accounted for an average of 8064 $m^3\ ha^{-1}$. CWU_{green} (i.e. volumes of daily orchard ET associated with rainfall events) accounted for an average of 1907 $m^3\ ha^{-1}$ over the two seasons (**Table 5-1**). Combining these water use values with yield data from the orchard resulted in the water footprint of the apples produced at the study site equating to 236.8 $m^3\ tonne^{-1}$ in 2008/2009 and 187.3 $m^3\ tonne^{-1}$ in 2009/2010, giving an average of 212.1 $m^3\ tonne^{-1}$. This comprised 62.7% WF_{blue} (surface and groundwater), 14.9% WF_{green} (rainwater) and 22.5% WF_{grey} (polluted water). Based on the above yield and water footprint results, crop water productivity figures for the orchard averaged at 4.72 kg m^{-3}.

Table 5-1: Observed water footprint and water productivity results for 'Cripps' Pink' apples over two growing seasons.

	2008/2009	2009/2010	Average
Crop Yield (tonnes ha^{-1})	54.0	69.0	61.5
CWU_{blue} ($m^3\ ha^{-1}$)	7941.9	8186.7	8064.3
CWU_{green} ($m^3\ ha^{-1}$)	1961.6	1853.2	1907.4
WF_{blue} ($m^3\ tonne^{-1}$)	147.1	118.6	132.9

WF_{green} (m^3 $tonne^{-1}$)	36.3	26.9	31.6
WF_{grey} (m^3 $tonne^{-1}$)	53.4	41.8	47.6
Total WF (m^3 $tonne^{-1}$)	**236.8**	**187.3**	**212.1**
Crop water productivity (kg m^{-3})	**4.22**	**5.34**	**4.72**

Orchard yield was 54 tonnes ha^{-1} in 2008/2009 and 69 tonnes ha^{-1} in 2009/2010, and relative to orchard tree density, this translated to fruit production of 27 kg $tree^{-1}$ in 2008/09 and 34 kg $tree^{-1}$ in 2009/10. Using an average fruit weight of 160g per apple in 2008/2009 and 158g per apple in 2009/2010, annual CWU volumes yielded a requirement of 38 ℓ of water per apple (237 ℓ kg^{-1}) produced in 2008/09 and 30 ℓ of water per apple (187 ℓ kg^{-1}) produced in 2009/10. Mekonnen and Hoekstra (2011) report that as a global average, 125 ℓ of water is required to produce a single 150g apple (822 ℓ kg^{-1}). Our study showed a significantly lower estimate which could either be attributed to higher production figures observed in our study (relative to those used by Mekonnen and Hoekstra, 2011), or lower water use, or both. As our study used field-based observations and verified modelled estimates of actual orchard ET in the WF calculations, it is possible that our water use values were lower than those used by Mekonnen and Hoekstra (2011). However differences between the studies are more clearly attributable to the substantial yield differences. Yields observed in our study (54 - 69 tonnes ha^{-1}) were representative of those observed in the industry at the time, although current production figures frequently exceed 100 tonnes ha^{-1}. On the other hand the yields reported in the Mekonnen and Hoekstra (2011) study (11 tonnes ha^{-1}) are substantially lower, possibly as they accounted for a global average, including low / marginal production zones. A further difference is in the relative proportions of the WF components. Unlike the Mekonnen and Hoekstra (2011) findings, our study indicated that the major proportion of the WF of apples constituted WF_{blue}, largely due to the high dependence on irrigation during the summer months of the growing season in this Mediterranean-type climatic area, when rainfall was minimal but ET rates were at their maximum. The WF_{green} component dominated the rainy winter months, however its relative proportion was lower as the apple trees were largely dormant (leafless) and ET rates were at their lowest during this period. It is also worth noting the annual variation in results over the two growing seasons. Crop water use volumes were similar for both years, resulting in consistent proportions of WF_{blue}, WF_{green} and WF_{grey} over both seasons. However, the more pronounced differences in annual yield between years had a disproportionately greater influence on the total WF and WP estimates, with higher yields resulting in lower WF values and higher WP values.

5.3.5 Citrus orchard

Observed data from the field measurements over a full monitoring year (September 2010 to August 2011) indicated that the ET of the citrus orchard was 8737 m^3 ha^{-1} (874 mm). Summing additional water uses associated with orchard and farm management (spraying, pack-house use, evaporation from dams etc.) supplementary water use was found to be approximately 1992 m^3 ha^{-1}. This relatively large amount was predominantly attributed to evaporation from 3 storage dams on the farm as well as to packhouse water use. Packhouse water use was monitored directly, over a full calendar year, using an in-line water meter on the main water supply pipeline to the facility, and was found to be 900 ℓ of water used per ton of citrus fruit processed. After assessing the volumes of daily orchard ET that could be directly attributed to irrigation applications over the growing season, and adding these to the supplementary water uses, it was found that CWU_{blue} accounted for 8900 m^3 ha^{-1}. CWU_{green} (i.e. volumes of daily orchard ET associated with rainfall events) accounted for 1828 m^3 ha^{-1} over the growing season (**Table 5-2**). Combining these water use values with yield data from the orchard resulted in the water footprint of the Navel oranges produced at the study site equating to 162.8 m^3 $tonnes^{-1}$ in 2010/2011. This comprised 69.2% WF_{blue} (surface and groundwater), 14.2% WF_{green}

(rainwater) and 16.6% WF_{grey} (polluted water). Based on the above yield and water footprint results, crop water productivity figures for the orchard were found to be 6.14 kg m^{-3}.

Table 5-2: Observed water footprint and water productivity results for 'Rustenburg' Navel oranges over a single growing season.

	2010/2011
Crop Yield (tonnes ha^{-1})	79.0
CWU_{blue} (m^3 ha^{-1})	8900.2
CWU_{green} (m^3 ha^{-1})	1828.4
WF_{blue} (m^3 $tonne^{-1}$)	112.7
WF_{green} (m^3 $tonne^{-1}$)	23.1
WF_{grey} (m^3 $tonne^{-1}$)	27.0
Total WF (m^3 $tonne^{-1}$)	**162.8**
Crop water productivity (kg m^{-3})	**6.14**

The yield of the citrus orchard over the monitoring period was 79 tonnes.ha^{-1}, and relative to orchard tree density, this translated to fruit production of 118 kg $tree^{-1}$. Using an average fruit weight of 184g per orange, annual CWU volumes provided an estimate of 30 ℓ of water per orange (163 ℓ kg^{-1}) produced. Mekonnen and Hoekstra (2011) report that, as a global average, 80 ℓ of water is required to produce a single 150g orange (560 ℓ kg^{-1}). As with the apple results above, our study showed a significantly lower water footprint estimate which is attributed to the high yields observed in our study, combined with lower water use data based on field observations and verified modelled estimates of actual orchard ET in the WF calculations. Again, the WF_{blue} was the dominant component due to the high dependence on irrigation, and WF_{green} was small as a result of the arid nature of the site.

5.4 Conclusions

This study highlights that detailed observations on volumes of water actually used by a particular crop greatly facilitate accurate water footprint calculations for products of that crop. These detailed field measurements also provide the necessary data and information for improved on-farm water management planning and irrigation scheduling. The deciduous fruit and citrus industries are significant contributors to the Gross Domestic Product of South Africa, leading to income generation and job creation. However, in order to grow in a sustainable manner, and in parallel to numerous other competing water users, water requirements for the industry need to be carefully considered, allocated and utilised in the most efficient ways possible. The importance of accurate observations of actual orchard water requirements is critical in this regard, not only at farm-scale, but also for local and regional water resource planning and allocation. The provision of T and ET data for fruit trees and orchards, that is as accurate as possible, will facilitate more efficient water use. Furthermore, the incorporation of this data into water footprint and water productivity assessments, as illustrated in this study, provides more accurate information on the true water use associated with the production of particular products.

6 CATCHMENT SCALE WATER FOOTPRINT OF THE STEENKOPPIES AQUIFER

by

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6.1 Introduction

In **Chapter 3** blue, green and grey water footprints (WFs) were calculated for cultivating vegetable and grain crops on the Steenkoppies Aquifer. The WF outcomes of different methodologies were compared and it was concluded that the Water Footprint Network (WFN) approach is more useful in a catchment or aquifer resource management context because of its quantitative nature. A number of studies have determined WFs of various crops according to the method given by the WFN (Aldaya and Hoekstra 2010, Bosire et al. 2015, Chapagain and Hoekstra 2007, Gerbens-Leenes et al. 2009, Mekonnen and Hoekstra 2011, Nyambo and Wakindiki 2015). Although these WFs provide useful information on the water used to produce different products, there is often a need to upscale the WFs and findings to a catchment scale to compare total water used with total available water within a catchment. In this chapter the WFN blue and green WFs are up-scaled to a catchment level for the Steenkoppies Aquifer to better understand how WFs can inform a water resource manager to ensure the sustainable use of the aquifer and possibly to better understand the geohydrology of the aquifer.

The Steenkoppies Aquifer is within the A21F quaternary catchment, which is in the upper reaches of the Crocodile West River Basin. According to current knowledge, the aquifer has one natural outlet, namely Maloney's Eye, from where it discharges into the Magalies River. The Magalies River supports important riparian ecosystems and provides irrigation water to a number of downstream farms (Vahrmeijer et al. 2013). Further downstream the Magalies River discharges into the Hartbeespoort Dam, which was constructed for irrigation purposes and is now well known for its hypertrophic water (Department of Water and Sanitation 2016). The catchment area of the Maloney's Eye is referred to as the Maloney's Eye Catchment and includes the Steenkoppies Aquifer and an area of 5 300 ha above the Steenkoppies Aquifer. The Maloney's Eye is the only known outlet for the Steenkoppies Aquifer, and is therefore also the only known outlet for all the water draining from the Maloney's Eye catchment.

During the 1980's, agricultural activities on the Steenkoppies Aquifer increased significantly, sourcing irrigation water from the aquifer through boreholes. Flow of water from Maloney's Eye was drastically reduced as a result (**Figure 6-1**) (Department of Water and Sanitation 2014). The initial decreasing trend coincided with unusually high flows from the Maloney's Eye in 1980. This decreasing trend continued and after 1986 the average flows were lower than previously. The reduction in flow resulted in conflict between farmers on the aquifer and downstream users, especially following two major droughts from 1990-1992 and 2002-2005 (Vahrmeijer et al. 2013). Downstream water users established the Magalies River Crisis Committee in an attempt to save their livelihoods and the ecological integrity of the river. They made a request to the South African Presidency to prohibit all abstractions from the Steenkoppies Aquifer, but the socio-economic impacts of such a measure were considered too high (Wiegmans et al., 2013). The largest carrot producer in Africa is situated on the

Steenkoppies Aquifer, and according to Vahrmeijer (2013) more than 4000 people are employed by all agricultural activities on the aquifer. The farmers on the aquifer disputed the claims that they are responsible for the reduction in flow from the Maloney's Eye (Wiegmans et al., 2013). Very little is currently being reported regarding this conflict.

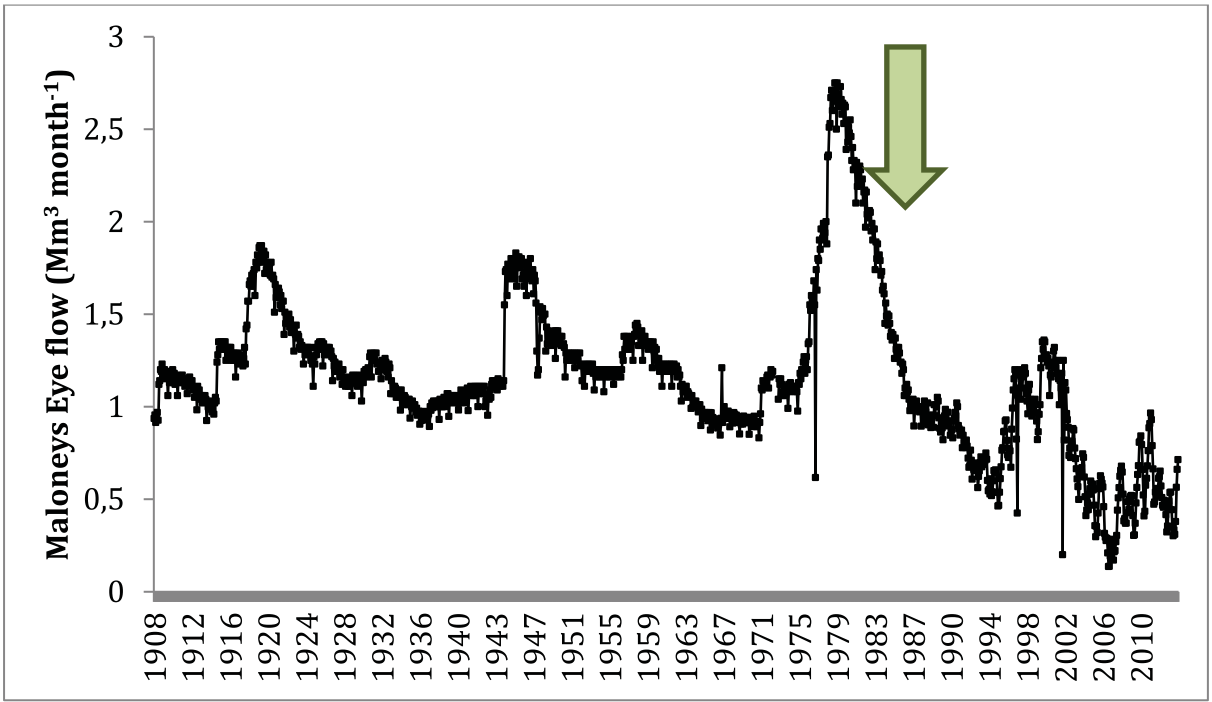


Figure 6-1: Maloney's Eye outflows from 1908-2012. Reduction in flow has been observed since the commencement of intensive irrigated agriculture in 1986 (Department of Water and Sanitation 2014).

The Steenkoppies Aquifer presented a unique opportunity to verify WF sustainability outcomes, because of the following characteristics:

- The geohydrology of the aquifer is relatively simple with no surface water flowing into the aquifer or into the Maloney's Eye Catchment, except for the Upper Rietspruit River which carries water from the Randfontein waste water treatment works (WWTW). There is also no surface water flowing out of the aquifer or out of the Maloney's Eye Catchment, because flow in the Upper Rietspruit River reduces to almost zero within the boundaries of the aquifer. Therefore, according to current understanding, precipitation falling onto the Steenkoppies Aquifer either evaporates or recharges the aquifer. The Maloney's Eye is also currently the only natural outlet currently known.
- Numerous studies have been conducted on the Steenkoppies Aquifer, including geohydrological studies (Barnard 1996, Barnard 1997, Bredenkamp et al. 1986b, Vahrmeijer et al. 2013, Wiegmans et al. 2013, Witthueser et al. 2009). These studies provided insights into water flows and could be used to validate results from the catchment scale WF assessment.
- Extensive datasets were available for different water flows and uses across the aquifer. The Maloney's Eye outflows have been monitored by the Department of Water and Sanitation on a daily basis since 1908. Some data exist for the outflows from the Randfontein WWTW. The Deodar weather station is also located within the Steenkoppies Aquifer (AgroClimatology Staff 2014). Data has been collected on agricultural activities on the aquifer, including crop areas, average yield and irrigation for each of the major vegetable crops (Vahrmeijer 2016).

Catchment scale water footprinting may also represent a simplified yet effective approach to managing water resources at this scale, which can be very complex, particularly if the key data and information is not available. Mitchell (1990) observed that catchment managers at an operational level are often overwhelmed by the complexity of water resource management and the number of water related issues that should be incorporated into decision making. This is also true for the Steenkoppies Aquifer, where a vast number of variables can be monitored including precipitation, abstractions for irrigation, drainage, runoff or outflows to other catchments, groundwater levels, planted areas and total crop yields. Monitoring all these variables is not always possible. In this study, we ask whether measuring and/or estimating key variables (such as precipitation, yields, WFs of crops and natural vegetation and non-agricultural blue WFs) and using them in a WF accounting framework can provide useful, quantitative data to manage a catchment's water resources when detailed hydrological information is absent. The catchment WF framework is proposed that can potentially quantify the volumes of water used by irrigated and dryland agriculture, which can assist in water allocation decisions and in setting sustainability targets. Outflows from many aquifers are not well recorded and the points of discharge are often unknown, thus the Maloney's Eye Catchment, with its simple geohydrology and available data, offers a unique opportunity to validate the catchment WF framework. Our study uses the original methodology proposed by the WFN, because it calculates a volume of water that is used per unit production, in this case evapotranspired through crop production, and the total volume of ET from agriculture on the aquifer can be used in a catchment water balance to better understand water flows through the catchment.

This chapter also reports on the WFs of vegetable waste produced on the Steenkoppies Aquifer. Phenomenal percentages of food wasted along the supply chain have been reported. Lundqvist et al. (2008) reported that up to 50% of production is lost from 'field to fork'. There is limited information published on wastage of specific vegetables. Nahman et al. (2012) determined the cost of household waste in South Africa, and Oelofse and Nahman (2013) determined the food wastage along the supply chain relative production. Gustavsson et al. (2011) determined food wasted for different commodity groups, including roots and tubers, and fruits and vegetables for different region across the world, including sub-Saharan Africa. The question is asked as to whether reductions in food wastage, with concomitant reductions in vegetable production could provide a way to achieve sustainable water use on this water stressed aquifer.

6.2 Materials and methods

6.2.1 Catchment scale water footprints of irrigated crops

Seasonal blue and green WFs of carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*), calculated according to the WFN in **Chapter 3** (**Table 3-10**), was linked to agricultural yields to obtain total agricultural water consumption on a catchment level from 1950 to 2012. The usefulness of this information was then assessed through comparisons with hydrological information. The catchment WF framework proposed here was used to calculate a water balance for the aquifer and the approach was validated by actual volumes of discharge from Maloney's Eye (**Section 6.2.2**). Thus, the grey WF, which does not provide a physical volume of water was not considered relevant to be used in the catchment water balance based on physical volumes.

Catchment scale water consumption of irrigated crops were determined for five distinct periods between 1950 and 2012. The years 1950 to1979 are considered the first period and 1980 to 1985 the second period. According to **Equation 2-3** and **2-4** (**Chapter 2**), over-irrigation would result in zero green WF.

Because of the crude methods used to determine irrigation requirements in earlier years, it was assumed that prior to 1980 more water was abstracted than what was required by the crop, which would result in zero green WFs and blue WFs equal to total abstraction. It was also assumed that abstractions exceeding crop ET were negligible, because available data indicated relatively low volumes abstracted in these periods, and any excess would not have a significant impact. In 1950, irrigated agriculture on the Steenkoppies Aquifer was practiced on a relatively small scale with maize being the main crop grown. About 4 Mm^3 water was reported to be abstracted for irrigation in 1980, representing blue WFs for the second period (Vahrmeijer et al. 2013) and for this study it was assumed that the blue WF for the first period was 2 $Mm^3\ yr^{-1}$. Thus, first and second periods are considered to represent periods with very little impact on the aquifer, and therefore serves as control periods which are less complex and can be used to validate the results. According to Bredenkamp et al. (1986) 13.45 $Mm^3\ yr^{-1}$ of water was abstracted in 1986 and this volume was assumed to represent the catchment scale blue and green water use for irrigated agriculture of the third period from 1986 to 1995. The year 1996 is when commercial irrigation drastically expanded on the Steenkoppies Aquifer (Vahrmeijer et al. 2013). **Figure 6-2** indicates irrigated field areas on the Steenkoppies Aquifer for the year 2015. These must be distinguished from cropped areas – the annual cropped area is higher than the physical field area as two or three crops may be planted on the same land each year.

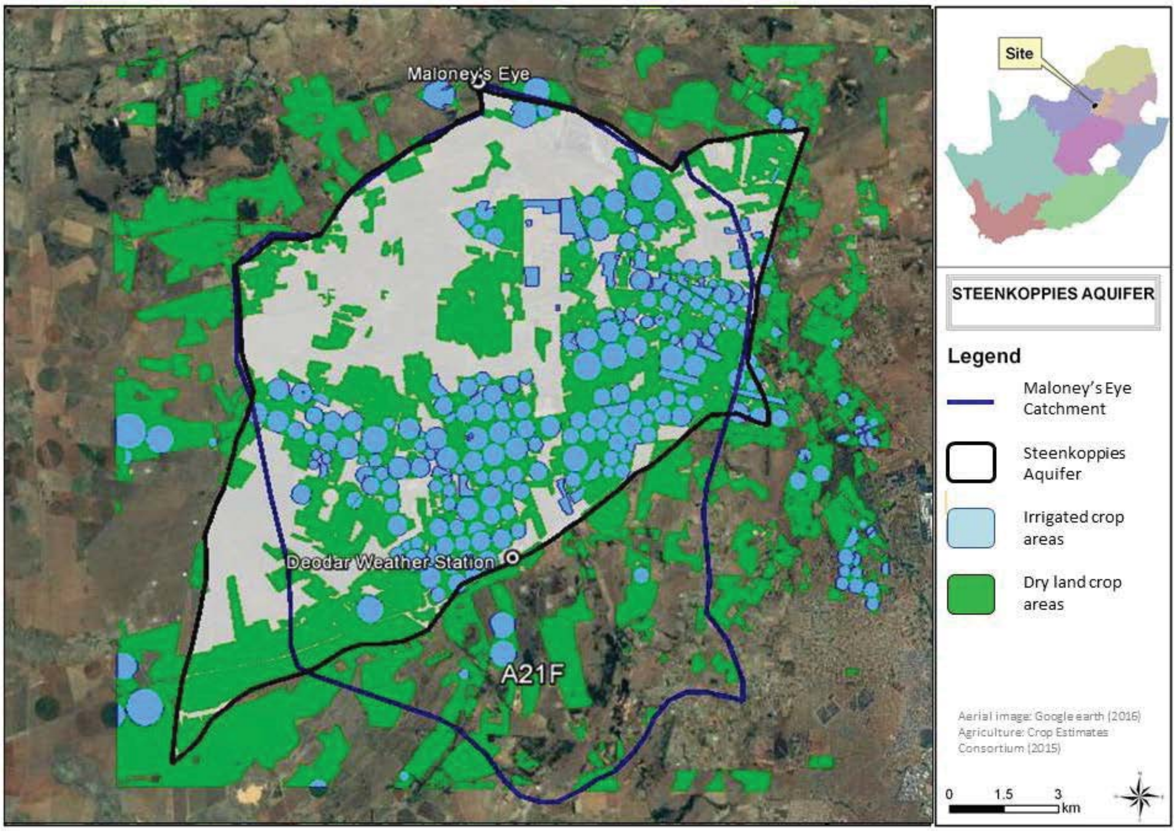


Figure 6-2: Agricultural activities on the Steenkoppies Aquifer, west of Tarlton, Gauteng, South Africa (Crop Estimates Consortium 2015)

Prior to 2015, updated information on total irrigated cropped areas and crop composition for 57% of total irrigated cropped areas became available in 1998. For 2005, total irrigated cropped areas were also available, but did not include data on crop composition. The crop composition determined for irrigated crops in 1998 was therefore assumed to be representative of the whole catchment and extrapolated to represent all years from 1996 onwards. Cropped areas of 1998 were used to represent the fourth period (1996 to 2004) and cropped areas of 2005 were used to represent the fifth period (2005 to 2012).

According to a study done by Vahrmeijer (2016) total irrigated cropped areas in 1998 and 2005 was 4183 and 5349 hectares respectively. Cropped areas of 1998 represented the fourth period (1996 to 2004) and cropped areas of 2005 represented the fifth period (2005 to 2012). For 2005 the crop composition was not determined, but for 1998 the crop composition for 57% of the total irrigated cropped area was determined (**Figure 6-3** and **Table 6-1**). The crop composition determined for irrigated crops in 1998 was therefore assumed to be representative of the whole catchment and extrapolated to represent all years from 1996 onwards (**Table 6-3**).

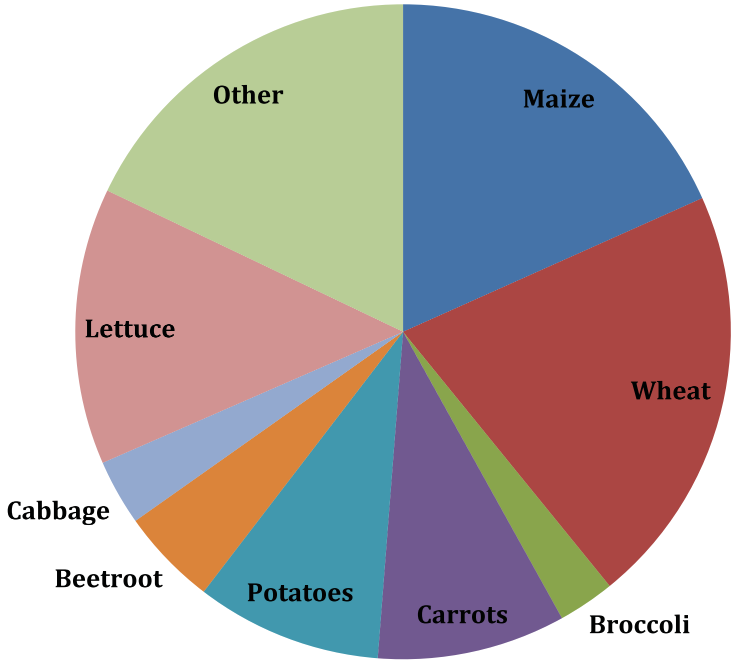


Figure 6-3: Crop constitution of the Steenkoppies Aquifer in 1998

Table 6-1: Summary of verified crop areas on the Steenkoppies Aquifer in 1998 and extrapolations to total crop areas for 1998 and 2005

Crop	Crop area verified (hectares)	Percentage of verified crop area	Extrapolate total crop areas for 1998 (hectares)	Extrapolate total crop areas for 2005 (hectares)
Maize	471	18.31%	765.8	979.3
Wheat	536	20.83%	871.5	1114.5
Broccoli	72	2.80%	117.1	149.7
Carrots	239	9.29%	388.6	496.9
Beetroot	123.4	4.80%	200.6	256.6
Cabbage	83.5	3.25%	135.8	173.6
Lettuce	351.07	13.65%	570.8	729.9

Potatoes	236	9.17%	383.7	490.7
Other	460.64	17.91%	749.0	957.8

A typical planting schedule for vegetables on the Steenkoppies Aquifer by commercial growers was used to derive crop areas planted each month and enable WF calculations on a monthly basis (**Table 6-2**). Regarding the cereals on the Steenkoppies Aquifer, maize is only planted in summer and wheat is only planted in winter.

Table 6-2: Area planted (ha) in 1998 for the selected vegetable crops taken from a farmer on the Steenkoppies Aquifer

Month	Beetroot	Carrots	Cabbage	Lettuce	Broccoli
January					
February			3	1	
March	4	4	4	4	
April	9	13			0.4
May	6	7			0.3
June	4		1	3	0.3
July		5	2	3	1
August		5	4	3	1
September	5	5	4	4	1
October			5	3	1
November	3	18	3	9	1
December	4	5	10	10	2

Irrigated crop areas were converted to yield using average yield per hectare in each of the correlating growing seasons (summer, autumn, winter and spring). Average yield for each crop was generated using the calibrated Soil Water Balance (SWB) crop model for simulations over a nine year period (2004 to 2012) (Annandale et al. 1999, Le Roux et al. 2016). Simulated yield data was verified with locally measured independent data and not with data that was used to obtain model parameters. Estimated yields of the selected irrigated crops on the aquifer were then multiplied by the blue and green WFs for the relevant season and added to obtain the total water consumed per calendar year. The selected crops cover 73% of the individual cropped areas determined for 1998. The remaining 27% of crops were assumed to use on average the same volume of water per surface area, so the water use of the selected crops was extrapolated to obtain the total water use of all crops on the aquifer. **Table 6-3** includes a summary of the available verification data on cropped areas as used in this study.

Table 6-3: Summary of Steenkoppies Aquifer cropped areas used to calculate the catchment scale water footprint

Cropped area	Period 1 1950 to 1979	Period 2 1980 to 1985	Period 3 1986 to 1995	Period 4 1996 to 2004	Period 5 2005 to 2012
Irrigated land					
Total irrigated cropped area	268 ha**	536 ha**	1 952 ha*(1)	4 183 ha*	5 349 ha*
Percentage of total cropped area for which crop composition was verified	Maize only**	Maize only**	Maize only**	57%*	57%**
Percentage of total crop area (as per 1998 verified data) represented by selected crops	Maize only**	Maize only**	Maize only**	73%*	73%*
Dry land					
Total dry land cropped area on the aquifer	3 108 ha**	3 108 ha**	6 215 ha**	6 215 ha**	6 215 ha*

* Verified data; ** Assumed / expert opinion, (1) taken from Barnard (1997)

The assumption that cropped areas for 1998 and 2005 represent all the years in the fourth and fifth period could be challenged, because cropped areas and species planted vary from year to year, as driven primarily by market prices and because of the large number of assumptions that were made regarding the crop composition. A sensitivity analysis was therefore conducted to determine how sensitive the catchment scale WF is to a particular crop composition. Two hundred iterations were composed of randomly crop compositions, always adding up to the total irrigated cropped area of 2005 used in this analysis. For each of the randomly selected crop compositions, a catchment scale WF was calculated as described above. The resulting catchment scale WFs were plotted as a histogram (**Figure 6-4**) to illustrate the variation and spread in the data. The average catchment scale WF for the 200 iterations is 30 Mm^3 and the standard deviation is 3.8 Mm^3. The catchment scale WF for 2005 that was obtained for this study was 31.8 Mm^3 (**Table 6-4**), which is within the standard deviation of the sensitivity analysis. The sensitivity analysis indicated that the catchment scale WF for the Steenkoppies Aquifer is, therefore, relatively insensitive to variations in cropping patterns. This is likely because most crops are short season vegetables with shallow root systems and relatively similar crop ET. The sensitivity analysis therefore reduces uncertainty in the catchment scale water use results for this particular study area.

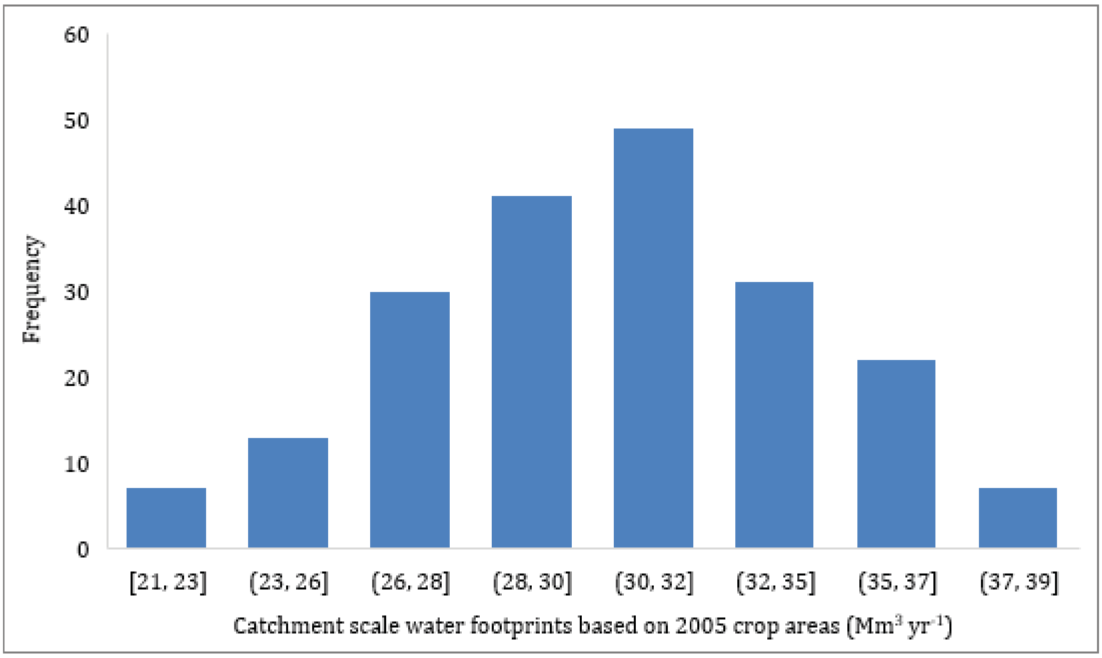


Figure 6-4: Analysis indicating the sensitivity of the catchment scale water footprint to randomly selected crop areas. All iterations in the analysis added up to the total cropped area of 2005.

6.2.2 Catchment water balance

After the volume of water consumed by irrigated agriculture on the aquifer was calculated using WF accounting, a catchment water balance was calculated. The catchment water balance was calculated for the Maloney's Eye Catchment. Catchment boundaries were defined as the part of quaternary catchment A21F that is the area draining into the Maloney's Eye (Department of Water and Sanitation 2016). Contour lines were used to delineate the northern boundary of the catchment, because the quaternary catchment includes a large area downstream of the Maloney's Eye, which is not relevant to this study. The northern boundary of the catchment is aligned with the northern boundary of the Steenkoppies Aquifer, because the aquifer boundary also coincides with ridges that define the northern boundary of the Maloney's Eye Catchment (**Figure 6-5**).

The other boundaries of the Maloney's Eye Catchment area are not exactly aligned with the boundaries of the Steenkoppies Aquifer. The aquifer overlaps the catchment to the east and west, and the catchment overlaps the aquifer to the south (**Figure 6-5**). Irrigated water used in the five periods between 1950 and 2012 were only related to irrigation activities above the aquifer, excluding the southern part of the catchment. Agricultural activities on this southern part of the catchment were considered insignificant, because the field areas under pivot irrigation are only 3% of total irrigation field areas within the Maloney's Eye Catchment (Crop Estimates Consortium 2015). The other components of the catchment water balance, namely precipitation, ET of natural vegetation and dry land maize, were for the Maloney's Eye Catchment area. It was also assumed that insignificant recharge of the aquifer occurs where the Steenkoppies Aquifer extends past the Maloney's Eye Catchment boundary to the east and west, because these areas are relatively small and if rainfall forms runoff it will not recharge the aquifer.

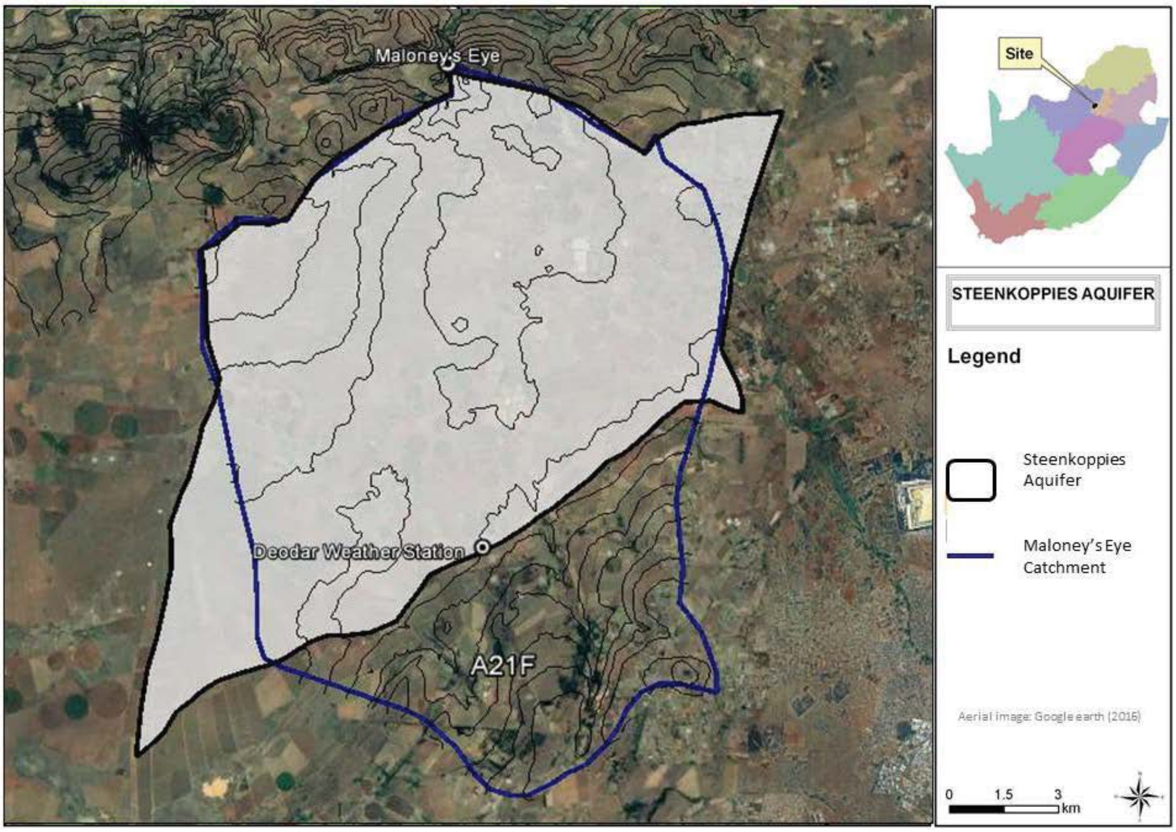


Figure 6-5. The Steenkoppies Aquifer and Maloney's Eye Catchment boundary used for the catchment water balance/footprint calculations. Contours indicate high points in the landscape, according to which the Maloney's Eye Catchment boundaries were delineated.

Based on the catchment water balance, annual outflows were then estimated using WF accounting. The first step was to estimate recharge of the aquifer ($Mm^3\ yr^{-1}$) according to **Equation 6-1**.

$$\begin{aligned} &Aquifer\ recharge \\ &\quad = Precipitation + Additional\ sources - ET\ of\ natural\ vegetation \\ &\quad - ET\ of\ agriculture - Additional\ uses \end{aligned}$$

Equation 6-1

Where *precipitation* and *additional sources* are the volume of water inflows into the catchment. For aquifers in general, additional sources will include runoff from other catchments, inter-basin transfers of water into the area, or return flows from urban areas that were originally sourced from other catchments. *Additional uses* include water abstracted from the aquifer for purposes other than irrigation and transferred out of the catchment

Volumes of precipitation for the catchment were estimated by multiplying measured daily precipitation data by the total surface area of the Maloney's Eye catchment. It was assumed that annual precipitation is relatively evenly distributed throughout the catchment, because the area is relatively small and has a flat topography. Actual precipitation data since 1984 was obtained for the Deodar weather station (Lat: S 26.1426; Long: E 27.57438, Altitude: 1591), while simulated precipitation data was used for the period from 1951 to 1983 that was obtained from a database developed by a team from the School of Bioresources Engineering and Environmental Hydrology at the University of KwaZulu-Natal using the South African Atlas of Climatology and Agro Hydrology (Van Heerden et al. 2009). The Maloney's Eye

Catchment does not receive any runoff water from adjacent catchments that needed to be considered (Wiegmans et al. 2013). The Upper Rietspruit River is the only surface water resources within the Steenkoppies Aquifer and due to abstractions and losses from the river bed, the flow in this river is reduced to zero within the study area (Wiegmans et al. 2013).

The Randfontein Waste Water Treatment Works discharges 2.9 Mm^3 yr^{-1} of effluent into the Maloney's Eye Catchment, of which 1.8 Mm^3 is used for irrigation. The 1.8 Mm^3 used for irrigation is an additional water source and was added to the water balance. The remaining 1.15 Mm^3 of the water is partly discharged into the Upper Rietspruit River and partly used for dust suppression. According to a geo-hydrological assessment by Wiegmans et al. (2013), none of the 2.9 Mm^3 yr^{-1} effluent water recharges the aquifer, so this remaining 1.15 Mm^3 was excluded from the water balance. Apart from the 1.8 Mm^3 of irrigation water from the Upper Rietspruit River that is an additional source of water, there are no additional sources or uses of water in the catchment.

ET of irrigated agriculture for the first, second and third periods was assumed to be 2, 4 and 13.45 Mm^3 yr^{-1}, respectively, as discussed in **Section 6.2.1**. The up-scaled irrigated crop WFs were used to estimate the total ET of irrigated agriculture for the fourth and fifth periods starting from 1996 and 2005, respectively. Dry land agriculture shown in **Figure 6-2** (Crop Estimates Consortium 2015) cover an area of 6 215 ha. This surface area was used to determine the ET of dry land maize for the third to fifth periods. Based on local knowledge of the Steenkoppies Aquifer, it was estimated that dry land agriculture totalled 3 107 ha during the first and second period (1950 to 1985) and this area was also used to estimate ET of dry land maize for the first two periods.

The Acocks (1988) classification for the natural vegetation in the Maloney's Eye Catchment is Themeda veld to Bankenveld transition. Monthly ET of natural vegetation for the study area was simulated using SWB. A 'crop' factor for this vegetation type was obtained from Pike and Schulze (2004). This area was assumed to include agricultural land left fallow, which is left unplanted at times during the year due to the relatively short growing season of vegetables crops and / or to 'rest' the soil. The area of natural vegetation was assumed to be the total catchment area minus irrigated and dry land cropped areas minus 'built structures'. According to SANBI (2009) the surface area of urban areas in 2009 was 207 ha, which is insignificant compared to the total area of the Maloney's Eye Catchment and was therefore assumed as 'built structure' areas for all years considered in this study. To estimate cropped areas before 1996 it was assumed that only maize was irrigated. Average irrigation volume of maize per surface area was estimated from SWB outputs to determine total cropped areas that would require 2 Mm^3, 4 Mm^3 and 13.45 Mm^3 irrigated water (**Table 6-3**). Average SWB results for 2004 to 2012 provided lengths of crop growing seasons for each crop. The areas covered by crops each month for the fourth (1996 to 2004) and fifth (2005 to 2012) periods were determined by combining the crop lifetimes for a specific growing season with the crop areas planted. The total volume evapotranspired by natural vegetation in the catchment was calculated by multiplying daily ET of natural vegetation by the total surface area of natural vegetation for each of the five periods.

Actual outflows from Maloney's Eye, as measured by Department of Water and Sanitation (2014), was compared to estimated values to validate the WF accounting method used. In order to estimate outflows from Maloney's Eye, for comparative purposes, an eight-year moving average of estimated recharge was calculated, to mimic potential physical outflow regulations by the aquifer. An eight-year period was selected as it most closely aligned with the measured outflows from Maloney's Eye. The estimated outflows from 1950 to 1995 were plotted against measured outflows to determine the square of the correlation coefficient (R^2) between them. Data from 1996 onwards were excluded, because high water uses by agriculture reduced the correlation between the variables.

Although the Steenkoppies Aquifer is considered relatively simple in terms of its geohydrology, lags in water flows through the aquifer complicate the understanding of the catchment water balance. Cumulative rainfall was compared to cumulative outflows from the aquifer to better understand possible lags in the Steenkoppies Aquifer.

6.2.3 Sustainability assessment

The sustainability of the catchment scale WF was assessed by comparing it with freshwater availability. In many cases average water availability over the year hides seasonal scarcities and it is therefore often important to consider monthly water availability or use (Hoekstra et al. 2011). However, water availability for the Steenkoppies Aquifer was calculated on an annual basis, because the aquifer has the ability to supply stored water during the dry seasons. Blue water availability (BWa) according to the WFN (Hoekstra et al. 2011) is calculated according to **Equation 2-8** (**Chapter 2**). Average outflows from Maloney's Eye between 1909 and 1995, when impacts of irrigation were minimal, were 14.7 Mm^3 yr^{-1} and were used as the natural runoff (R_{nat}). Measured outflows after 1996 were excluded, because abstractions for irrigation impacted on the outflows during this time. The EFR for water flowing out of the Maloney's Eye and further downstream in the Magalies River was determined by the Department of Water Affairs (2011), as 46% of natural Mean Annual Runoff (MAR) in the Magalies River, downstream of the Maloney's Eye. The EFR for this study was therefore taken as 46% of the 14.7 Mm^3 yr^{-1} natural annual outflows from the Maloney's Eye.

In the past only BWa was considered to be important, but according to the WFN green water is also scarce and can be used unsustainably. Green water availability (GWa) was calculated according to **Equation 2-6** (**Chapter 2**). ET_{green} was calculated by multiplying annual ET of natural vegetation with the surface area of the whole catchment. The study area does not have any significant nature conservation areas so ET_{env} was calculated according to a target conservation percentage for the veld type. According to Mucina and Rutherford (2006), the study area lies primarily within the Carletonville Dolomite Grassland (Gh15) for which a conservation target of 24% is set. The ET_{env} is therefore calculated as ET of natural vegetation multiplied by 24% of the total catchment area. Total unproductive land includes all urban areas, which were multiplied by an estimated ET of 400 mm for unproductive land and urban areas, as taken from the WFN handbook (Hoekstra et al. 2011). Potential green water ET from irrigated areas was included in ET_{green}, because the green WF that is compared to this GWa includes green water used by both dry land agriculture and irrigated crops.

6.2.4 Obtaining data on percentage wastage along the supply chain

Measured or estimated data was obtained on wastage of carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*) and lettuce (*Lactuca sativa*) at different stages along the supply chain. For each stage the percentage wastage was determined in terms of the volumes of vegetables delivered to the particular stage. Therefore, the percentages did not represent total wastage along the supply chain, but for that stage only. Total production figures on the Steenkoppies Aquifer in 2005 (**Chapter 6**) was then used to determine total wastage from field to fork. For each stage along the supply chain, wastage was determined by subtracting wastage at all preceding stages from total production and multiplying the remainder with the percentage wasted in the particular stage. This was done for each crop in each of the four seasons.

6.2.4.1 Wastage at the packhouse

At farm level, there are three stages during which crop material can be discarded, namely:

- Discards at planting stage, which represents seedlings that don't grow.
- Discards during growing stages, which represents crops that don't develop into a harvestable product.
- Discards at harvest which represent vegetables that are not marketable.

Discards during planting and growing are not considered wastage, because these plants never develop into an edible product and are also not recorded as production. The seedlings use relatively little water and therefore do not have a significant impact on water resources. Vegetables wasted at harvest represent an edible product, and should therefore be considered as food wastage.

Daily production reports for the year 2015 for a packhouse on one of the farms on the Steenkoppies Aquifer were obtained which indicated the input and output volumes of carrots, cabbage and lettuce (Production Report 2016). The difference between input and output volumes equals the wasted material. Beetroot and broccoli are not currently packed on the Steenkoppies Aquifer, and data on wastage in the packhouse was therefore not available for these two crops. Recording data for these crops in the packhouse are recommended for future research. Wastage of beetroot in the packhouse was assumed to be the same as carrots, because both are subsurface crops and treatment in the packhouse will be similar. Wastage of broccoli in the packhouse was assumed to be the same as cabbage, because the two crops are closely related. Although cabbage and lettuce data was given in terms of crops heads, it was used to calculate a percentage wastage at the packhouse, which was multiplied by total yields measured in weight for the total production in 2005 to provide a total wastage in terms of weight. Therefore, calculations on wastage in the remainder of the supply chain was done in terms of weight.

The question was asked whether data on total weights of crops received by the packhouse might have included non-edible portions of the crops, which would have wrongfully increased total food wastage of crops with a lower harvest index. This potential problem was not relevant to cabbage and lettuce, because the data for the packhouse was reported in terms of crop heads, instead of weight. For carrots, this was also not a problem, because the leaves of the carrots are cut during harvest and left in the fields as mulch.

6.2.4.2 Wastage at the fresh produce market or distribution point

The Tshwane Fresh Produce Market provided data on all crops that were received daily from the Steenkoppies Aquifer as well as those sold and discarded by them from July 2011 to July 2014 (Tshwane Fresh Produce Market 2014). The data was detailed and reflected masses of each vegetable received, sold and discarded for each farm on the Steenkoppies Aquifer specifically. The percentage of each vegetable received from all farms of the Steenkoppies Aquifer that were discarded was calculated per season.

6.2.4.3 Wastage at the retailer level

Quantitative data on wastage at the retail level was not available, because retailers do not normally record food losses. Retailers that do record losses are often unwilling to disclose the data. Theoretically, it can be assumed that the difference between products bought and sold by the retailer will be equal to the wastage. In reality it is more complicated, because although the processing of vegetables reduces the percentage of food losses, it also complicates estimations of food losses. It is not always recorded how much of a particular vegetable, like carrots, are used in each of these pre-packed products and is therefore not possible to record exactly how much of the particular vegetable was sold. Even if wasted products are weighed, there is the challenge that the vegetables that are wasted often have much lower water contents than the fresh products, potentially underestimating the wastage in terms of mass of fresh product that was bought. Estimations of wastage at retail level are based on information obtained during several semi-structured interviews with experienced retailers.

6.2.4.4 Wastage by consumers

Estimating wastage by consumers is outside the scope of this study. Percentage wastage by consumers in South Africa was therefore taken from relevant literature sources.

6.2.5 Estimating the water footprints of wastage of selected vegetables

The volume of blue plus green water lost due to the wastage of the selected vegetables produced on the Steenkoppies Aquifer in 2005 was estimated using the crop water footprints estimated in **Chapter 3**. WFs were also determined for wastage, for each season specifically, at each step of the supply chain by multiplying the total wastage at each step with the crop WFs.

6.3 Results

6.3.1 Crop and catchment level water footprints of irrigated crops

Average estimated blue and green water consumption by agriculture on the Steenkoppies Aquifer for the five periods investigated is given in **Table 6-4.** The catchment scale blue and green WFs for the fourth and fifth periods given in **Table 6-4** indicates that blue water is much higher than green water use, comprising 80% of the blue plus green WF. It highlights the large dependence of agriculture on irrigation water from the aquifer. The dramatic increase in blue plus green WFs of the catchment from the first to the fifth periods reflects the expansion of irrigation activities on the aquifer.

Table 6-4: Total average blue and green water consumed by irrigated agriculture on the Steenkoppies Aquifer for five distinct periods between 1950 and 2012

Period	**Cropped area planted per year (ha)**	**Water used by irrigated crops on the Steenkoppies Aquifer ($Mm^3\ yr^{-1}$)**		
		Blue	Green	Blue + Green
1950 to 1979	268	-	-	2
1980 to 1985	537	-	-	4
1986 to 1995	2 335	-	-	13.5
1996 to 2004	4 183	19.9	4.8	24.6
2005 to 2012	5 349	25.4	6.2	31.5

*** Zero green water footprint assumed**

6.3.2 Catchment water balance

The annual catchment water balance for the Steenkoppies Aquifer from 1950 to 2012, as estimated using WF accounting is illustrated in **Figure 6-6**. During low rainfall years before 1996, annual water losses are similar to precipitation influxes. Average water influx from precipitation exceeds average water losses from the aquifer by 19 Mm^3 and the discrepancy is most pronounced during high rainfall years before 1996, when the water influx apparently exceeded the hydrologic conductivity of the system. During low rainfall years before 1996, water losses are similar to precipitation influxes. The first and second periods (before 1986) represent the natural condition, because abstraction from the aquifer for irrigation was still minimal (estimated at 2 to 4 Mm^3 yr^{-1}). Potential errors in the assumptions made for agricultural WF purposes can therefore not be responsible for the discrepancy between water in- and outflows, although errors in the ET of natural vegetation are one possible reason for the discrepancy between in- and outflows. Estimating ET of natural vegetation is, however, complex and further improvements are required in future research. It is also possible that excess water during high rainfall years recharges the aquifer, but this theory is contradicted by the fact that Maloney's Eye outflow drastically reduced when large-scale irrigation activities started despite the surplus water entering the aquifer during high rainfall years. Annual water losses from the aquifer before 1996 almost never exceed the annual inflow. There is also a possibility that the aquifer boundaries are not completely impervious, as currently understood, and that excess water during high rainfall years can be lost through unknown outlets.

The third period, when commercial agriculture started to expand, is also the time first associated with significant reductions in Maloney's Eye outflows (**Figure 6-1**). During the fourth period considered (1996 to 2004), a few years with exceptionally high rainfall still caused a mismatch between water in- and outflows. However, during the fifth period (2005 to 2012) with relatively high water use for irrigation, coupled with some extremely low rainfall years, the total water losses resemble the inflows much more closely. Water losses are even higher than inflows for three years, 1999, 2004 and 2008.

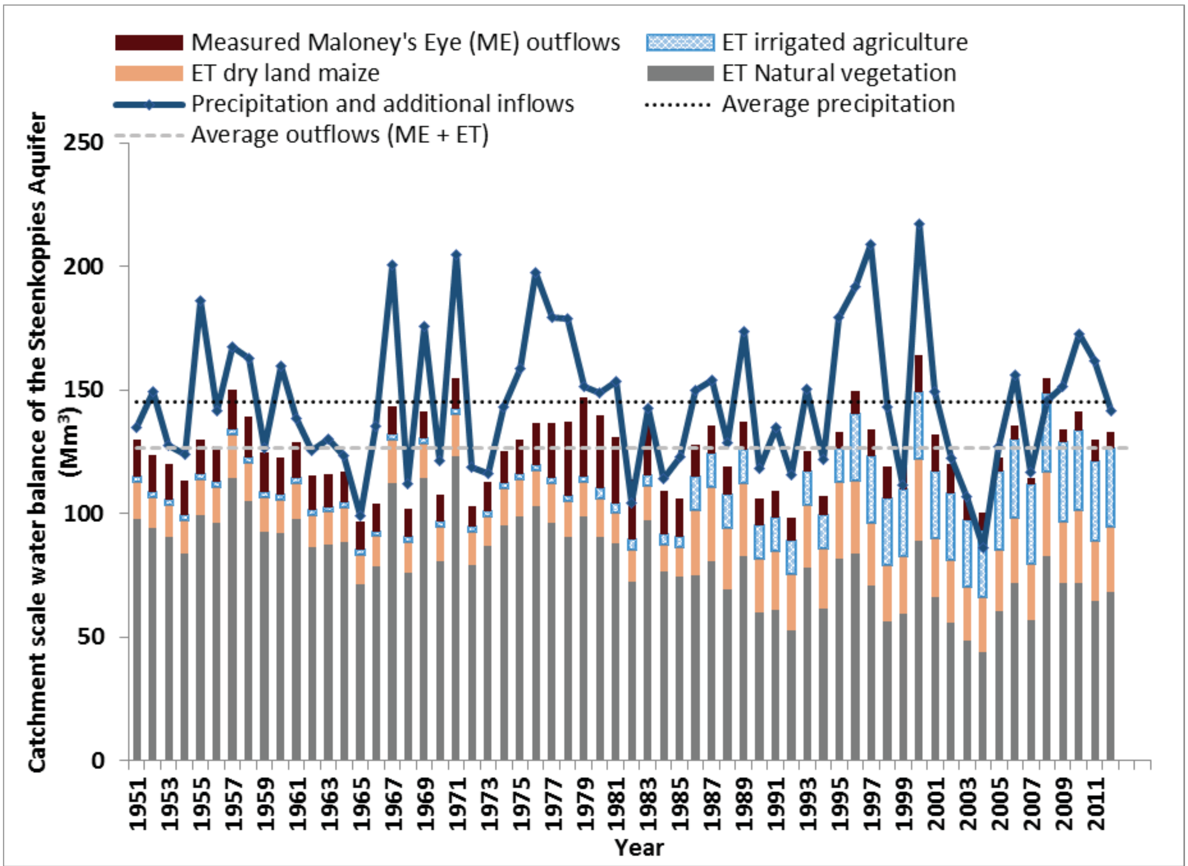


Figure 6-6: Annual catchment water balance estimated using water footprint accounting and measured Malonye's Eye outflows for the Steenkoppies Aquifer. Outflows consist of evapotranspiration of natural vegetation dry land and irrigated agriculture and aquifer discharge from Maloney's Eye (ME)

Estimated annual recharge and estimated outflows (eight year moving average), were compared to measured outflows from Maloney's Eye (**Figure 6-7**). The eight-year moving average of the recharge represents estimated Maloney's Eye outflows. **Figure 6-8** indicates the correlation between measured and estimated outflows. Estimated outflows from Maloney's Eye has good correlation with measured Maloney's Eye outflows (R^2 = 0.75) from 1950 to 1995 (**Figure 6-8**). For the fourth period (1996 to 2004) there was also good correlation between estimated and measured outflows (R^2 = 0.86) but this period followed a different trend from 1950 to 1995, because of reduced flow rates in the Maloney's Eye that occurred at this stage. A poor correlation between estimated and measured outflows (R^2 = 0.07) was found for the fifth period (2005 to 2012). However, although the volume is more closely aligned to actual outflows during the fifth period, it is overestimated for all years (**Figure 6-7**).

Cumulative precipitation versus cumulative outflows from the Steenkoppies Aquifer is given in **Figure 6-9** for each of the five periods from 1950 to 2012. Over time cumulative precipitation gradually exceeds cumulative outflows, due to the inflows in high rainfall years that cannot be accounted for in the catchment water balance. However, cumulative precipitation was closely related to cumulative outflows in Periods 2 and 5, because these were dry periods. The lag in the system is also seen in the Periods 2 and 5 graphs, where water inflows initially exceed outflows after which total estimated outflows catch up within about 1 year.

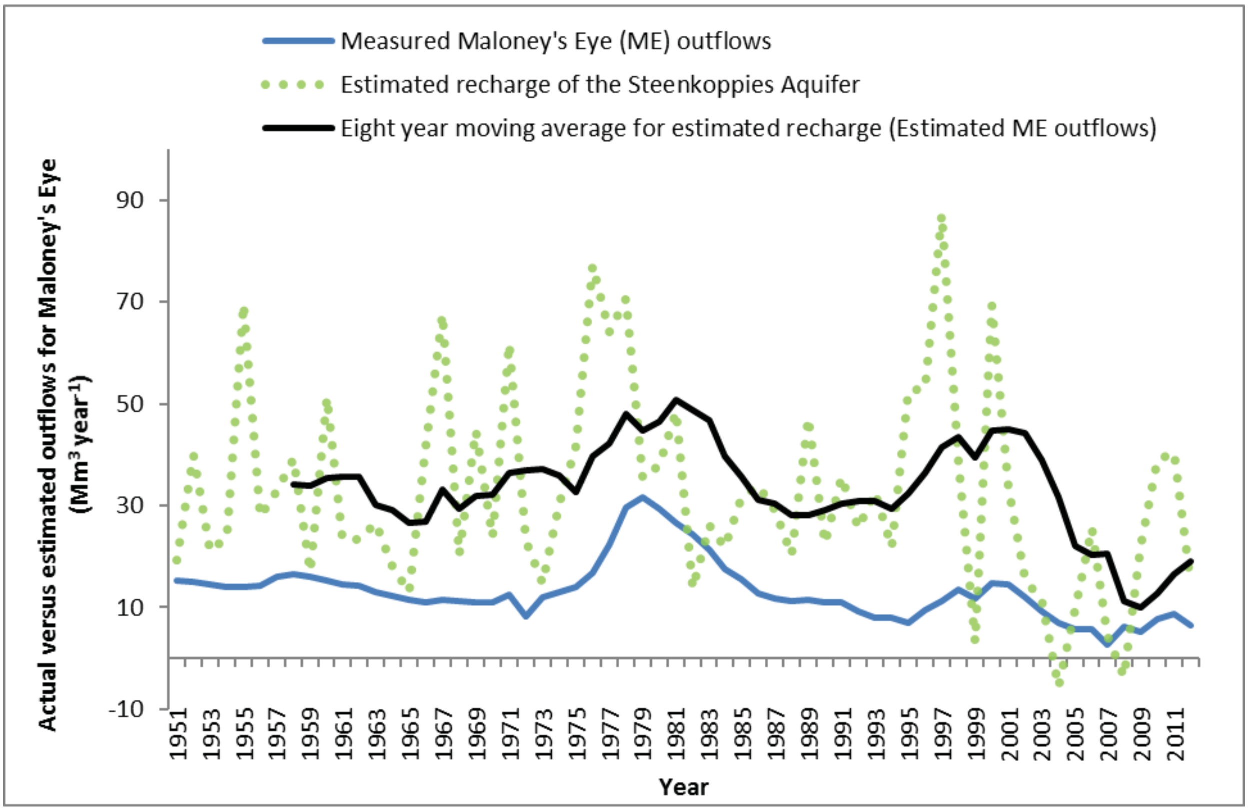


Figure 6-7: Measured outflows from Maloney's Eye (ME) versus recharge of the aquifer estimated using water footprint accounting and estimated Maloney's Eye outflows represented by the eight-year moving average of estimated recharge

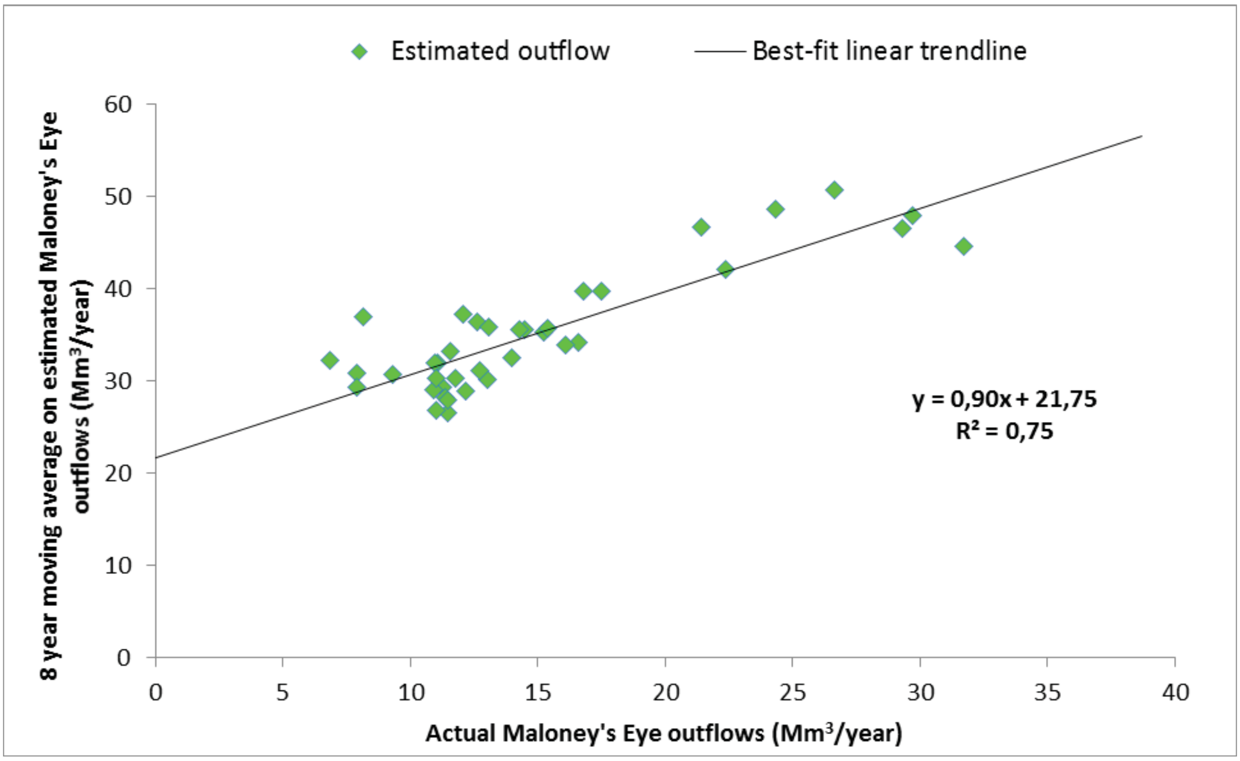
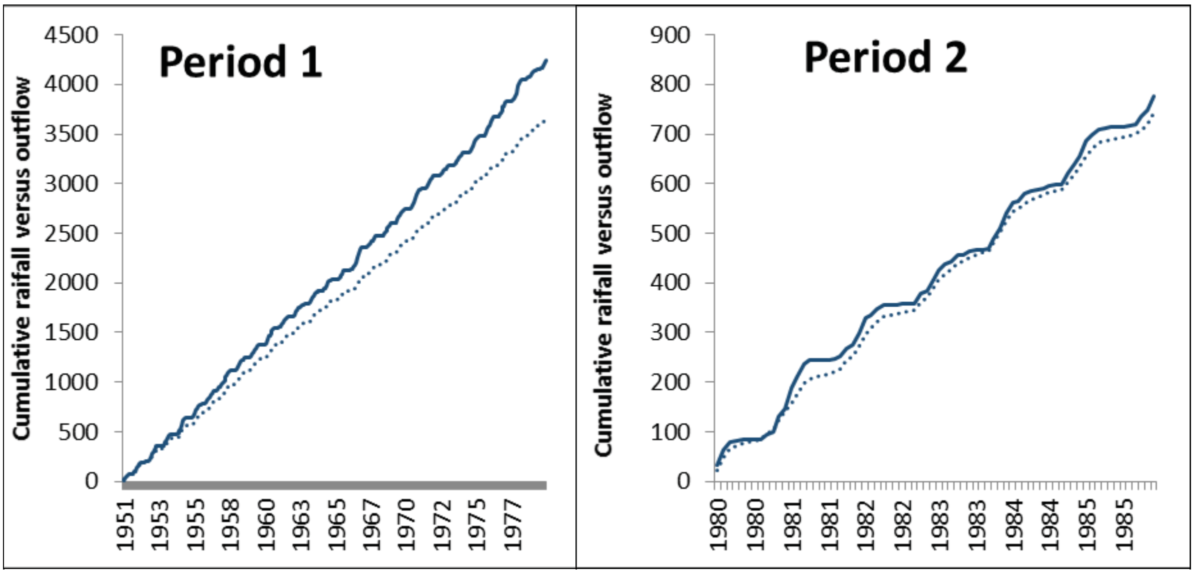


Figure 6-8: Correlation between measured and estimated Maloney's Eye outflows from 1950 to 1995



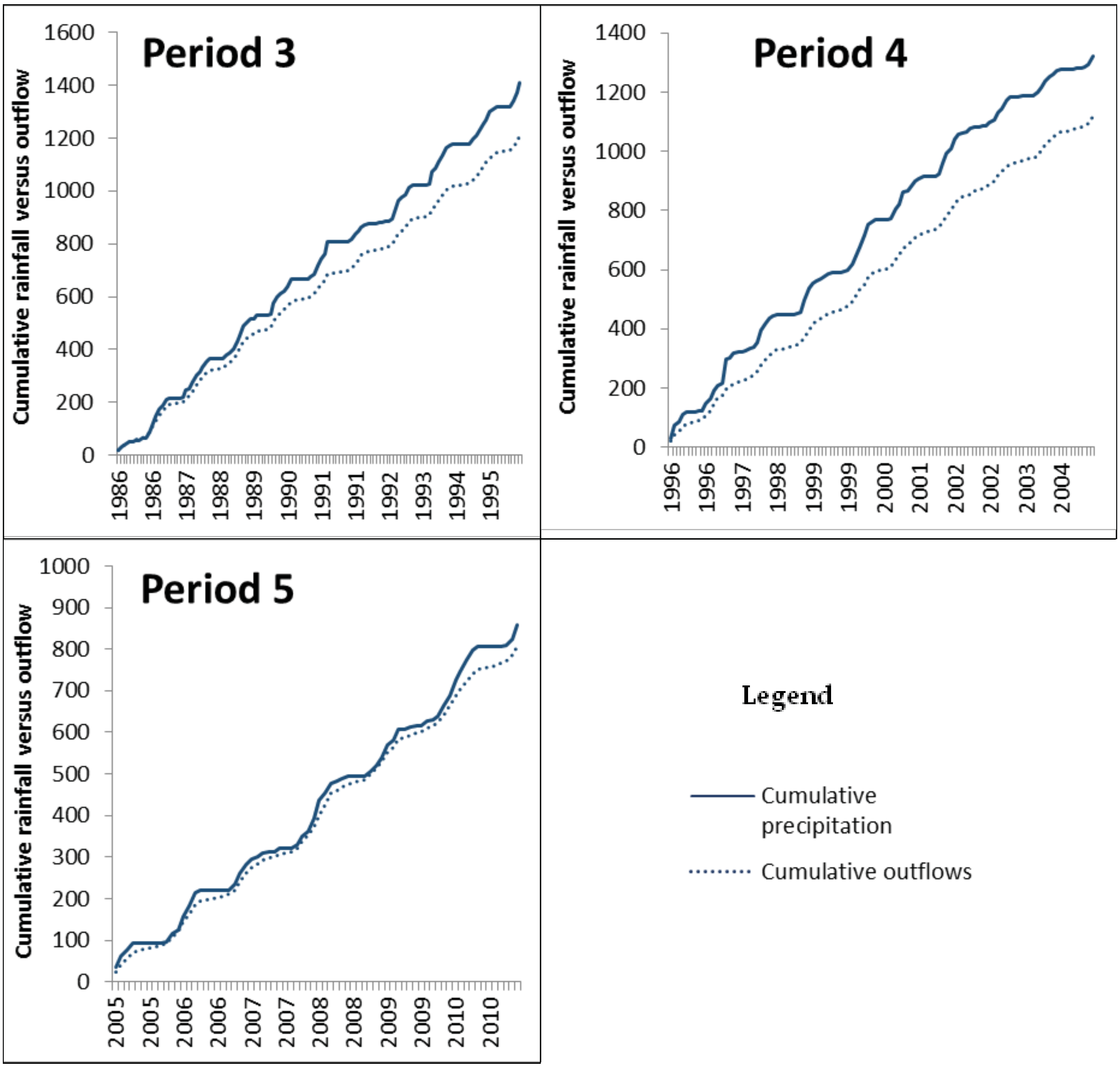


Figure 6-9: Cumulative precipitation versus cumulative estimated outflows on the Steenkoppies Aquifer for the five periods from 1950 - 2012

6.3.3 Sustainability assessment

The annual catchment scale blue WF of irrigated agriculture on the Steenkoppies Aquifer was compared to the annual BWa in **Figure 6-10**. Although available blue water was not fully utilised during the first and second period (1950 to 1985), irrigated agriculture became unsustainable during the third period (1986 to 1995) (**Figure 6-10**). The discrepancy between BWa and consumption reached critical levels during the fifth period (2005 to 2012), due to further intensification of irrigated agriculture. Agricultural blue water use on the aquifer also exceeds Maloney's Eye outflows after 1986. This additional blue water is either sourced from groundwater stored in past years in the aquifer, or could also be explained by possible water movements across the boundary of the aquifer, where outflows from unknown outlets are reduced or possibly through water moving into the aquifer. Reductions in borehole levels taken at 26.04'37.6S; 27.34'35.1E, confirm the results of this sustainability assessment that water from the aquifer is being used faster than it is recharged (**Figure 6-11**). Borehole levels decline from the average after the year 2005, roughly coinciding with Periods 5 when abstractions for irrigation reached peak levels. The decline in borehole levels cannot be motivated by reduced rainfall, because despite dry years, the average annual rainfall during Period 5 (654 mm) was similar to the long term annual average since 1950 (671 mm)., confirm the results of this sustainability assessment that blue water from the aquifer is being over-utilised.

Figure 6-12 shows the catchment scale green water used versus GWa. Green water consumed by agriculture is less than available and there is still capacity left to increase dry land agriculture within sustainable limits. Current agricultural green water use per hectare is relatively similar to the ET of natural vegetation, which defines GWa. Therefore, the additional GWa results from areas under natural vegetation on the aquifer that can still be developed, if the conservation target of 24% is assumed (**Section 6.2.3**). For the blue and green WF calculations in **Chapter 3** optimal irrigation scheduling under pivot irrigation systems was assumed, as the crop was only irrigated when a specific soil water depletion threshold was reached. Thus, irrigation scheduling cannot be improved to use green water more efficiently. However, green water use can potentially be further optimised through more efficient irrigation systems, such as drip irrigation or through water conservation techniques such as rainwater harvesting or mulching. As opposed to increasing dryland agriculture, such measures to increase green WF use will also reduce the blue WF, which is highly encouraged considering the current unsustainable blue water use.

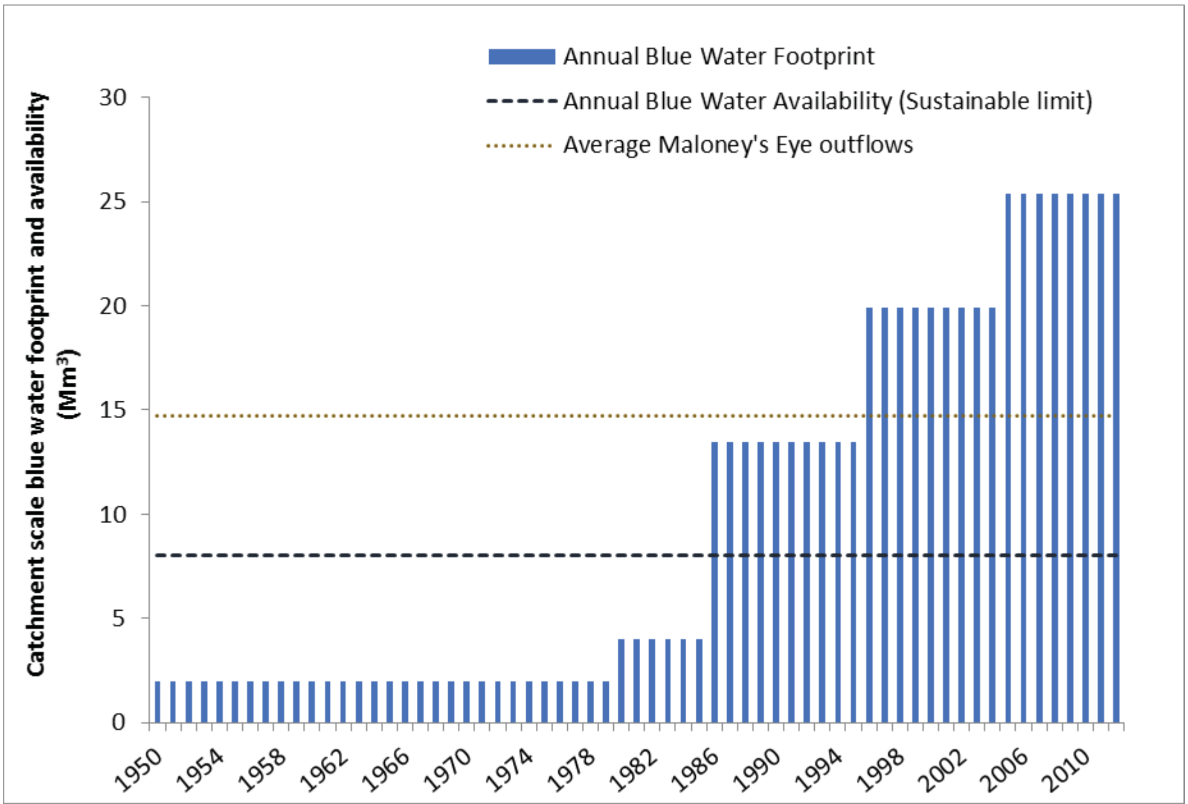


Figure 6-10: Catchment scale blue water use of the Steenkoppies Aquifer versus the availability of blue water in the aquifer.

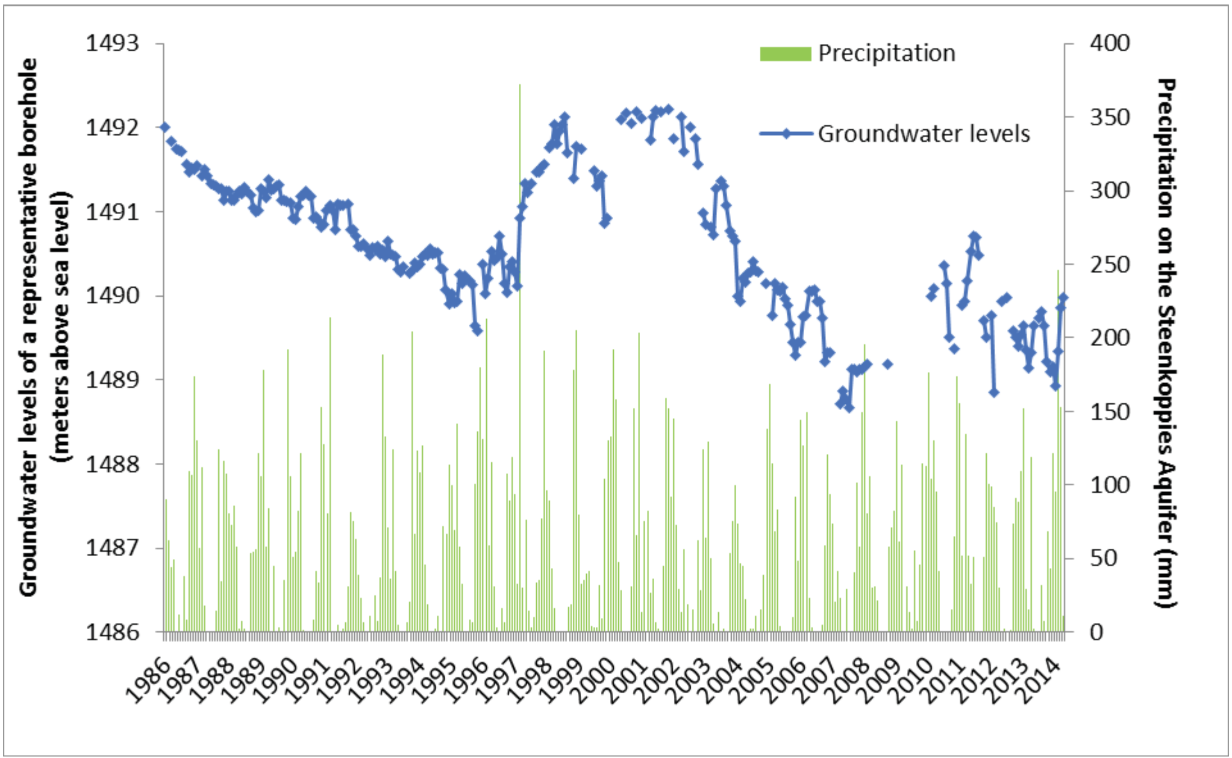


Figure 6-11: Representative borehole levels which demonstrate reductions in groundwater level potentially due to abstractions for irrigation.

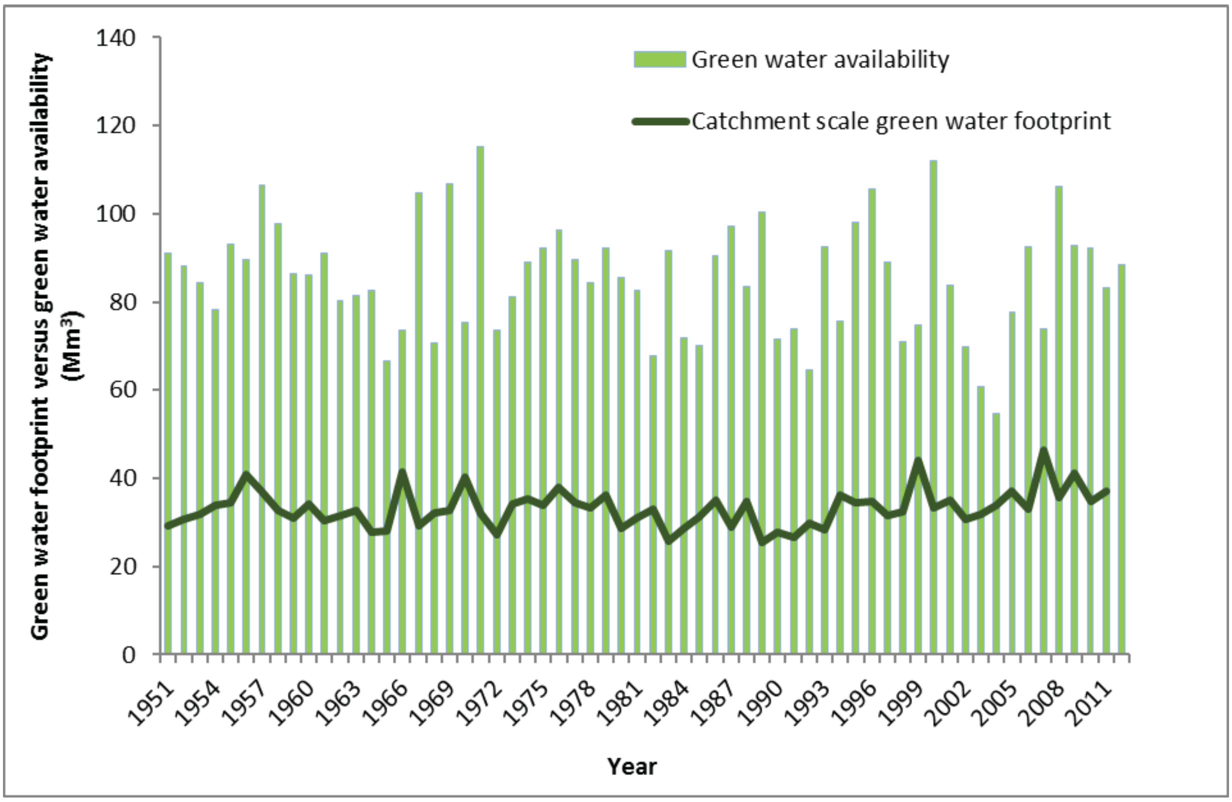


Figure 6-12: Catchment scale green water use of agriculture of the Steenkoppies Aquifer versus green water availability for the catchment.

6.3.4 Data on percentage wastage along the supply chain

Vegetables produced on the Steenkoppies Aquifer are wasted at each step along the supply chain (**Figure 6-13**). At farm level, wastage is mostly due to pests and diseases or because crops have unmarketable properties. The farm that was assessed was the sole provider for a large supermarket group and there have not been any cases reported where vegetables were wasted because of low demands or flooded markets. Wastage at the retailers mostly occurs when vegetables reach the end of their sell-by date or shelf-life. Offcuts, such as those shown in **Figure 6-13 C** are not counted as wastage, because they are not considered fit for human consumption and are not included in total production figures. Considering that these offcuts are fit for livestock consumption complicates the calculations, because it can be considered to reduce the WFs of the crops and if it is not used for another beneficial purpose it could increase the wastage.

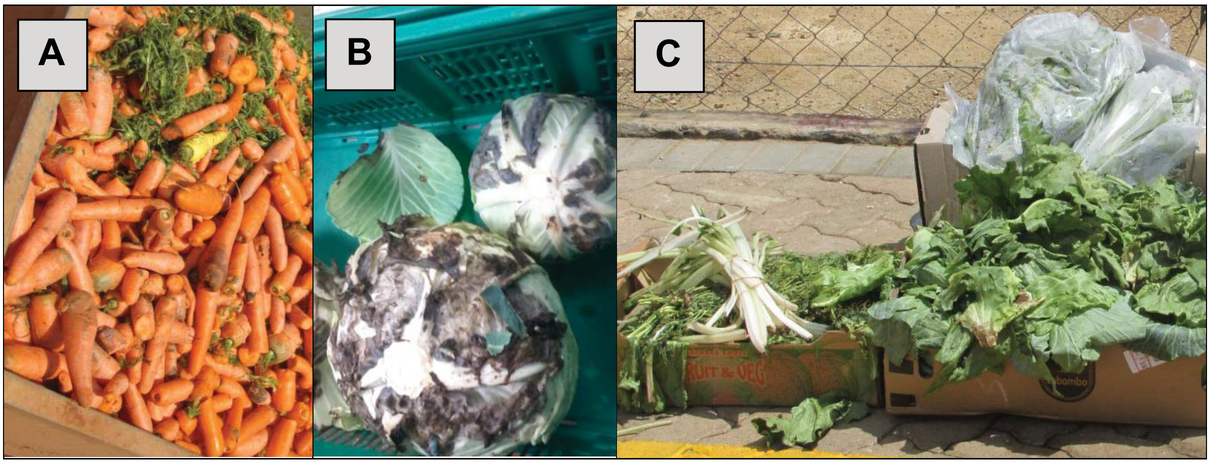


Figure 6-13: Vegetables produced on the Steenkoppies Aquifer that are wasted along the supply chain. A and B, respectively, shows carrots and cabbage wasted at the farm level; C represents vegetable offcuts including the outer leaves of cabbage that have been cut and removed at a green grocer. Offcuts are not counted as wastage, because they are not considered fit for human consumption.

6.3.4.1 Wastage at the farm level

Percentages of carrots, cabbage and lettuce wasted at the packhouse level in each season are given in **Figure 6-14**. Compared to carrots and lettuce, percentage wastage of cabbage in the packhouse is very low. Wastage during this stage is not closely correlated with seasons, because the wastage is not so much due to rotting during this first stage, but due to unmarketable traits.

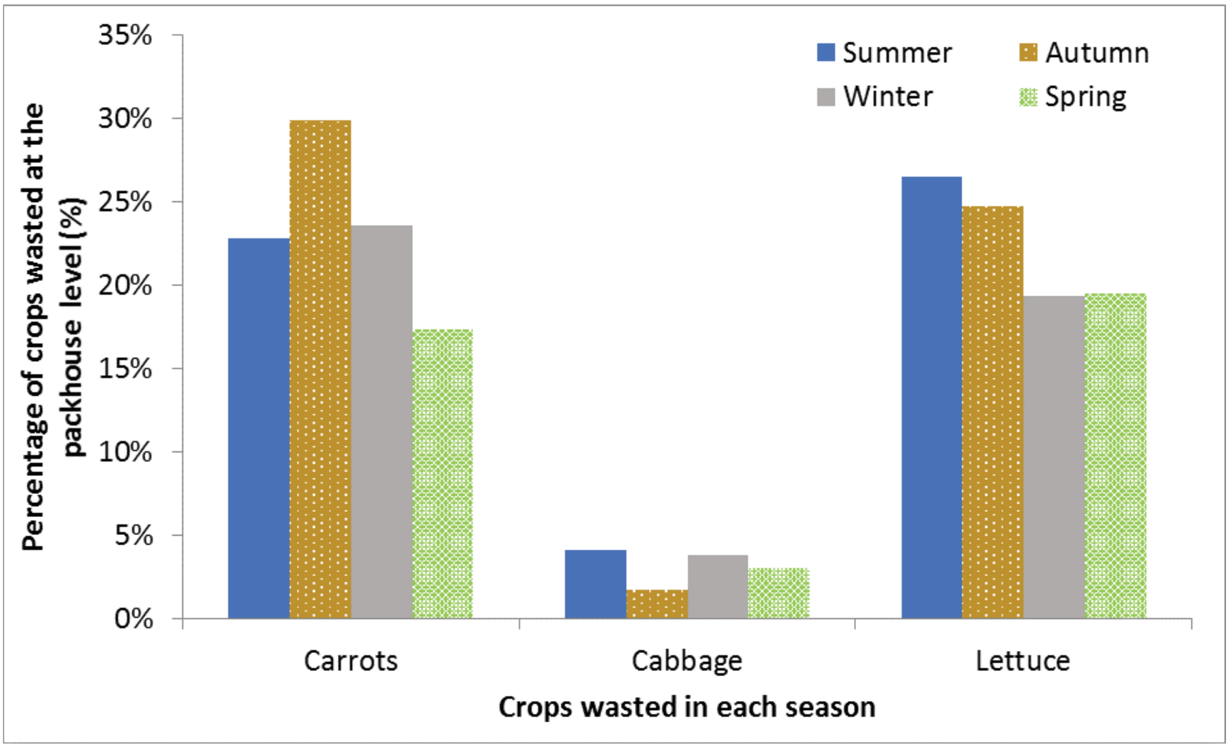


Figure 6-14: Wastage of carrots, cabbage and lettuce in each season in 2015 in a packhouse on the Steenkoppies Aquifer

The carrot production report is in kilograms of the harvest index, while cabbage and lettuce are reported in 'heads'. Carrots that are not marketable or sold include broken pieces that are too short to be marketed in a low value pack as well as grossly mis-formed, cracked, extremely thick or thin carrots. In the case of cabbage and lettuce, most waste heads are edible except those with serious insect infestation and those that are rotten or decayed. Cabbage heads that are not marketable include those that have decay, worm damage, black rings, discolouration, dehydration, *Anthropoda* infestation and those with incorrect head sizes. Lettuce heads that are not marketable include those that have browning, decay, worms, sun scorch, deep cuts, incorrect sizes, malformation and bruising. The trimmed leaves and non-marketable vegetables are fed to the cattle on the farm.

The packhouse WF calculations that were done in **Chapter 3** used produce delivered to the packhouse as the functional unit. However, in some cases the produce cleaned and packed for the market were much lower than the production inputs. If the packhouse blue WFs are multiplied by the difference between inputs and outputs (wastage at the packhouse level) the blue water used daily to pack wasted carrots, cabbage and lettuce is 11 m^3, 0.3 m^3 and 3 m^3, respectively. This amounts to 5338 m^3 per year. This volume of water could, however, be misleading if crops that are wasted are sorted early in the packhouse production line before any blue water is used.

6.3.4.2 Wastage at the market / distribution point

Figure 6-15 gives the percentage discard in terms of what the market received from the Steenkoppies Aquifer for each crop in each season. At this stage of the supply chain wastage is due to rotting of the crops, which is why waste percentages are higher in summer and higher for more perishable crops, like lettuce. Wastage of beetroot is particularly low for all seasons, except for summer. Wasted products at the market are used to make compost in a digester on site, which is a more recent development that was launched in 2014.

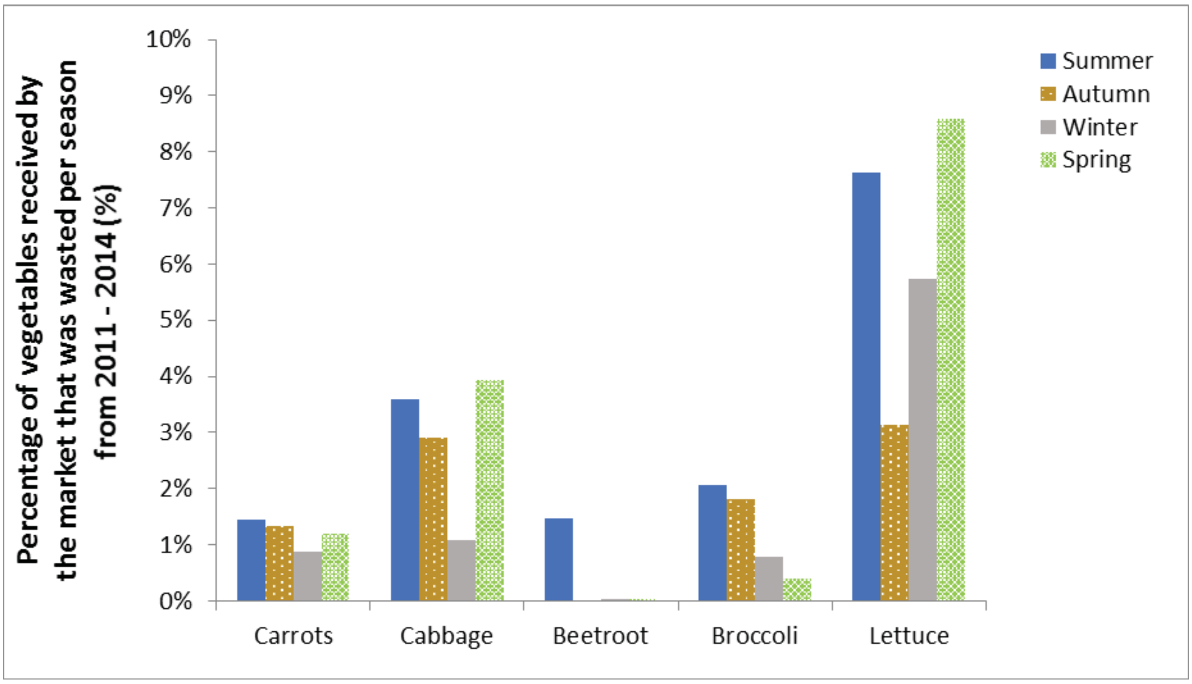


Figure 6-15: Percentage of crops received by the Tshwane Market from 2011 – 2014 that was discarded

6.3.4.3 Wastage at retailers

Weather conditions impact on food wastage at the retailer level, but management decisions also play an important role in terms of percentage food losses. Retailers that order too many vegetables once or twice a week generally have more losses than retailers that order less vegetables more often, or even daily. Most green grocers cut and combine vegetables that approach the end of their shelf life into pre-packed products for salads, soups or stir-fry vegetables. In supermarkets ageing vegetables are used to make salads and sandwiches in the supermarket delis. This greatly reduces food losses at the retail level, but in the case of lettuce, for example, there is a limit to how much salad can be sold in a deli and wastage cannot be completely avoided. Wastage from the retailer is often given to soup kitchens, or livestock farms or used for composting.

Carrots, cabbage, beetroot and broccoli have a relatively long shelf-life and wastage is generally low. According to experienced retailers (dos Santos 2014, Gathino 2016, Mentis 2016), wastage of these vegetable at retail level is between 1% and 5%. It was therefore assumed that wastage of these vegetables at the retailer is 5% in summer, 3% in autumn and spring and 1% in winter. Lettuce is more perishable and according to experienced retailers average wastage of lettuce at retail level is between 7% and 10%. It was therefore assumed that wastage of lettuce at the retailer is 10% in summer, 9% in autumn and spring and 7% in winter.

6.3.4.4 Wastage by consumers

According to Gustavsson et al. (2011), as cited by Oelofse and Nahman (2013), wastage of roots and tubers in South African households is 2% and wastage of fruit and vegetables in South African households is 5%. Thus, the wastage of carrots and beetroot was assumed to be 2% and wastage of cabbage, broccoli and lettuce was assumed to be 5% at the household level. Data was not available on total food wastage per household in South Africa, but according to Nahman et al. (2012) most wastage in South Africa occurs in low income communities (**Figure 6-16**). This is, however, because of the number of low income households in South Africa, which is much more compared to high income houses and does not reflect higher wastage per household in low income communities.

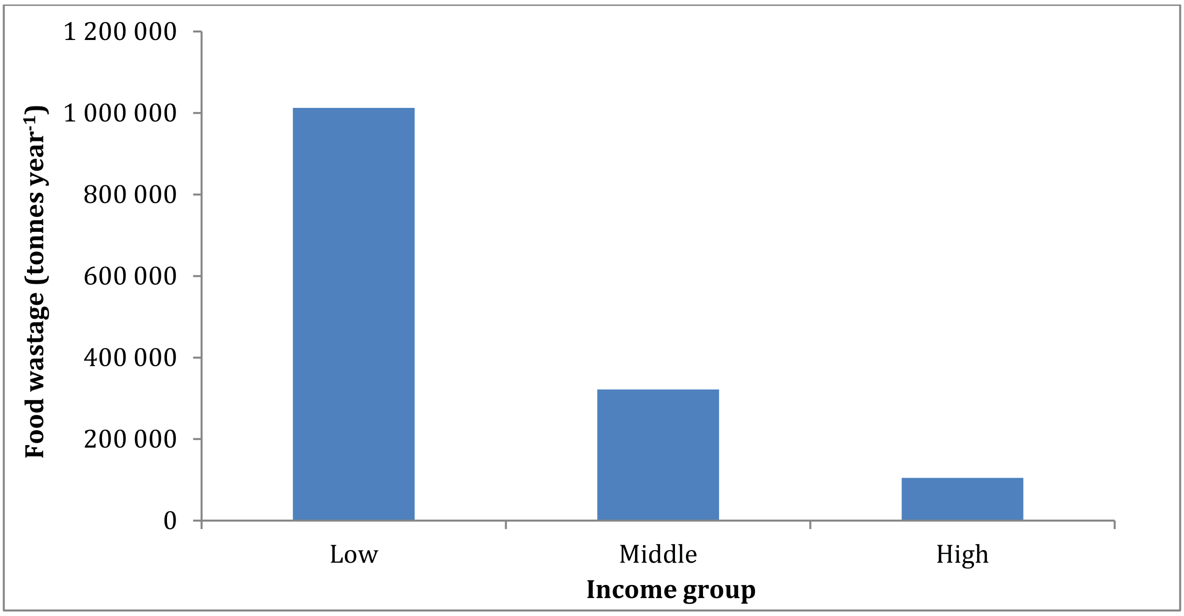


Figure 6-16: Total food wastage generated by different income groups in South Africa (Nahman et al. 2012)

6.3.4.5 Total wastage of vegetables from the Steenkoppies Aquifer along the supply chain to the consumer

Table 6-5 summarises wastage at each stage of the supply chain to the consumer in terms of annual production of each vegetable on the Steenkoppies Aquifer in 2005. Wastage of cabbage and broccoli is relatively low, because of low percentage wastage in the packhouse and the general longer shelf lives of these crops. Lettuce has the highest percentage wastage for all seasons, because of high percentage wastage in the packhouse and the short shelf life of the crop. As indicated in **Table 6-5**, an estimated 29% of the annual production of carrots and beetroot (root vegetables) and 32% of the annual production of cabbage, broccoli and lettuce is lost due to wastage. This is much lower than indicated by Oelofse and Nahman (2013), who estimate annual wastage of 44% of roots and tubers and 51.5% of other vegetables in terms of average annual food production. The percentage wastage estimated by Oelofse and Nahman (2013) was based on percentage wastage given by Gustavsson et al. (2011) for sub-Saharan Africa. The percentage contribution to total wastage (including all five vegetables) by each step along the supply chain, as calculated in this study, is given in **Figure 6-17,** and compared to the findings of food wastage along the supply chain in South Africa as published by Oelofse and Nahman (2013) and given in **Figure 6-18**. Oelofse and Nahman (2013) estimated that 79 % of total wastage occurs before distribution during agricultural production, post-harvest handling and storage, and processing and packaging. Our packhouse level data includes all three of these losses combined. The average percentages wastage in the packhouse on the Steenkoppies Aquifer were 70% of total food wastage along the supply chain, which correlates well with estimates from Oelofse and Nahman (2013). Oelofse and Nahman (2013) also reported wastage during distribution, which included our market and retail stages. Our percentages wastage for the market and retail stages was 9% and 12% in terms of total wastage along the supply chain, respectively, the sum which correlated well with the 17% wastage during distribution as reported by Oelofse and Nahman (2013). We estimate 8% wastage at the household level in terms of total wastage, compared to 4% estimated by Oelofse and Nahman (2013).

There is, however, variation in average annual wastage between different crops, which varied from 13% for broccoli to 38% for lettuce, as illustrated in **Figure 6-19**.

Table 6-5: Summary of wastage of carrots, cabbage, beetroot, broccoli and lettuce along the supply chain from the farm to the consumer in terms of total production on the Steenkoppies Aquifer in 2005

Crop	Season	Total production for 2005 (tonnes)	Percentage wastage in terms of mass received by each stage (%)				Total wastage at each stage (tonnes)					Total percentage wastage (%)
			Farm	Market	Retail	Consumer	Farm	Market	Retail	Consumer	Total	
Carrots	Summer	13487	23%	1%	5%	2%	3076	150	513	195	3934	29%
	Autumn	8455	30%	1%	3%	2%	2527	79	175	114	2895	34%
	Winter	9194	24%	1%	1%	2%	2167	62	70	138	2437	27%
	Spring	3222	17%	1%	3%	2%	558	32	79	51	720	22%
Beetroot	Summer	3094	23%	2%	5%	2%	706	35	118	45	903	29%
	Autumn	4769	30%	0%	3%	2%	1425,	0	100	65	1591	33%
	Winter	4218	24%	0,02%	1%	2%	994	1	32	64	1091	26%
	Spring	2586	17%	0,01%	3%	2%	448	0	64	42	553	21%
Subtotal 1 *		**49023**					**11901**	**359**	**1151**	**712**	**14124**	**29%**
Cabbage	Summer	3700	3%	4%	5%	5%	125	128	172	164	589	16%
	Autumn	1369	2%	3%	3%	5%	22	39	39	63	164	12%
	Winter	2705	4%	1%	1%	5%	100	28	26	128	281	10%
	Spring	2373	3%	4%	3%	5%	81	90	66	107	344	15%
Broccoli	Summer	1016	3%	2%	5%	5%	34	20	48	46	148	15%
	Autumn	62	2%	2%	3%	5%	1	1	2	3	7	11%
	Winter	482	4%	1%	1%	5%	18	4	5	23	49	10%
	Spring	672	3%	0%	3%	5%	23	3	19	31	76	11%
Lettuce	Summer	15855	27%	8%	10%	5%	4205	889	1076	484	6654	42%
	Autumn	2965	25%	3%	9%	5%	732	70	195	98	1095	37%
	Winter	9918	19%	6%	7%	5%	1918	459	528	351	3255	33%
	Spring	6858	19%	9%	9%	5%	1337	474	454	230	2495	36%
Subtotal 2 **		**47977**					**8597**	**2205**	**2630**	**1727**	**15159**	**32%**

***Subtotal 1 for carrots and beetroot (root vegetables), ** Subtotal 2 for cabbage, broccoli and lettuce**

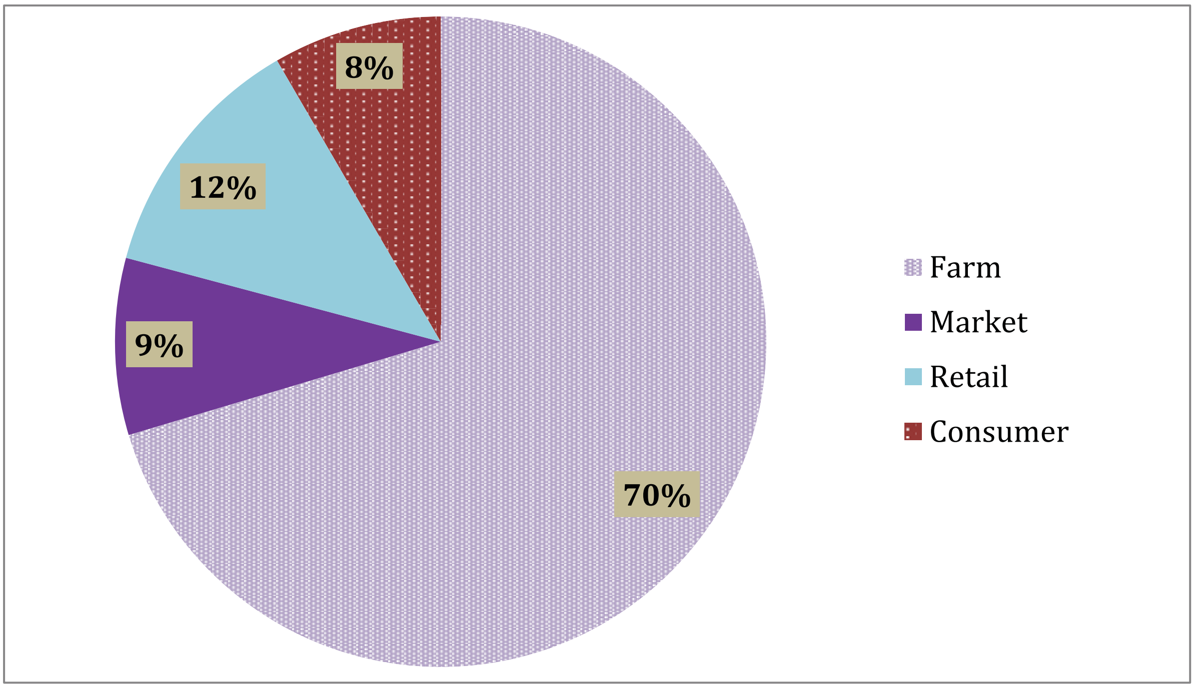


Figure 6-17: Average percentages of total annual wastage of carrots, cabbage, beetroot, broccoli and lettuce produced on the Steenkoppies Aquifer at different stages along the supply chain from 'field to fork'

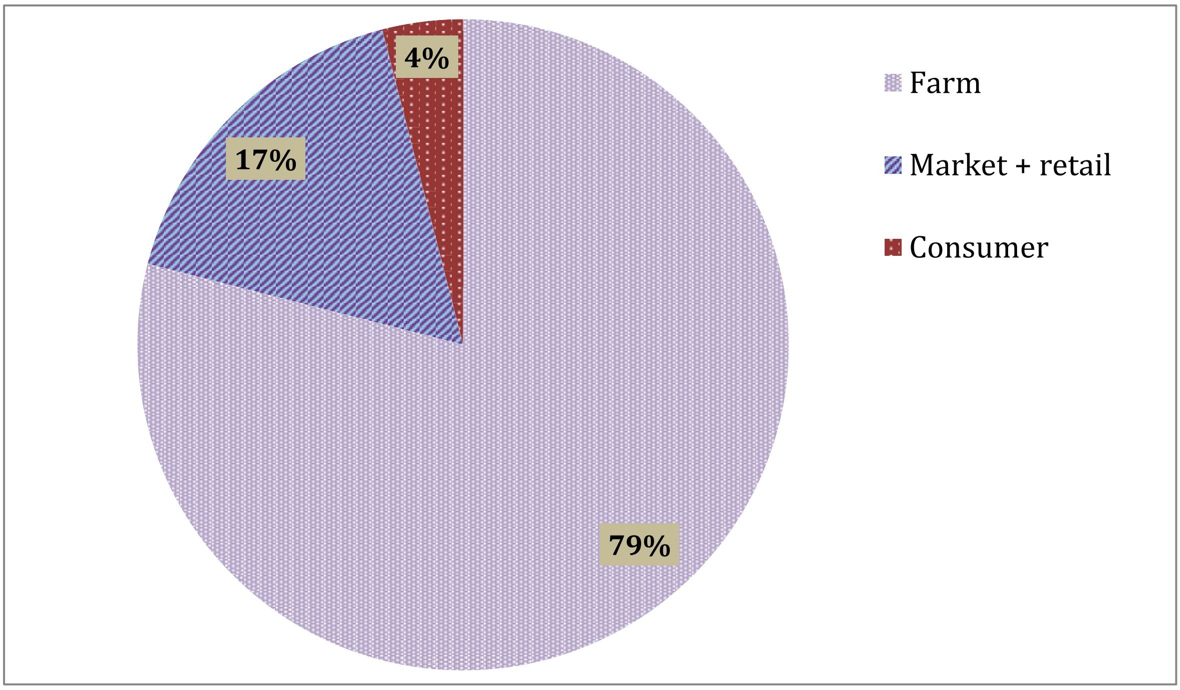


Figure 6-18: Wastage of food along the supply chain in South Africa as estimated by Oelofse and Nahman (2013)

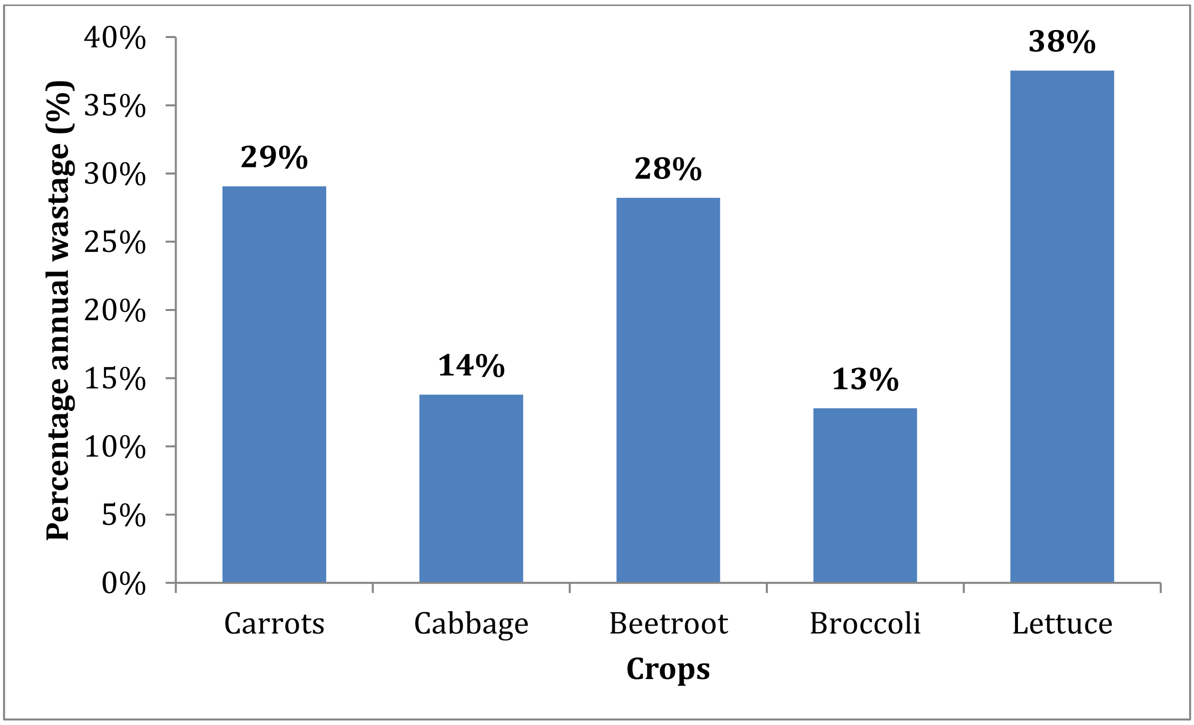


Figure 6-19: Percentage annual wastage form 'field to fork' of the five selected vegetable crops in terms of total production on the Steenkoppies Aquifer in 2005

6.3.4.6 Water footprint of wastage of selected vegetables

The blue plus green WFs of seasonal discards along the supply chain to the consumer of the selected vegetable crops produced on the Steenkoppies Aquifer in 2005, are given in **Table 6-6** and **Figure 6-20.** In 2005, an estimated 2.4 Mm^3 blue plus green water was lost due this wastage of the selected vegetable crops, of which 1.9 Mm^3 was blue water. Most of the wastage occurred in the packhouse, and due to wastage of lettuce along the whole supply chain.

Table 6-6: Blue plus green water lost due to wastage of vegetables produced on the Steenkoppies Aquifer in 2005

Crop	Season	Blue plus green water lost due to wastage (Mm^3)				Total
		Farm	Market	Retail	Consumer	
Carrots	Summer	0.188	0.009	0.031	0.012	**0.24**
	Autumn	0.294	0.009	0.020	0.013	**0.34**
	Winter	0.206	0.006	0.007	0.013	**0.23**
	Spring	0.035	0.002	0.005	0.003	**0.04**
Cabbage	Summer	0.008	0.009	0.011	0.011	**0.04**
	Autumn	0.001	0.003	0.003	0.004	**0.01**
	Winter	0.008	0.002	0.002	0.010	**0.02**
	Spring	0.006	0.007	0.005	0.008	**0.03**
Beetroot	Summer	0.070	0.003	0.012	0.004	**0.09**
	Autumn	0.144	0.000	0.010	0.007	**0.16**
	Winter	0.123	0.000	0.004	0.008	**0.13**
	Spring	0.053	0.000	0.008	0.005	**0.07**
Broccoli	Summer	0.009	0.005	0.013	0.012	**0.04**
	Autumn	0.000	0.000	0.001	0.001	**0.00**
	Winter	0.006	0.001	0.002	0.007	**0.02**
	Spring	0.005	0.001	0.004	0.007	**0.02**
Lettuce	Summer	0.234	0.049	0.060	0.027	**0.37**
	Autumn	0.052	0.005	0.014	0.007	**0.08**
	Winter	0.179	0.043	0.049	0.033	**0.30**
	Spring	0.083	0.029	0.028	0.014	**0.15**
Total		**1.71**	**0.18**	**0.29**	**0.21**	**2.38**

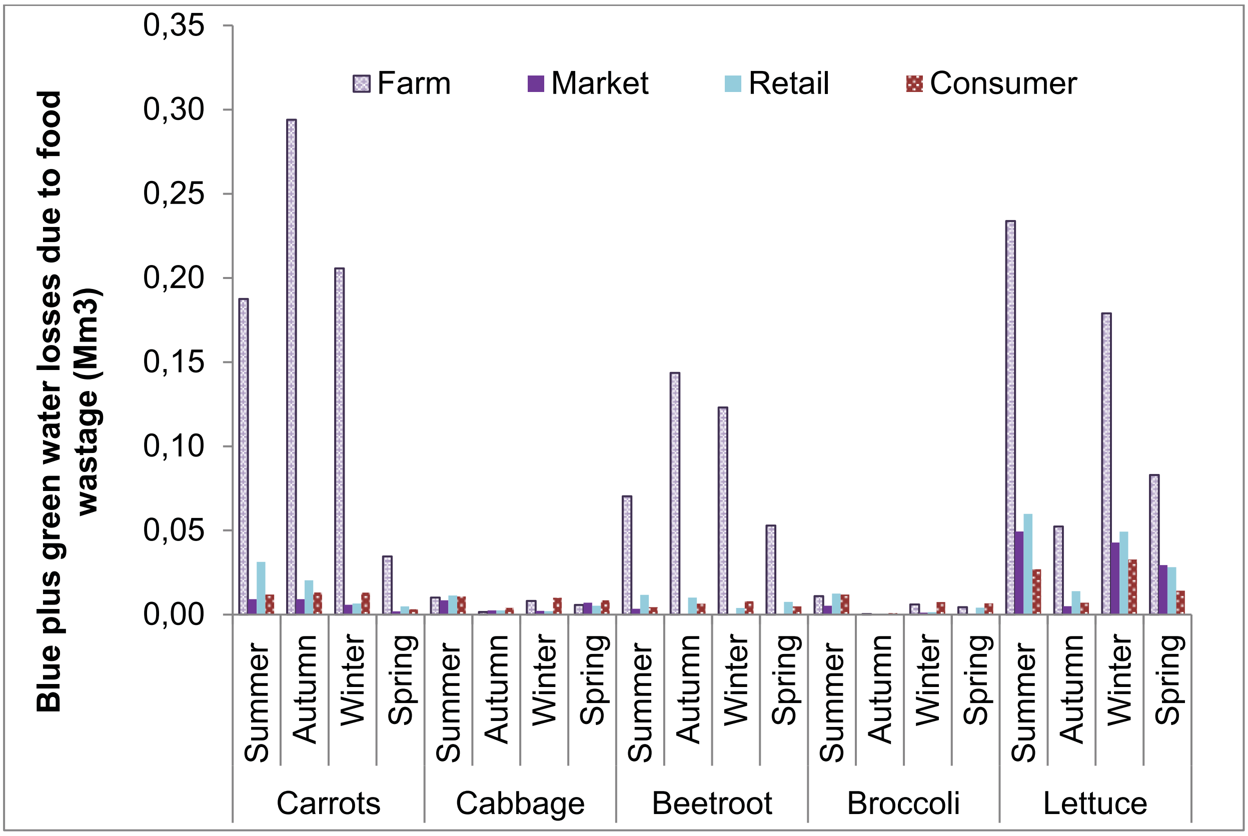


Figure 6-20: Water footprint of vegetables produced on the Steenkoppies Aquifer in 2005 that was wasted along the supply chain from the farm to the consumer

6.4 Discussion

In this study, agricultural water consumption was calculated for the catchment of the Steenkoppies Aquifer using water footprinting in a framework that we call the catchment WF framework. The catchment WF framework multiplied WFs calculated according to Hoekstra et al. (2011) with total yields to estimate agricultural water use on a catchment scale, which were then used with other water flows to determine a catchment water balance. A similar study was conducted for the High Plains Aquifer (HPA) (Multsch et al. 2016), where total yields were also linked to WFs to determine water used on the aquifer. The main difference between the catchment WF framework proposed here and the HPA study is scale. The HPA study was done on a smaller scale evaluating water use in different areas above the aquifer according to local impacts on groundwater levels. The strength of the HPA study was to highlight specific areas of concern within the aquifer, which is useful information for a water resources manager. The catchment WF framework proposed here evaluated the catchment and compared it to impacts on outflows and its strength is that it improved the understanding of the geohydrology and sustainability of current water use on the Steenkoppies Aquifer. In the past, total ET of the Maloney's Eye Catchment has not been quantified in hydrological studies on the Steenkoppies Aquifer, and this information can now be used to improve hydrological models. Using WFs to determine the water balance of the catchment can, however, also be considered part of a process towards developing a simplified and more cost-effective approach to understanding water dynamics of aquifers in general, in contrast to complex and expensive hydrological assessments.

As illustrated by the catchment water balance (**Figure 6-6**), water flowing into the Steenkoppies Aquifer exceeds water losses, the reason for this being a key question that arises from this study. Since there is also no runoff from the catchment apart from Maloney's Eye, there are currently four plausible explanations for this:

- Errors in the assumptions made to calculate the catchment scale water use, particularly in estimating ET of natural vegetation. Estimating ET of natural vegetation is complex and further improvements are required in future research.
- Errors in estimating rainfall inflows due to spatial variability.
- Errors introduced via Steenkoppies Aquifer and Maloney's Eye Catchment spatial overlap assumptions.
- Poor understanding of soil and aquifer storage and conductivity dynamics.
- Other losses occurring from the aquifer boundaries that are currently not known. Although Maloney's Eye is currently considered to be the only natural outlet, a geo-hydrologist studying the Steenkoppies Aquifer recently had similar findings with hydrological models, and is investigating possible movement of water across the north-western boundary of the aquifer (Holland 2016).

Although the WF approach currently overestimates Maloney's Eye outflows, there was a good correlation between estimated and measured outflows, and water outflows are very similar to precipitation inflows during years with low rainfall and / or high agricultural water use. These results affirm that the approach can potentially be developed into a useful and simplified tool to estimate outflows from an aquifer and better manage water resources, including through crop constitution decisions.

Agricultural blue and green WFs on a catchment scale can also be compared to water availability in a sustainability assessment, which is more informative than a volumetric crop WF in terms of crop yield. The blue water sustainability assessment for the Steenkoppies Aquifer indicated that irrigated agriculture became unsustainable after 1986, which is in line with measured reductions in the outflows from Maloney's Eye as well as reductions in groundwater levels during this time.

This catchment WF framework can potentially be applied to catchments in general to estimate volumes of water used by various water users in a catchment, some of which are difficult to measure, such as ET of crops and natural vegetation. Quantifying these water uses can provide useful near real time data to a catchment water resource manager to assess sustainability and improve decision-making. For example, the data can improve water allocation decisions, it can be used to set sustainable water use limits, and to assess the water productivity of different crops.

The catchment WF framework requires relatively little information for an agriculture-dominated catchment, including rainfall data, the total yield of different crops cultivated and their respective WFs, and the WF of natural vegetation. By using WFs calculated according to the WFN methodology the approach automatically accounts for deep drainage of any excess irrigation water that is applied (by assuming that blue WF is the minimum between irrigation applied and crop ET), alleviating the need to measure or estimate abstractions or percolation back into the aquifer. This should not create the impression that over-irrigation does not need to be addressed, because it can result in water logging, soil salinization, groundwater pollution, leaching of nutrients, and impacts on the soil such as acidification (Mostafa 1977, Postel 1999, Zilberman et al. 1997). The WFN methodology, however, does provide a way of reflecting over-irrigation as reduced or even zero green WF. It is therefore important to maximize green WFs together when using the catchment WF framework, in order to ensure that irrigation is conducted in a sustainable manner.

A key issue in the calculation of the BW_a for aquifers in general will be to determine the natural runoff. In most catchments natural runoff (which becomes blue water) is not known, either because of poor monitoring, complex systems with many outflows, or because of uncertainty regarding the impact of existing land use on natural flows. A number of additional components can be included in the calculation of BWa. Water allocated to downstream users should be subtracted from the natural runoff, for example, in this case from the Maloney's Eye outflows to calculate the volume of water that is available to irrigators on the Steenkoppies Aquifer. If ET of the natural vegetation is higher than ET of a dryland crop, there will be more water recharging the aquifer under the latter land use, which would increase BWa. And if natural vegetation is replaced by urban areas with lower ET, and the stormwater is directed through artificial recharge to the aquifer, this will also increase BWa. For our case study the green water sustainability assessment indicated that there is GWa currently not utilised. This GWa may present an opportunity either to expand dry land cropping based on a natural vegetation conservation target of 24%, or to improve irrigation efficiency to utilise more green water under irrigated agriculture, thus alleviating pressure on blue water.

According to Gleeson et al. (2012), long term multigenerational (50 to 100 years) sustainability targets in terms of water quality and quantity must be set for the management of groundwater resources. Policies must then be developed through backcasting, which as opposed to forecasting, starts with a future sustainability target and works backwards to determine shorter term aims and policies that will get you from the present state to the future target. The emphasis of Gleeson et al. (2012) is on ongoing monitoring and adaptation of strategies to ensure that progress is made towards the long term sustainability target. The catchment WF framework can potentially be applied within this framework. For example, long term sustainability targets can be set for groundwater levels of the Steenkoppies Aquifer, specifying a range of acceptable groundwater levels for both the long term and, through backcasting, targets can be set to ensure shorter term increases in groundwater levels. Once the long-term sustainability target has been reached, a suitable range for groundwater levels should be specified within which groundwater levels are to be maintained. For this purpose, it will be extremely useful for a catchment water resource manager to know how much agricultural production can be permitted to achieve these objectives. For example, 7 Mm^3 of water can be used to produce x tonnes of carrots, y tonnes of cabbage and z tonnes of maize, or different combinations thereof. Our proposed approach links the total yields from the aquifer with WFs to determine total agricultural water use on the aquifer. This can be done in reverse (determining production based on water availability), to determine and more easily regulate maximum agricultural yields from an aquifer when water for agriculture is restricted as specified by a sustainability target.

Average wastage for carrots, cabbage, beetroot, broccoli and lettuce along the supply chain that was calculated in this study was lower than estimates from the literature for sub-Saharan Africa (Oelofse and Nahman 2013). The results also indicated that there is a large variation in food wastage between different crops, which translates to significant differences in WFs of wastage of the different crops. For example, literature sources indicating that 51.5% of vegetables are wasted along the supply chain overestimates wastage of cabbage which ranges between 10.4% in winter and 15.9% in summer.

The results also indicated high inter-seasonal variation in vegetable wastage. For carrots and beetroot, there is 12% difference between highest food wastage in autumn and lowest food wastage in spring. Maximum wastage of lettuce in summer was 10% more than minimum wastage of lettuce in winter. Large differences in total production may affect the percentage wastage, where lower production may be easier to manage and have less wastage. For all crops percentage wastage was higher in summer compared to winter, partly because of shorter shelf lives when temperatures are higher.

The main challenge in quantifying food wastage is to classify waste. Offcuts, which includes non-edible parts of the crops, was not considered wastage. These offcuts were also not included in total production figures, because for cabbage and lettuce the figures were given in head counts, and the leaves of carrots are cut in the field. Most of the wastage reported in this chapter was not simply discarded. Wastage at the farm level is fed to livestock, wastage at the Tshwane Market was used for composting, and wastage at many of the green grocers that were contacted was given to charity organisations or livestock farmers. The beneficial use of these vegetables could disqualify them from being classified as waste, especially if they substitute better quality foods used for livestock feed. However, in the face of food insecurities it is still worth considering these losses from the food supply chain. Another challenge in quantifying vegetable wastages is the loss of water content as the vegetables age, which results in low masses wastage compared to what was bought. If products are measured in terms of vegetable counts, like cabbage heads with more or less standard sizes, that problem could potentially be overcome.

It could be argued that the reduction in food wastage may be one of the simpler ways to address food insecurities and water scarcities. Potential savings in green water used through reductions in food wastage was assumed to be negligible, because these wasted crops replaced natural vegetation that would also use green water. According to the 2005 crop areas a total of 6 Mm^3 of blue water was required to grow the five selected vegetables, of which an estimated 2 Mm^3 was used to produce the wastage. According to the 2005 crop areas 12 Mm^3 blue water was used to grow maize and wheat on the Steenkoppies Aquifer. The wastage of maize and wheat has not been determined, but Gustavsson et al. (2011) reported 19% wastage of cereals in sub-Saharan Africa, therefore it is estimated that wastage of maize and wheat would use 2 Mm^3 of blue water. Total wastage on the Steenkoppies Aquifer would use an estimated 4 Mm^3 of blue water, which is 25% of the estimated volume of the 17 $Mm^3\ yr^{-1}$ blue water that exceeded sustainable limits. However, not all wastage can be prevented. For example, considering the intensive use of pesticides on modern farms, further reductions in losses due to pests come with associated ecological impacts. In a global study on food losses the minimum wastage recorded for fruits and vegetables was 37%, which was recorded in industrialised Asia and the minimum of 33% wastage of root and tubers was recorded in northern Africa, western and central Asia (Gustavsson et al. 2011). Losses recorded for this study is therefore below the recorded minimum and with current technologies further reductions are unlikely. Thus, by reducing food wastage to reduce total production is will be difficult and is likely to have a relatively low impact on addressing the sustainable use of the aquifer. Addressing food wastage must be considered as one of multiple management objectives that will have to be implemented to achieve sustainability targets for the Steenkoppies Aquifer.

6.5 Conclusion

It is envisaged that the catchment WF framework proposed here can be used to improve the water resource management of similar aquifers around the world. The framework proposes that volumetric blue and green WFs are linked to crop yields to provide a catchment manager with a relatively simple way to quantify and regulate water use of agriculture in the catchment. The framework could potentially be applied in catchments where surface water is the main source of irrigation, as long at the excess water abstracted for irrigation (where irrigation > crop ET) is returned to the same surface water resource in the same time period. In some cases, natural areas (which defines GWa) may serve a function in recharging the aquifer (thus increasing the blue water availability), and in such cases green water availability should not be interpreted in isolation from blue water availability, as they are closely linked.

The potential use of the catchment WF framework has been tested in a case study on the Steenkoppies Aquifer. This assessment is the first attempt to quantify total ET on a catchment level for the Steenkoppies Aquifer using water footprinting. The lack of sustainability of blue water use on the Steenkoppies Aquifer is worrisome, with results being confirmed with observed reductions in groundwater levels and Maloney's Eye outflows. The water balance gave insights into the geohydrology of the aquifer, which indicated possible water movement across the boundaries of the aquifer, which was previously thought not to occur. The correlation between estimated and measured outflows from Maloney's Eye indicates that a method such as this can potentially be developed to estimate outflows from an aquifer using the WF approach. Despite the good correlation between estimated and measured outflows, however, the estimated outflows exceed measured outflows before irrigated agriculture became a significant user. The WF approach is therefore still in development and does not replace hydrological assessments and monitoring. In other areas, hydrological information may be even more important, because the Steenkoppies Aquifer is relatively simple from a hydrological perspective (with no surface runoff into or out of the catchment and only one known natural outlet). Future research required to refine and further develop the catchment WF framework should include

- Record actual crop yields produced by the farmers over the long term.
- Improve the quantification of water use by natural vegetation.
- Improve the interplay between WF accounting and hydrological assessments to improve the understanding of the dynamics and sustainable water use for the system.
- Conduct a catchment scale grey WF assessment.

It was observed that wastage of different types of vegetables can be variable, with small fractions of some crops, like cabbage, and high fractions of other crops, like lettuce, being wasted. Care should therefore be taken when using published data on wastage of fruits and vegetables in general. The results have shown that the highest percentage of wastage occurs during the production stage for a number of reasons, including damage by pests and diseases, and unmarketable properties of some crops, so efforts to limit wastage should focus on this stage. Accounting for food wastage is complicated by the facts that vegetables that are classified as wasted are often used for other purposes such as animal feed and compost.

Further reductions in recorded food wastage to achieve sustainability targets for the Steenkoppies Aquifer does not seem to be feasible given the current technologies and is complicated by the associated ecological impacts, for example through the increased use of pesticides. Household based cultivation may present a better opportunity to reduce the high wastage of vegetables, because people are more likely to eat crops with unmarketable properties that are grown in their gardens, and crops like lettuce will be eaten directly after it is harvested, which will prevent the decay that happens along the supply chain.

The information generated by the WF calculations using the WFN methodology thus indicates that addressing food wastage through improved technologies is important, but other management objectives must also be implemented to achieve sustainability targets, such as limiting total production or selecting crops and cultivars with lower water requirements. In the next chapter, crop parameters are developed for two 'fancy' lettuce cultivars, namely cos and butterhead lettuce, that are also cultivated on the Steenkoppies Aquifer. The WFs of cos and butterhead lettuce are then assessed to determine whether alternative cultivars can potentially be used to reduce the catchment scale WF on the Steenkoppies Aquifer.

7 WATER FOOTPRINTS WITHIN THE OLIFANTS-DOORN CATCHMENT

by

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7.1 Introduction and approach

Field scale estimates of the water footprints (WF) of crops, based on actual measurements, provide valuable and detailed information for on-farm water use management. However, catchment-based WF assessments are more appropriate for large-scale water resources management beyond the farm boundaries. Consequently, the objective of this component of the project was to use crop-specific 'blue', 'green' and 'grey' water use information gathered from field measurements of transpiration, total evaporation, weather and additional seasonal water use by selected fruit tree species (apples and citrus), to scale up to water footprints for these crops at quaternary catchment (QC) and Water Management Area (WMA) scales. This information was utilised to derive the best-estimates of green, blue and grey crop water footprints within the Olifants-Doorn WMA according to the Water Footprint Network method (Hoekstra et al. 2011). Green and blue water use was determined through field-observed crop factors combined with FAO-56 ET_0 estimates from weather data (Allen et al. 1998). Grey water use estimates were based on the method described by Hoekstra et al. (2011). From a water resources management perspective, what was critical for this process was to have accurate estimates of the areas in each QC under the selected crop types A. The QC was deemed to be a useful scale for this assessment as it is a unit commonly used for water resources management and planning purposes in South Africa. The case study consequently applied the following approach:

- Production chain classification, data collection (observed or modelled water use, yield, weather data, farm water use activities) and distinction between / calculation of blue, green and grey water footprint (WF) components.
- Calculation of WFs for the selected crop types in m^3/ ton, using field observed data (blue, green, grey) from individual farms.
- Derive Water Footprint crop factors for these crop types, incorporating blue, green and grey water footprint info.
- Obtain data on crop type area per Quaternary Catchment within the Olifants-Doorn catchment and thus for the Water Management Area as a whole.
- Scale up to WMA using QC-specific crop areas, crop factors and weather data (ET_0).
- Describe the challenges and learning that have taken place (e.g. difference in crop area between estimation approaches, non-differentiation between crops such as Viticulture / Horticulture), representativeness of the weather data used to calculate reference potential evaporation etc.

7.2 Background and location

The Olifants/Doorn Water Management Area (WMA) is located in the winter rainfall region of the Western Cape Province (**Figure 7-1**). This WMA was one of an original 19 WMAs subsequently consolidated to 9, and now forms part of the new Berg-Olifants WMA comprising the original Berg WMA and the Olifants-Doorn WMA (Department of Water Affairs 2013). However, for the purposes of this study it was analysed in its original capacity. There are 89 Quaternary Catchments (QCs) included in the Olifants-Doorn WMA.

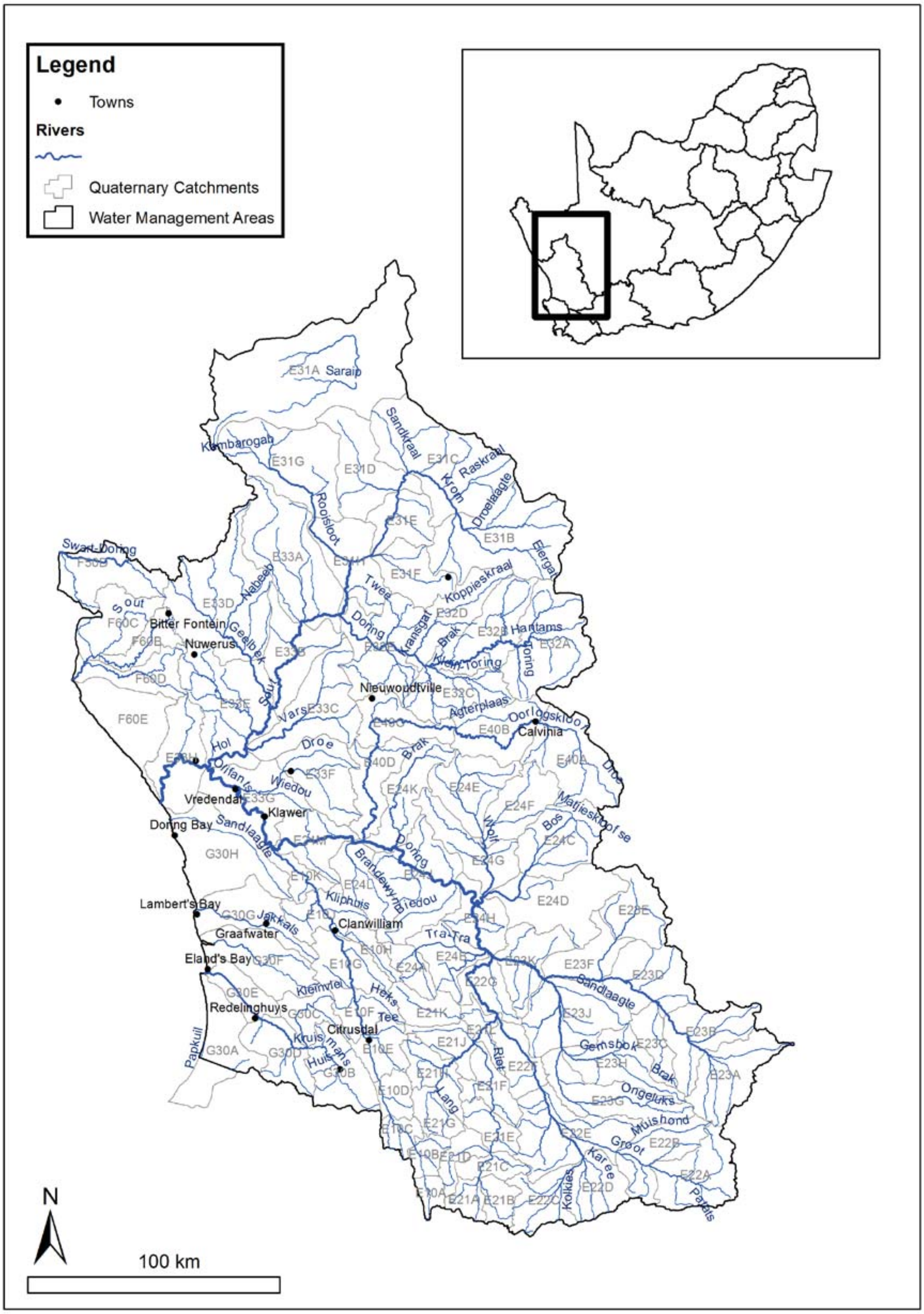

Figure 7-1: Locality Map of the Olifants/Doorn Water Management Area showing the main towns, rivers and the quaternary catchments.

Climatic conditions vary considerably across the Olifants-Doorn WMA as a result of the variation in topography. The mean annual precipitation ranges from approximately 1 500 mm in the Cederberg Mountains in the south-west, decreasing sharply to about 200 mm to the north, east and west thereof, and to less than 100 mm in the far north (DEA&DP 2011). The WMA depends heavily on surface water (76%) and groundwater (16%) as respective sources of supply. The major river contributing to the surface flow in the WMA is the Olifants River, of which the Doring River (draining the Koue Bokkeveld and Doring area) and the Sout River (draining the Knersvlakte area) are the main tributaries. The Olifants and Doring Rivers are perennial and have high flows in winter, while the Sout River is ephemeral and flows seasonally. Surface water in the Olifants River is regulated by the Clanwilliam Dam and the Bulshoek Barrage. There are no large dams on the Doring River, although a large number of farm dams have been constructed on the upper tributaries.

With the mean annual precipitation over much of the WMA being less than 200 mm, the result is that, except in the wetter south-west, the climate is not suitable for dryland farming on a large scale. It is a region experiencing extreme water scarcity, with a particularly high dependence upon groundwater (as a direct source of supply) in the Sandveld region (CSIR 2012). Consequently, more than 90% of the land in the Olifants-Doorn WMA is used as grazing for livestock, predominantly for sheep and goats. However, the principal economic activity in the WMA is irrigated agriculture, and 87% of total water use is for irrigation (DEA&DP, 2011). A recent estimate (Bailey and Pitman 2015) puts the total area under irrigation in this WMA at 730 km².

Farms were selected (**Table 7-1**) to provide the required blue, green and grey water footprint data for two important fruit tree crops produced in the Olifants-Doorn WMA, namely apples and oranges. Further details of these farms, and the data that were collected, are provided in **Chapter 5**. The farms were selected due to their representativeness, co-operation from the land-owners, and availability of good data.

Table 7-1: Details of the farms selected for field data collection and extrapolation to the Olifants-Doorn WMA.

Area	Farm Name	Crop	Coordinates
Koue Bokkeveld	Nooitgedacht	Apples	S33.200766; E19.338525
Citrusdal (Upper Olifants River)	Patrysberg	Oranges	S32.454910, E18.979293

7.3 Water footprint determination (catchments)

7.3.1 Determining catchment-specific crop areas

A process was followed to determine crop-specific areas present in each QC in the Olifants-Doorn WMA. Determining accurate crop-specific areas at a Quaternary Catchment scale was necessary because the crop factors for calculating water use and water footprints are species-specific. What was required were accurate estimates of total agricultural area in the Olifants-Doorn WMA, and the areas per QC under apple orchard and citrus orchards. Obtaining this information in the required format presented some challenges. There are two main datasets which give an indication of the amount of crops within the Olifants-Doorn catchment. The first is the publically available DAFF (2013) field boundary dataset. The second is the latest 2013/2014 National Land Cover dataset (Geoterraimage 2015).

In the DAFF field boundary dataset fields were digitised from 2.5m resolution, pan-merged 2011 SPOT5 imagery with a release date of 01/02/2013. The Fields dataset comprises a range of classes, namely Annual Crop Cultivation/Planted Pastures Rotation; Horticulture/Viticulture; Old Fields; Pivot Irrigation; Shade Net; Small Holdings; Strip Field Cultivation; and Subsistence Farming (**Figure 7-2**). The total agricultural area represented by the different classes (in square metres) was calculated for each quaternary catchment in the study area and summed to find the total agriculture activities in the WMA (**Table 7-2**). From an irrigation perspective, agricultural classes comprising Annual Crop Cultivation, Old Fields, Small Holdings, Strip Field Cultivation and Subsistence Farming were presumed to be predominantly dry-land and were excluded, giving a total irrigated area for the WMA of 755 046 727 m² (755 km²), which is similar to the WR2012 estimate (730 km²). The categories allow distinction to be made between broad crop categories per QC, but do not state specific crop species. For example Horticulture & Viticulture are lumped together, and Pivots doesn't distinguish between crop types. This was problematic in terms of assigning species-specific crop-factors to areas of particular crops in each QC.

Table 7-2: Summary of the DAFF field boundary dataset (2013) for the Olifants-Doorn WMA.

Agricultural Landcover Class	Area (m^2)
Annual Crop Cultivation / Planted Pastures Rotation	2 157 827 123
Horticulture / Viticulture	681 409 463
Old Fields	125 597 000
Pivot Irrigation	72 595 502
ShadeNet	1 041 763
Small Holdings	249 484
Strip Field Cultivation	407 324 800
Subsistence Farming	1 797 121
Total	3 447 842 255

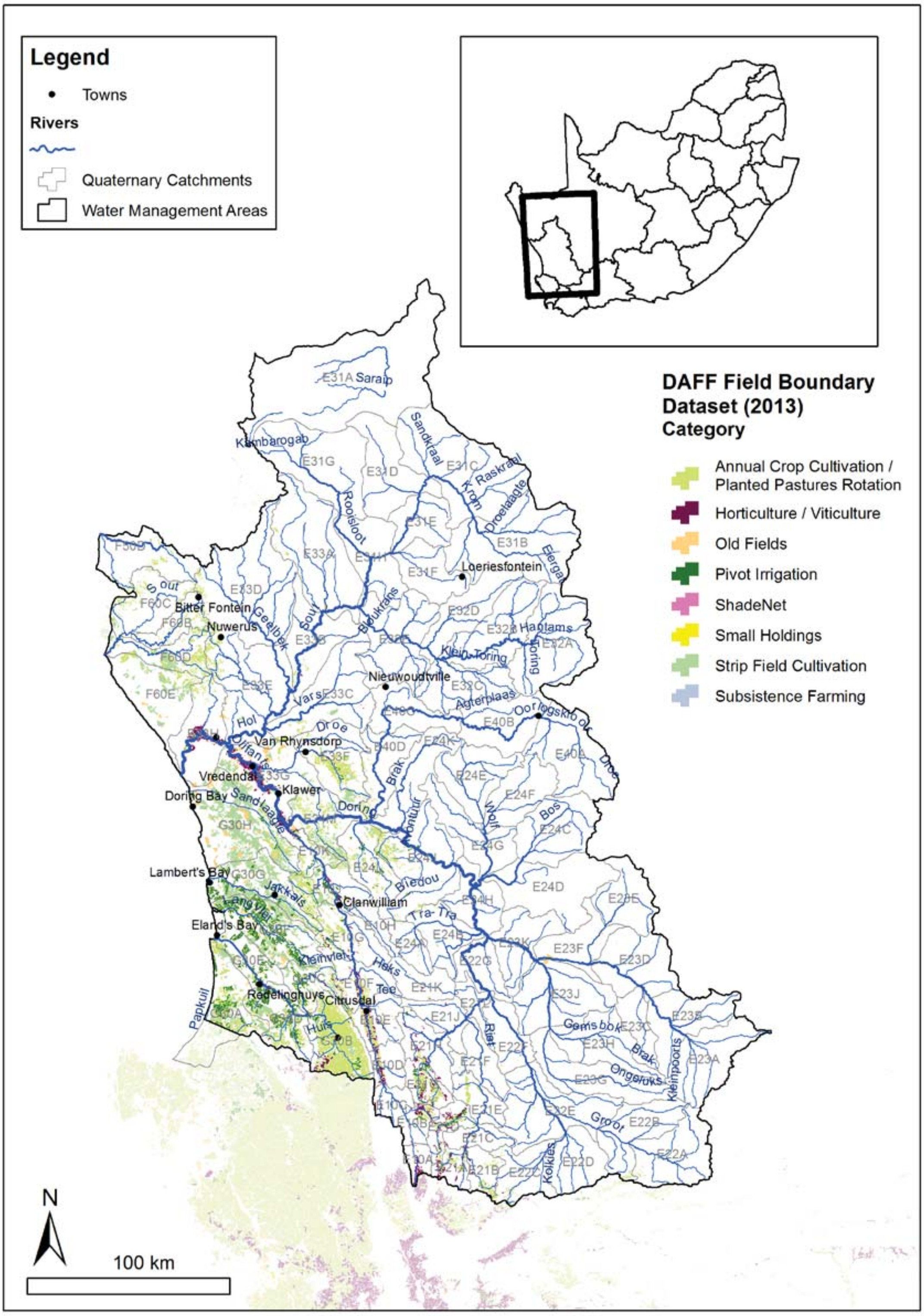

Figure 7-2: The DAFF 2011 Field boundary dataset (2013) digitised from SPOT5 2011 imagery.

The second dataset with agriculture data is the newly released National Landcover 2013-2014 released by GeoTerraImage (2014) which has 72 land cover classes (**Figure 7-3**). The Cultivated Lands dataset was modelled from Landsat8 imagery over the period 2013 to 2014 and was reported to be an update on the 2013 DAFF Fields dataset (GeoTerraImage, 2014).

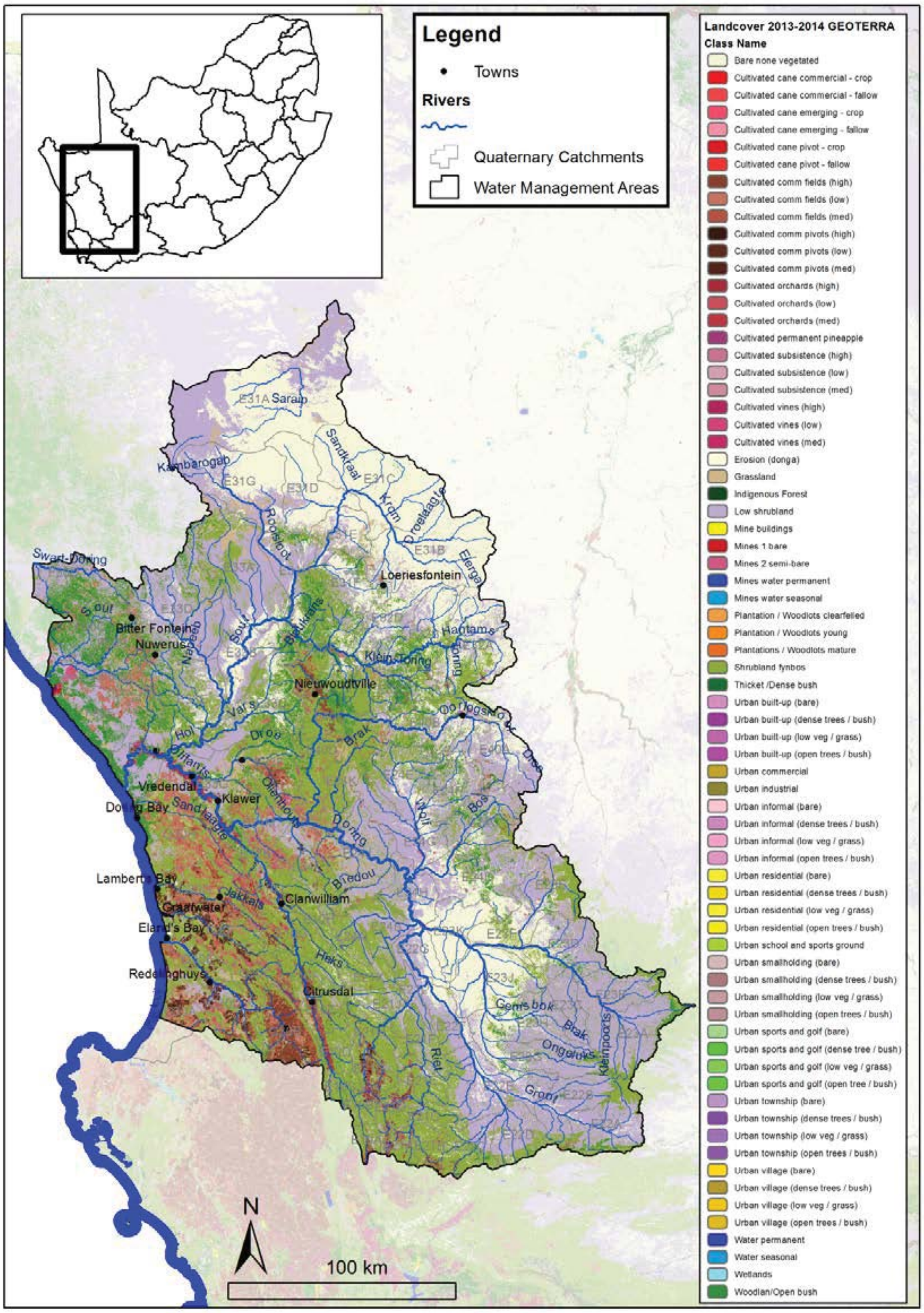

Figure 7-3: The 2013-2014 National Landcover Dataset produced by GeoTerraImage (2014)

Using the Tabulate Area function in ArcGIS, the total area of each landcover class was calculated per quaternary catchment. The results were summed to obtain the total agriculture activity for the study area (**Table 7-3**). This dataset makes distinction between orchards and vineyards, but is also not species-specific. Also there seems to be major differences in crop area estimates between the DAFF data and the NLC data. The DAFF estimate of agricultural area in the Olifants-Doorn WMA is 3447 km², while the NLC estimate is 4499 km². In terms of irrigated agriculture, summing the classes described as Cultivated Commercial Pivots, Cultivated Orchards and Cultivated Vines yields a total area of 1184 km² (compared to the 755 km² for the DAFF 2013 dataset). These increases are attributed to the new cultivated lands captured by the NLC2013-2014 (predominantly in the Northern Cape Province), and it consequently has more quaternary catchments with agricultural activity.

Table 7-3: Summary of agricultural landcover per class (m²) from the NLC2013-2014 (GeoTerraImage, 2014).

Agricultural Landcover Class	Area (m²)
Cultivated comm fields (high)	560 985 300
Cultivated comm fields (med)	644 015 700
Cultivated comm fields (low)	2 092 216 500
Cultivated comm pivots (high)	132 953 400
Cultivated comm pivots (med)	126 012 600
Cultivated comm pivots (low)	199 128 600
Cultivated orchards (high)	150 740 100
Cultivated orchards (med)	115 385 400
Cultivated orchards (low)	267 217 200
Cultivated vines (high)	122 037 300
Cultivated vines (med)	54 630 900
Cultivated vines (low)	15 960 600
Cultivated subsistence (high)	345 600
Cultivated subsistence (med)	1 746 000
Cultivated subsistence (low)	15 573 600
Total	**4 498 948 800**

In order to meet the objectives of this task a more detailed dataset was required which made distinction between specific crop types at a spatial scale, within the area of interest (Olifants-Doorn WMA) in the Western Cape. The Cape Farm Mapper (http://gis.elsenburg.com/apps/cfm/) is a free web-based mapping application that gives access to spatial databases and web services. The tool allows users to see where different crop types are cultivated across the Western Cape, access information on rainfall patterns, temperatures during the year, evaporation in specific areas, geology etc. (**Figure 7-4**). The source data for this tool was requested from the Western Cape Government Department of Agriculture at Elsenburg, and it was kindly made available to the project team under a data-sharing agreement. The source data included most of the Olifants-Doorn WMA, only excluding areas of this WMA that were located in the Northern Cape Province. This was not a limitation to the analysis as the growing areas of the crops of interest are almost exclusively in the area of the Olifants-Doorn WMA that falls into the Western Cape Province.

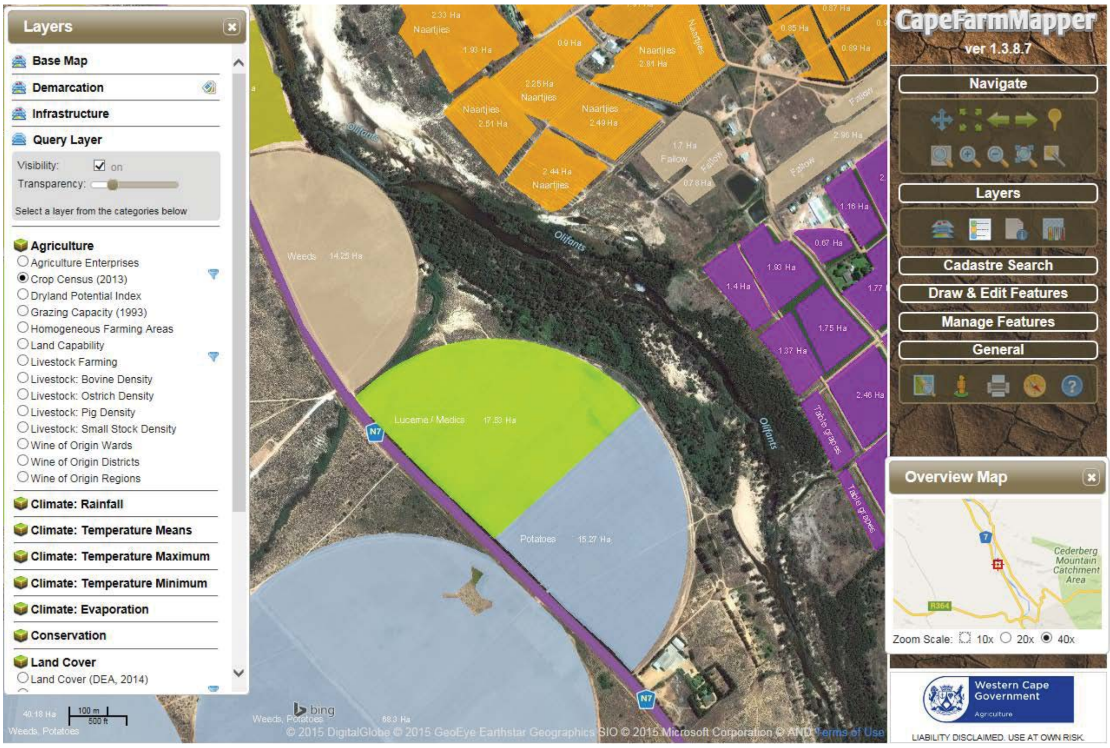

Figure 7-4: Example of CapeFarmMapper user interface.

Total agricultural area (all cultivated land categories) from this dataset amounted to 3631 km² for the WMA (excluding Northern Cape Province). This is similar to the 3448 km² total from the DAFF dataset. Total irrigated area extracted from the dataset amounted to 398 km² (compared to the 755 km² for the DAFF 2013 dataset, and 1184 km² for the NLC dataset). The areas under the irrigated crops of interest in the WMA were 42.4352 km² for apple orchards, and 79.3376 km² for citrus orchards (Oranges = 65.6 km²; Naartjies = 10.9 km²; Lemons = 2.7 km²; Grapefruit = 0.2 km²). QC-scale crop areas were subsequently obtained from the Cape Farm Mapper product.

7.3.2 Extrapolating from field to catchment using crop factors

Site specific (farm-scale) WF results, as described in **Chapter 5**, were upscaled to QC and WMA scales. This was done primarily through the application of the monthly crop coefficients (K_c) determined for the apple and citrus orchards from the field study estimates of ET and ET_o. For both fruit types each monthly K_c value determined from the field observations was partitioned into a $K_{c\text{-blue}}$ and $K_{c\text{-green}}$ component (**Table 7-4**) based on the average monthly proportions of CWU_{blue} and CWU_{green} observed from the field study data.

Table 7-4: Monthly fractional distinction between CWU_{blue} and CWU_{green} used to partition field-derived apple and citrus crop factors into K_{c-blue} and $K_{c-green}$ components.

		Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun
Apples	K_c	0.14	0.21	0.25	0.58	0.59	0.77	0.75	0.74	0.79	0.75	0.57	0.17
	K_{c-blue} fraction	0	0	0	0.21	0.92	1	1	1	1	0.9	0.33	0
	$K_{c-green}$ fraction	1	1	1	0.79	0.08	0	0	0	0	0.1	0.67	1
Oranges	K_c	0.91	0.59	0.70	0.80	0.52	0.54	0.45	0.52	0.65	0.69	0.96	0.91
	K_{c-blue} fraction	0.51	0.05	0.77	0.9	0.89	0.78	0.97	0.98	0.99	0.82	0.66	0.04
	$K_{c-green}$ fraction	0.49	0.95	0.23	0.1	0.11	0.22	0.03	0.02	0.01	0.18	0.34	0.96

Each monthly K_{c-blue} and $K_{c-green}$ crop factor was subsequently multiplied by the corresponding monthly ET_o value (mm) for each QC within the WMA (determined from Schulze RE (2007)) to calculate QC-specific monthly CWU_{blue} and CWU_{green} values (mm). Monthly 'blue' and 'green' orchard CWU values were summed for the year and then converted to a volumetric equivalent (m^3) by multiplying them by the area under apple or citrus orchards in each QC obtained from the Cape Farm Mapper product. Volumetric CWU values were then divided by representative orchard yields to derive WF_{blue} and WF_{green} values (m^3 $tonne^{-1}$) for each QC. Average orchard yields of 61.5 tonnes ha^{-1} for apples, and 79 tonnes ha^{-1} for citrus were used, as these corresponded with the field observations from which the crop factors were derived. To these were added the WF_{grey} component, which was assigned a fixed value linked to yield (based on the field study results). The respective WF components were summed in order to determine the total WF (m^3 $tonne^{-1}$) and WP (kg m^3) value for each QC. QC-specific CWU values were also summed for all QCs in the WMA to determine the overall water requirement for apple and citrus production in this basin.

7.4 Results and discussion

7.4.1 Apples

For all the QCs of the Olifants / Doorn WMA where apples are cultivated (14 in total) the average total water footprint (WF) for this crop was 228.4 m^3 $tonne^{-1}$ (**Figure 7-5**). Of this, WF_{blue} accounted for 65.2% (149 m^3 $tonne^{-1}$), WF_{green} for 13.9% (31.8 m^3 $tonne^{-1}$) and WF_{grey} for 20.8% (47.6 m^3 $tonne^{-1}$) (**Table 7-5**). WF values across the WMA ranged from 198.9 m^3 $tonne^{-1}$ to 268 m^3 $tonne^{-1}$. Equivalent crop water productivity ranged from 3.73 kg m^{-3} to 5.03 kg m^{-3}, with an average of 4.4 kg m^{-3}. Based on crop factors derived from the field study described here, QC-specific ET_o data and the latest available figures on apple orchard area per QC (Cape Farm Mapper 2016), the associated water (blue, green and grey) required to sustain this industry across the WMA as a whole was estimated at approximately 57.3 million m^3 yr^{-1}. Of this, 37 million m^3 yr^{-1} (64.5%) represents the irrigation water required by the industry (**Figure 7-5**).

Table 7-5 Water footprint and water productivity estimates for 'Cripps' Pink' apples in all the QCs of the Olifants / Doorn WMA where this crop is cultivated.

QC	Blue WU (m^3)	Green WU (m^3)	Grey WU (m^3)	Total WU (m^3)	Blue WF (m^3 $tonne^{-1}$)	Green WF (m^3 $tonne^{-1}$)	Grey WF (m^3 $tonne^{-1}$)	Total WF (m^3 $tonne^{-1}$)	WP (kg m^{-3})
E10A	5413172.7	1186059.4	2076844.0	**8676076.1**	124.1	27.2	47.6	**198.9**	5.03
E10B	4257190.0	892291.0	1427592.5	**6577073.5**	141.9	29.8	47.6	**219.3**	4.56
E10C	186173.3	39519.7	58422.5	**284115.4**	151.7	32.2	47.6	**231.5**	4.32
E21A	5145420.4	1106462.4	1855541.2	**8107423.9**	132.0	28.4	47.6	**208.0**	4.81
E21B	855345.0	180364.6	301114.6	**1336824.2**	135.2	28.5	47.6	**211.3**	4.73
E21C	537347.9	112914.4	176043.1	**826305.4**	145.3	30.5	47.6	**223.4**	4.48
E21D	8172512.5	1720839.9	2717014.1	**12610366.4**	143.2	30.1	47.6	**220.9**	4.53
E21E	187.7	39.6	59.7	**287.0**	149.7	31.5	47.6	**228.9**	4.37
E21F	81926.5	17443.0	25447.1	**124816.6**	153.2	32.6	47.6	**233.5**	4.28
E21G	10374399.1	2168625.6	3264385.7	**15807410.4**	151.3	31.6	47.6	**230.5**	4.34
E21H	1284426.8	272332.4	433627.7	**1990386.8**	141.0	29.9	47.6	**218.5**	4.58
E22C	617711.6	131752.0	183996.6	**933460.3**	159.8	34.1	47.6	**241.5**	4.14
G30B	925.7	202.5	243.6	**1371.8**	180.9	39.6	47.6	**268.0**	3.73
G30D	30931.3	6790.8	8343.0	**46065.2**	176.5	38.7	47.6	**262.8**	3.80
Total	**36957670.5**	**7835637.2**	**12528675.4**	**57321983.1**					
Average					**149.0**	**31.8**	**47.6**	**228.4**	**4.41**
%	**64.5%**	**13.7%**	**21.9%**	**100.0%**	**65.2%**	**13.9%**	**20.8%**	**100.0%**	

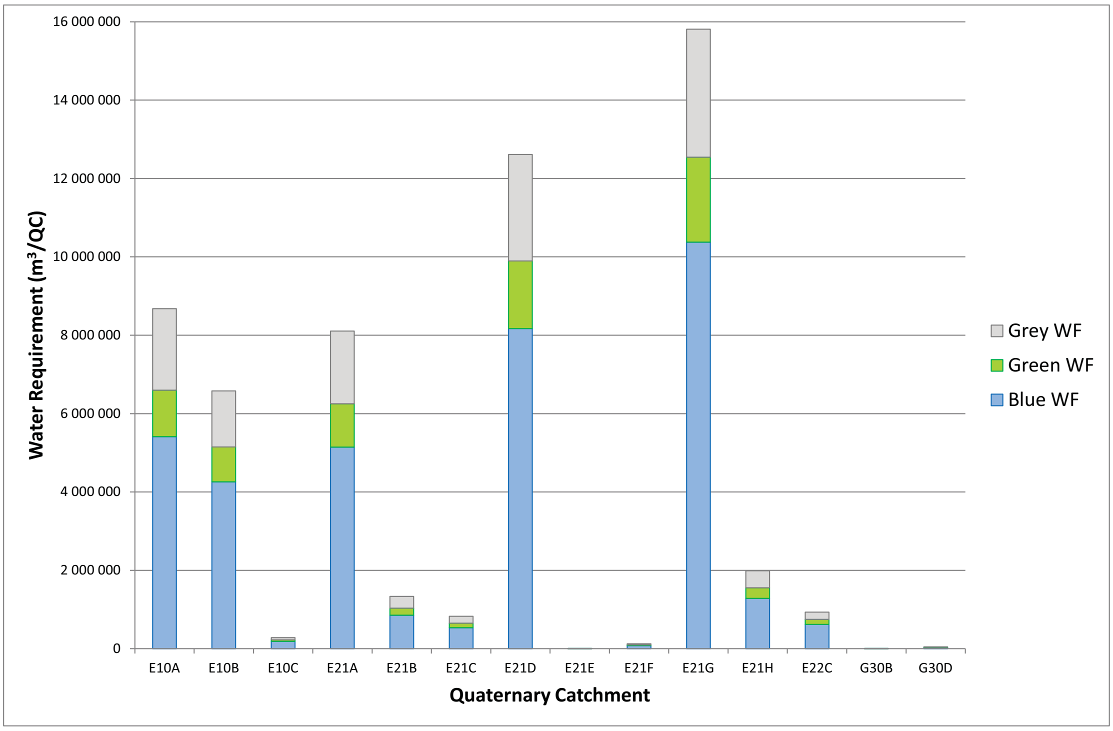

Figure 7-5: Volumes of water required for apple production in those QC's within the Olifants-Doorn WMA where apples are cultivated, as estimated using field measurements, modelling and the WFN approach.

7.4.2 Citrus

For all the QCs of the Olifants / Doorn WMA where citrus is cultivated (16 in total) the average total water footprint (WF) for this crop was 210.5 m³ tonne⁻¹ (**Table 7-6**). Of this, WF_{blue} accounted for 69% (145.3 m³ tonne⁻¹), WF_{green} for 18.1% (38.2 m³ tonne⁻¹) and WF_{grey} for 12.8% (27 m³ tonne⁻¹). WF values across the WMA ranged from 182.9 m³ tonne⁻¹ to 228.2 m³ tonne⁻¹. Equivalent crop water productivity ranged from 4.38 kg m⁻³ to 5.47 kg m⁻³, with an average of 4.77 kg m⁻³. Based on crop factors derived from the field study described here, QC-specific ET_o data and the latest available figures on citrus orchard area per QC, the associated water (blue, green and grey) required to sustain this industry across the WMA as a whole was estimated at approximately 135.8 million m³ yr⁻¹. Of this, 93.7 million m³ yr⁻¹ (69%) represents the irrigation water required by the industry (**Figure 7-6**).

Table 7-6: Water footprint and water productivity estimates for 'Rustenburg' navel oranges in all the QCs of the Olifants / Doorn WMA where this crop is cultivated.

QC	Blue WU (m³)	Green WU (m³)	Grey WU (m³)	Total WU (m³)	Blue WF (m³ tonne⁻¹)	Green WF (m³ tonne⁻¹)	Grey WF (m³ tonne⁻¹)	Total WF (m³ tonne⁻¹)	WP (kg m⁻³)
E10C	702357.0	177754.8	139821.3	**1019933.1**	135.7	34.4	27.0	**197.1**	5.07
E10D	17454953.2	4453860.6	3453137.8	**25361951.7**	136.6	34.9	27.0	**198.5**	5.04
E10E	24094106.3	6208546.4	4678049.6	**34980702.3**	139.2	35.9	27.0	**202.0**	4.95
E10F	17534610.8	4561738.5	3275142.0	**25371491.2**	144.7	37.6	27.0	**209.3**	4.78
E10G	12996873.6	3437147.4	2334288.0	**18768309.0**	150.4	39.8	27.0	**217.2**	4.60
E10H	529099.5	139478.3	115885.8	**784463.6**	123.4	32.5	27.0	**182.9**	5.47
E10J	8230956.9	2213470.0	1472432.4	**11916859.3**	151.0	40.6	27.0	**218.7**	4.57
E21H	581429.9	144334.8	123189.6	**848954.2**	127.5	31.7	27.0	**186.2**	5.37
E21J	383146.2	97151.5	77427.1	**557724.7**	133.7	33.9	27.0	**194.6**	5.14
E24J	172646.6	46757.2	29464.6	**248868.4**	158.3	42.9	27.0	**228.2**	4.38
E24M	41604.1	11180.2	7116.7	**59901.0**	158.0	42.4	27.0	**227.4**	4.40
G30B	1143804.7	300829.2	194595.2	**1639229.0**	158.8	41.8	27.0	**227.6**	4.39
G30C	5467880.5	1439042.3	954864.8	**7861787.5**	154.7	40.7	27.0	**222.5**	4.50
G30D	2845701.4	749325.3	494189.3	**4089216.0**	155.6	41.0	27.0	**223.6**	4.47
G30F	1026166.4	277959.3	181157.1	**1485282.9**	153.1	41.5	27.0	**221.5**	4.51
G30G	523210.1	141641.3	97783.5	**762634.9**	144.6	39.1	27.0	**210.7**	4.75
Total	**93728547.2**	**24400216.9**	**17628544.7**	**135757308.7**					
Average					**145.3**	**38.2**	**27.0**	**210.5**	**4.77**
%	**69.0%**	**18.0%**	**13.0%**	**100.0%**	**69.0%**	**18.1%**	**12.8%**	**100.0%**	

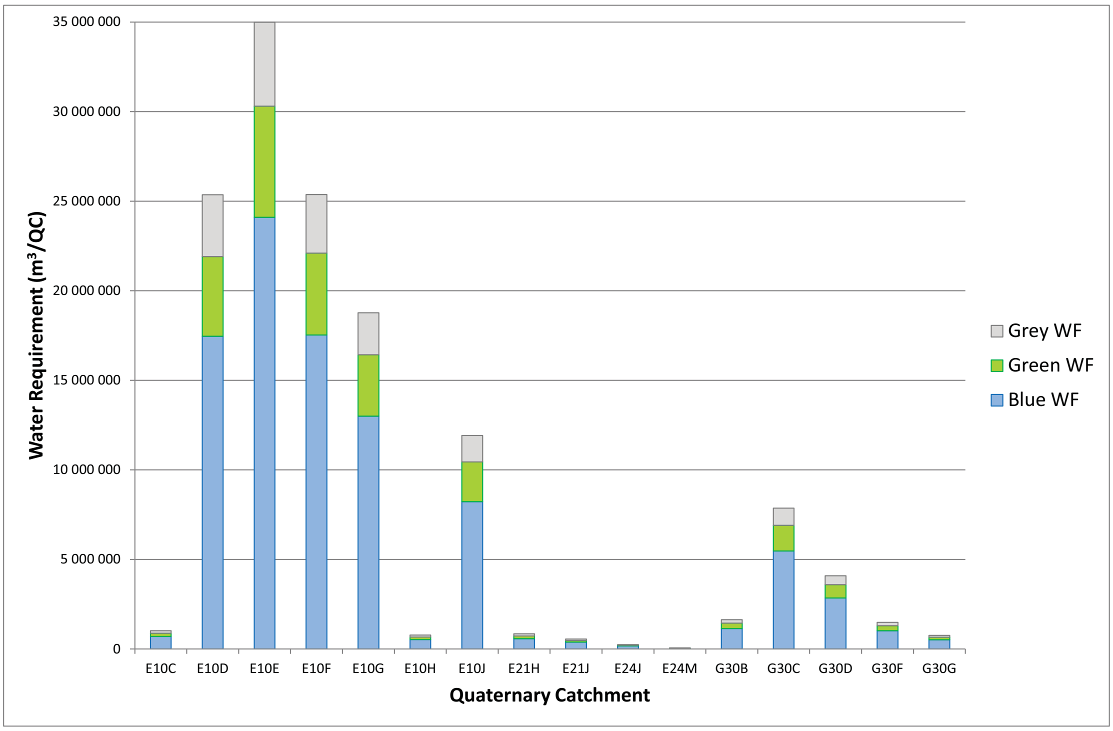

Figure 7-6: Volumes of water required for citrus production in those QC's within the Olifants-Doorn WMA where citrus orchards are grown, as estimated using field measurements, modelling and the WFN approach.

7.5 Conclusions

An advantage of calculating the water footprints of apple and citrus orchards within each QC of the Olifants-Doorn WMA is that it provides a reasonable estimate of the overall volume of water required for the production of these crops. It also indicates how their water requirements vary across the WMA. This information is potentially useful for catchment water management and allocation decisions. The distinction between the blue, green and grey components also provides a means of easily assessing the crop-specific irrigation requirements for an area, in comparison to the dependence upon rainfall. A recommendation for future research would be to determine accurate WF estimates for all crops grown in the Olifants-Doorn WMA, in order to gauge the overall water requirement of irrigated agriculture, and also to facilitate cost-benefit analyses for the various crops that are produced.

8 DISCUSSION

by

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This study was conducted to better understand the usefulness of water footprint (WF) information for fruit and vegetable crops to farmers (local level), water resource managers (catchment/basin level), policy makers (regional/national level), and consumers (although the latter two were beyond the immediate scope of this project from a research perspective). In addition to a literature review, a WF methodology comparison using actual data was made, WFs were calculated for selected important fruit and vegetable crops, WF accounting was up-scaled to the catchment level using the Steenkoppies Aquifer and Olifants/Doorn Water Management Areas as case studies, and important ways to utilise this information were identified. In the following section, the results are discussed section by section in a manner envisaged to be useful to other stakeholders in the water and agricultural sectors.

8.1 Comparison between water footprint accounting methods

The methodologies proposed by the Water Footprint Network (WFN) (Hoekstra et al. 2011), the Life Cycle Assessment (LCA) communities (i Canals et al. 2009, Pfister et al. 2009), and the hydrological-based WF communities (Deurer et al. 2011) were evaluated in a literature review. Three methodologies were further compared in a case study on the cultivation of carrots (*Daucus carota*), beetroot (*Beta vulgaris*), cabbage and broccoli (*Brassica oleracea*), lettuce (*Lactuca sativa*), maize (*Zea mays*) and wheat (*Triticum aestivum*) on the Steenkoppies Aquifer, Gauteng, South Africa. A key aim was to identify one or more simple yet effective method(s) that can be applied in South Africa for various purposes, including decision-making and through the raising of consumer awareness.

Although the WFN methodology's volumetric WFs are not considered appropriate as is for awareness raising, for example by simply stating that it takes 100 ℓ to produce a kg of carrots, it was selected as the key methodology for this research project. Reasons for this include the following:

- The methodology is well-developed, and WFs are relatively simple to calculate and understand
- The quantitative nature of these WFs can potentially be used in different information systems, such as water use licensing services and up-scaling to a catchment level and quantifying water consumed by different users for allocation purposes.

- By altering the functional units, these metrics can be used for applications such as understanding WFs per nutritional unit produced, economic gain or labour opportunities provided.
- These WFs can reveal impacts on water resources in different seasons of a hydrological or calendar year.
- It can indicate high WFs of certain crop species, such as broccoli, or certain growing regions, such as those which experience relatively high vapour pressure deficits or with poor soils.
- It allows for local contextualisation if there is suitable information to conduct the sustainability assessment

The hydrological-based methodology was considered useful in improving understanding of water use in a cropping system, but at this stage it still has a number of shortcomings that may limit its widespread application. For example, because it calculates WFs of one or more crop products over a hydrological year, it potentially conceals seasonal water scarcities and the high WFs of specific crops when several are rotated, as observed for vegetables. Determining WFs of crop sequences also complicates up-scaling to a catchment level, because of the number of crop sequences that are likely to occur on an aquifer. The idea of a negative blue WF, when recharge is greater than irrigation is interesting. However, it does not reflect the opportunity cost in the consumption of blue water resources. Downstream requirements are not accounted for in this methodology, for example a zero blue WF according to the hydrological methodology would mean no net recharge of the aquifer and, eventually, zero outflows. It is furthermore expected that a negative blue WF will mostly occur in wetter parts of the world where water scarcity that WF assessment aims to address is less of a problem. It furthermore does not reflect the irrigation and associated environmental impacts that are taking place (although it is acknowledged that neither do the other methods when reported simply as a WF). Blue WFs estimated according to the hydrological-based method will often be lower than the WFN approach, but impact on water quality must be assessed simultaneously and this is an even more complex exercise than estimating water consumption. For example Witthueser et al. (2009) indicated that initially more rainfall increases pollution due to leaching, but above a certain threshold (900mm yr^{-1} for the Steenkoppies Aquifer) the recharge is enough to dilute the contaminants.

Clear advantages exist for calculating the WF of a product, entity or activity within a LCA framework. For example, simultaneous estimations of the carbon footprint and other environmental impacts allow for more informed management decisions and the screening for any 'pollution swapping' (Thorburn and Wilkinson, 2012) or 'problem shifting' (Finnveden et al., 2009). This has led LCA groups to propose modified methodologies that are compatible with LCA, but these methodologies have their own weaknesses that will potentially prevent their widespread application. According to the knowledge hierarchy, data (a volume of water used to produce a product) can be calculated by a computer, while higher orders of the hierarchy such as wisdom (knowing whether a water use is good or bad) cannot (currently) be calculated by a computer or programmed (Rowley 2007). The methodology does not account for green water, but if less green water is used by a specific land use it may lead to increased blue water in rivers and aquifer as a result of higher levels of runoff or drainage. The International Standards Organization (ISO) published a global WF standard (ISO 14046) in August 2014, closely resembling the LCA methodology proposed by Pfister et al. (2009). The widespread adoption of ISO 14046 remains to be seen.

The complexity of the ecological, social and economic factors which must to be considered when assessing the impact of water use and the trade-offs that are required to choose between one water use and another, highlights the complexity or even impossibility of calculating a WF as a single numerical value that will assist consumers to make wise decisions about their water use. It is recognised that change in consumer behaviour is key to achieving sustainable water use, but it is unlikely that a single numerical value can be developed to inform consumers to make wise decisions on their water use, which is a key aim of the LCA WF methodology. Other options, such as education, advertising and government subsidies should be considered in addition to creating consumer awareness, but the WF is not yet that far developed. Essentially, the choice of WF method selected will be based on the objectives of the exercise.

Packhouse WFs were calculated to quantify the volume of water used in cleaning and/or packaging a unit yield of carrots, cabbage and lettuce in a packhouse on the Steenkoppies Aquifer according to the WFN methodology. As observed in previous studies, packhouse WFs were relatively low compared to the WFs linked to the cultivation phase (ET) (1.9% of the total for carrots, 0.5% for cabbage, 1.6% for lettuce, 0.1% for apples and 0.8% for citrus). If it is assumed that packing and cleaning of beetroot, broccoli, maize and wheat, which are not included in the packhouse assessment requires as much water as carrots (1.3 m^3 $tonne^{-1}$), the catchment scale water use for cleaning and packing selected crops based on 2005 production (**Chapter 6**) is estimated to be 0.12 Mm^3. By extrapolating this water use to all crops cultivated on the Steenkoppies Aquifer, it is estimated that packing all vegetables produced in 2005 on the Steenkoppies Aquifer will require 0.17 Mm^3. This volume is only 0.7% of the total blue WF of cultivation in 2005, which highlights the relatively high water use during cultivation (ET) as a priority for management actions towards sustainable water use. Considering the current management practices in the packhouse that was evaluated, which includes the recycling and purification of water, further potential reductions of the impacts of the water use at the packhouse level is limited. However, the major reductions in blue WFs that are necessary to achieve sustainable blue water use necessitates savings at all levels and the water use in the packhouses should be incorporated as one of several measures to reduce total blue WF on the catchment.

Using phosphorus (P) as the critical pollutant, packhouse grey WFs were estimated to be larger than the packhouse blue WFs. For carrots, cabbage and lettuce, packhouse grey WFs were 8, 2 and 3%, respectively, of the grey WF linked to the cultivation of these crops. The inclusion of recycling and filtration systems, final fate of the disposed water and associated pollutants, and assimilation capacity of the natural environment make the estimation and interpretation of grey WFs challenging.

It was unfortunate that a number of big producers approached as part of this research project were unwilling to share data from their packhouse or allow monitoring by the team, for example, using flowmeters. This was most likely due to two reasons, a perceived threat of bad publicity, and case of managers just being too busy to give this request attention.

8.2 Complexities involved in calculating water footprints

Even though the WFN presented the most simplified methodology to calculate WFs, the following challenges were encountered in a crop production context:

- The vegetable crops grown on the Steenkoppies Aquifer are mostly short season crops and are grown in different seasons. In addition to differences caused by natural inter-annual weather variability, the growing season and planting date had an impact on crop WFs. For example, the summer blue plus green WFs of carrots is 61 m^3 $tonne^{-1}$, compared to 116 m^3 $tonne^{-1}$ in autumn. And summer blue plus green WFs of lettuce was 56 m^3 $tonne^{-1}$, compared to 93 m^3 $tonne^{-1}$ in winter. In winter, blue WFs are higher and green WFs are lower for all crops, simply because the study area is a summer rainfall region.
- Compared to measured solar radiation, estimated values according to FAO 56 (Allen et al. 1998) for 1983 to 2003 were observed to result in noticeably different daily summer and spring ET_o and yield estimates, in turn impacting the WF estimates (which use cumulative crop ET values and yield in their calculation). This effect was less significant for crops planted in autumn and winter. The reason why this effect is more prominent in summer and spring is possibly because the study area is a summer rainfall region and solar radiation is more accurately estimated in the absence of cloud cover. It is recommended that the weather data that is used for crop parameterisation, whether specific variables are estimated or measured, must be used consistently over the simulation period to estimate WFs.
- The functional unit, for example, yield in fresh mass or dry matter, used to calculate WFs can have a notable impact on the relative size of a crop's WF. For example, the grain crops with low moisture content in the harvested grain have relatively high WFs in terms of fresh mass, but in terms of dry matter these crops have relatively low WFs, as compared to vegetable crops (which can have around 90% moisture content). Other functional units, such as nutritional content and economic gain are potentially more useful, because they connect the volume of water use to a specific benefit derived from the crop.
- The WFs of crops with a small harvest index, such as broccoli over all seasons are high, because of the small harvestable portion used in the WF calculation. However, these high WFs could be misleading if the rest of the broccoli plant is used for other beneficial purposes, such as composting and animal feed.
- The relatively high grey WFs do not match the good quality water of the Steenkoppies Aquifer with regard to nitrate levels. This highlights the uncertainties regarding the fate of N after application to the field.

8.3 Catchment scale water footprints: Steenkoppies Aquifer and Olifants-Doorn WMA Case Studies

In **Chapter 6** WFs according to the WFN were used to develop the catchment WF framework, in which total ET from agriculture was estimated by linking WFs of crops with total yields produced on the aquifer. Catchment scale agricultural water use were then used together with other water flows to calculate a catchment water balance. According to the catchment water balance, water flowing into the aquifer exceeds water losses, which is an important question arising from this study. This can either be explained by errors in the assumptions made for this study, or by the possibility that other losses may occur from the aquifer boundaries that are currently not known. There was, however, a good correlation between estimated and measured outflows, and water outflows are very similar to precipitation inflows during years with low rainfall and / or high agricultural water use. Through this framework, total ET estimates of a catchment can potentially be used to improve hydrological models. Using WFs to determine a water balance of the catchment is, however, also considered to be part of a process towards developing a simplified and more cost-effective approach to understanding water dynamics of an aquifer, in contrast to complex and expensive hydrological assessments. The framework requires relatively little information for an agriculture-dominated catchment, including rainfall data, the total yield of different crops cultivated and their respective WFs, and the WF of natural vegetation.

The blue WF sustainability assessment indicated that irrigated agriculture became unsustainable after 1986, which is in line with measured reductions in the outflows from Maloney's Eye, as well as reductions in groundwater levels during this time. The green WF sustainability assessment indicates that there is still further opportunity to expand rainfed crops based on a natural vegetation conservation target of 24%. To a certain extent more efficient irrigation systems can also be implemented to optimise the use of green water by irrigated crops, to alleviate pressure on blue water sources.

Whether this framework can be applied to other catchments depends on the specific characteristics of that catchment. The WFN WFs do consider the difference between over-irrigation and ET, assuming that any excess water applied will recharge the blue water source. This framework only therefore applies to situations where the difference between over-irrigation and ET can be considered unimportant or as recharge to the same water resource. For example, the framework will definitely apply to aquifers where the deep drainage caused by over-irrigation will recharge the aquifer and become available to the same users in the future. Impacts on water quality will, however, need to be addressed simultaneously. If water is discharged into a river, the blue water will become available to downstream users including the environment and/or flow into the sea (which also plays an important role in estuary ecology), in which case the framework may not apply as effectively. However, if water was taken from the same river and would have left the catchment even if abstraction did not take place, this framework could apply. It is also important to emphasize that when using this framework, green WF proportions must be maximised as an indication that irrigation is applied effectively. This will also reduce other ecological impacts associated with over-irrigation and the impact of lags (due to temporary unavailability in the vadose zone) on blue water availability in systems like the Steenkoppies Aquifer.

From the Olifants-Doorn Case Study (**Chapter 7**), it is concluded that field scale estimates of the WFs of fruit tree orchards, based on actual measurements, provide valuable and detailed information for on-farm water use management. However, catchment-based WF assessments are more appropriate for large-scale water resources management beyond the farm boundaries. Accurate crop factors, representative weather / ET_o data, reliable crop areas (preferably cultivar specific), and crop yield data within each QC are critical requirements in terms of upscaling WF estimates. It should also be borne in mind that water use and yield trends (and thus resultant WFs) are cultivar-specific. With due consideration of these the information then has potential application in water allocation decisions, cost-benefit analyses and other water resource management decisions.

The following opportunities for future research for catchment scale WF assessments have been identified:

- Further refine the catchment WF framework to estimate outflows from the aquifer more accurately (assuming these can be accurately measured).

- Linked to the point above, estimations of ET of the natural vegetation must be improved and verified.
- Record actual production within the catchment for the estimation of WFs. This will require a willingness of farmers to share their production records.
- Future geohydrological assessments are required to confirm the hypothesis of an unknown outlet for the Steenkoppies Case Study.
- Using catchment scale WFs to determine maximum allowable production on an aquifer (or in a catchment) to achieve multi-generational sustainability targets as proposed by Gleeson et al. (2012).
- The blue and green WF sustainability assessments can be further improved in future research, specifically with regards to determination of natural runoff, additional components that can be included in the calculation of blue water availability (such as water allocated to downstream users), and accounting for recharge of the aquifer (or other water resource) under natural vegetation, which may be defined as available blue water.

8.4 Water footprints of wastage

Water footprints of food wastage between harvesting and the consumer present opportunities to reduce water use. However, reductions or even elimination in wastage of crops produced on the Steenkoppies Aquifer alone will not be sufficient to achieve blue water sustainability targets. Furthermore, percentage wastage calculated here is already much lower than what has been recorded in other studies for other parts of the world and for sub-Saharan Africa. Food wastage is still important and should therefore be considered as only one of several measures to be implemented to reduce the WFs on the Steenkoppies Aquifer.

Classifying waste is complex, because wasted food all along the supply chain up to the retailer are used for other beneficial purposes such as composting and animal feed. Lettuce has relatively high wastage rates along the supply chain, partly because the crop has a short shelf-life, and because it cannot be preserved or frozen. This information should motivate some awareness raising among consumers to plant these crops in homestead gardens. Further reductions in food wastage may come at a cost, for example ecological impacts due to pesticide application, or carbon emissions associated with energy use or refrigeration. Buying less food more often requires more frequent transporting and increased carbon emissions. Future research studies are, therefore, required to:

- Improve classification of wastage to account for other beneficial uses of produce that is not suitable for selling.
- Compare the increased ecological and carbon footprints with the gains of reducing water footprints when implementing different strategies to reduce food wastage.

9 CONCLUSIONS AND RECOMMENDATIONS

by

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The research conducted in this project aimed to not only estimate WF metrics for important fruit and vegetable crops, but also to explore the use of different WF assessment approaches and to interpret the usefulness/applicability of the information generated. To aid in this objective, two catchment case studies were selected at the onset of the project, the first being the Steenkoppies Aquifer located in Tarlton, Krugersdorp, and the second being the Olifants-Doorn Water Management Area (WMA).

A comparison of different WF methodologies (WFN, LCA, hydrological-based) using data generated within the two case studies as part of this research highlighted strengths and weaknesses associated with each approach. Because the most work on WF assessments around the globe has been done using the WFN approach, it was a useful exercise to calculate WFs for important South African fruit and vegetable crops according to this methodology and compare to the results of other researchers. Vast differences were observed between WFs as a result of crop species, inter-annual weather variation, and the growing season in which the crop was cultivated (spring, summer, autumn, winter).

As a modification of the original approach and similar to the ISO14016 recommendation, the LCA approach aims to adjust blue WFs according to local conditions using a water stress index, which has been calculated for the globe, but can also be calculated in more detail for a specific region of interest. Blue WFs for the LCA approach were lower than for the WFN approach as they were simply multiplied by the water stress index for the region, which was 0.78 in the case of Steenkoppies Aquifer. We find the recommendation to report the WF as water equivalents or 'H_2O-e' is a concept that people outside of the LCA community will have trouble grasping, at least initially. A major strength of the LCA approach, however, is the advanced methodology and databases that exist for the calculation of other environmental impacts such as the carbon footprint, eutrophication, freshwater ecotoxicity, aquatic and terrestrial acidification and human health. As the method takes multiple environmental impacts into account simultaneously, it can monitor for 'problem shifting' or 'pollution swapping'. In this regard, the LCA method rejects the use of the grey WF concept. Proponents of the LCA approach argue that green water use is not considered an impact, because of the inseparability of green water and land occupation. However, our judgement is that if less green water is used by a specific land use it may lead to increased blue water in rivers and aquifers as a result of higher levels of runoff or drainage.

Using the hydrological-based method for South African fruit or vegetable crops for which drainage plus runoff is higher than irrigation, a negative blue WF is possible. This was observed for apples grown in the Koue Bokkeveld, where the blue WF was estimated to be − 41 m^3 $tonne^{-1}$. While it may be useful to know that under this land use recharge of water resources is greater than irrigation, it is confusing to obtain a negative blue WF for a crop that is so heavily reliant on irrigation, even if deep drainage plus runoff is greater than the total amount irrigated. This is largely because irrigation is applied during the dry summer season, which more than compensates for the water used by the orchard over this period, while rainfall during the wet winter months (when the orchard is dormant) results in recharge and runoff. The blue:green WF ratio for this approach was observed to be almost the inverse of the results according the WFN method. While it was acknowledged that this approach can lead to further understanding of the hydrology of the system using the WF value alone, this method does not appear to be more effective in creating a WF that is useful for consumer awareness or for water resources management.

The Water Footprint Network (WFN) methodology proposed by Hoekstra et al. (2011) was therefore selected as the most appropriate for water footprint (WF) assessments. The value of their approach can be seen on different levels.

9.1 Value of WFN water footprints on a local level

On a local or farm level, the WFN methodology makes it possible to:

- Calculate WFs for well-managed farms which can be used as benchmarks for other farmers in the region.
- Calculate spatially-explicit WFs using local yield data and remotely-sensed estimates of crop water use (e.g. FruitLook).
- Determine whether efficient irrigation management practices were used, which are reflected by maximum green WFs and minimum blue WFs.
- Determine which crops and cultivars have low WFs, so that these can be selected during dry years when water limitations are enforced.
- Make decisions about what a farmer wants to achieve with the available water, for example in terms of economic gain, nutritional value or job creation.

However, some complexities of calculating WFs according to the WFN approach must be kept in mind.

- Water footprints can differ depending on the growing season and it also varies between years and between different locations. Water footprints must therefore be calculated with local data, and be specific to the growing season and context in which they are applied. Longer-term crops such as fruit tree orchards calculate WFs over a full calendar year, although annual variation is evident, due to changes in total evaporation and yield as the orchard matures. Upon maturity, crop water use volumes (and resultant proportions of WF_{blue}, WF_{green} and WF_{grey}) may be relatively consistent year-to-year, however, differences in annual yield between years has a disproportionately greater influence on total WF and WP estimates. Higher yields result in lower WF values and higher WP values, and vice versa.
- Observations on volumes of water actually used by a particular crop will greatly improve the accuracy of water footprint calculations for products of that crop. Detailed field

measurements are necessary for more realistic subsequent calculations of catchment WFs. The quality of data used for crop water use modelling can have notable impacts on the WF outcomes. If estimated weather variables, such as solar radiation data, were used to develop crop parameters, estimated data should also be used when using these crop parameters during application of the model, otherwise ETo and other outcomes could potentially be over- or under-estimated, which will impact yield and WF outcomes. The same rule should be applied when using measured data to parameterize a crop.

- The functional unit that is used to calculate WFs can strongly impact the outcomes, for example, WFs of grain crops calculated in fresh mass are higher than for vegetables, but when calculated with dry matter these WFs are lower than for vegetables. This is because of the low water contents of the grains relative to the vegetables (for example, 13% for wheat versus 96% for lettuce). Using other functional units, such as nutritional content, economic gain or job creation may therefore be more useful in future work.
- Crop residues that are normally used for other purposes, such as composting and animal feed, are not currently included in WF calculations, which may cause an overestimation of WFs.
- Grey WF methodology still requires improvements, because the results were not successfully verified by groundwater quality analyses for the Steenkoppies Case Study. Uncertainties exist with regard to the most appropriate methodology for accounting for concentrations of certain pollutants in soil and water, particularly pesticides and metals. Further studies on leaching rates of pollutants from irrigation water to soil and groundwater are required. South Africa does not have any maximum contaminant levels for pesticides (they are not supposed to be present at all) and the maximum concentration applied in the WF_{grey} equation has a significant impact on the final grey WF calculation. This currently leads to inordinately high WF_{grey} values associated with pesticides, essentially rendering them unusable. More regional studies on leaching potential, and metal and pesticide content of water and soil, are needed to determine a more representative grey WF calculation that incorporates all relevant pollutants in a realistic and practical manner.

9.2 Value of Water Footprint Network (WFN) water footprints on a regional level

For aquifers and catchments in general, the WFN methodology is considered to be most useful, because it is quantitative and can be interpreted within a catchment manager's information systems. Water footprints that are calculated according to the WFN methodology provide a simple way to estimate the total evapotranspiration (ET) of agriculture and to assess the sustainability of this ET. For the Steenkoppies Aquifer Case Study, the conclusion was made that agricultural water uses between 1986 and 2012 were unsustainable, as determined by the WFN methodology. This conclusion was supported by the fact that groundwater levels and outflows from Maloney's Eye were consistently reduced during this period. In this study the methodology proposed by (Hoekstra et al. 2011) has been expanded by providing the framework in which the WF methodology can be better applied. According to this framework, total production on an aquifer can be multiplied by the WFs of the crops to obtain the total agricultural water use (ET) on the aquifer. The total ET of agriculture, together with precipitation, WFs of natural vegetation, other water uses and in- and outflows from the aquifer, can be used to estimate the water balance of an aquifer and in this case study it improved the understanding of the geohydrology of the aquifer. This framework is simple because it requires relatively little information, of which the crop WFs, total production and natural vegetation ET are the most important. Water footprints, according to the WFN, were able to provide the quantitative data needed to prioritise actions and measures that are required to achieve sustainable water use on the Steenkoppies Aquifer, which will apply to aquifers in general. For example, addressing potential water savings in the packhouses and the reduction of food wastage are very important, but will not be sufficient measures to achieve sustainable water uses on the Steenkoppies Aquifer and must be applied together with other measures. Selecting alternative cultivars with lower WFs could, however, be successfully used to achieve sustainable water use on the Steenkoppies Aquifer, or aquifers in general. Cos and butterleaf lettuce varieties, for example, had much lower ET compared to the more common iceberg lettuce and these varieties could result in notably lower catchment scale WFs.

In the Olifants-Doorn case study an advantage of calculating the water footprints of apple and citrus orchards at a quaternary catchment (QC) scale was that it provided a reasonable estimate of the overall volume of water required for the production of these crops. It also indicated how their water requirements vary across the region. This information is potentially useful for catchment water management and allocation decisions. However, for comprehensive decisions, accurate WF for all crops in the catchment will need to be assessed and included. The distinction between the blue, green and grey components also provides a means of easily assessing the crop-specific irrigation requirements for an area, in comparison to the dependence upon rainfall.

9.3 Use of Water Footprints on a National Level

In the modern world, consumers are often unaware of the environmental impacts associated with the production of the products they buy and are therefore unable to make decisions and act according to their values. It is recognised that changing consumer behaviour and demands are key to reaching sustainable water use targets. The term virtual WF has been proposed as a way to inform water users of the impact on water resources of a product that is produced in another location or country. Virtual water is therefore applicable on a national level where decisions must be made on exports and imports, and it also applies to raising awareness of consumers. However, WFs according to the WFN without a sustainability assessment are not considered suitable for awareness raising or labelling of products, because the data is not informative outside the local environmental context. Because of the complexity of the ecological, social and economic systems in which water is used, methods that aim to provide information that will enable a distant consumer or country to make wise decisions about their virtual water use are likely to fail. Alternative ways to influence consumers or countries where products are exported to, such as education, advertising and subsidies, should be considered in future research. It is expected that WFs can play an important role in generating the required information and knowledge that will ultimately lead to wise decisions being made in terms of sustainable water use.

South Africa's National Water Resources Strategy (NWRS-2, 2013), calls for substantial water savings in agriculture and has the implementation of water-use efficiency (water productivity) measures as one of its core strategies. Accurate WF assessments are one means of facilitating more efficient and productive use of water within the sector. The particular scale at which a WF assessment is done (farm or catchment) also has the potential to facilitate both on-farm water management planning and irrigation scheduling, as well as crop-specific water use allocation guidelines and sustainability improvements within catchments. Potential applications of the latter include the provision of data for Water Stewardship (AWS, 2014) and / or Global Gap assessments, or even future water-use related certification schemes.

It is concluded that WFs according to the WFN methodology can provide reliable and useful data on the use of water. This data must be interpreted according to the local knowledge of the ecological, economic and social environment in which the water is used to provide information for those who must make decisions. Decision makers need knowledge and experience to know how to respond to the information provided and the wisdom on how to achieve sustainable water use. Without adequately processing good data, we do not have reliable information or knowledge, and will not be able to make wise decisions, as T.S. Eliot (1934) said in his poem 'The Rock':

Where is the wisdom that we have lost in knowledge?
Where is the knowledge that we have lost in information?

9.4 Recommendations for future research

Based on the results of this project, our recommendations for future research are:

- Develop WF methodology to incorporate the beneficial uses of crop residues in the WF estimation. Linked to this, improve classification of wastage to account for other beneficial uses of biomass that is not suitable for direct selling.
- Determine how significant the variations in WFs are between different crops and crop cultivars.
- Further develop WF approaches using alternative functional units, such as crop nutritional content, economic gain or job creation per unit water used.
- Improve the understanding of how initial soil water content at planting, and where this water originated from, impacts the blue, green and grey WF.
- Begin compiling a national database of crop and cultivar WFs for specific regions under specific management practices.
- Consider the ecological and carbon footprints simulataneously to WFs when assessing potential impact.
- Record actual crop yields produced by the farmers at the catchment scale over the long term for more accurate estimation of catchment scale WFs.
- Improve the quantification of water use by natural vegetation.
- Further refine the catchment WF framework to accurately estimate outflows from an aquifer (assuming these can be accurately measured).
- Use catchment scale WFs to determine maximum allowable production on an aquifer (or in a catchment) to achieve multi-generational sustainability targets as proposed by Gleeson et al. (2012).
- Improve the interplay between WF accounting and hydrological assessments to improve the understanding of the dynamics and sustainable water use for a particular system.
- Blue and green WF sustainability assessments can be improved specifically with regards to determination of natural runoff, additional components that can be included in the calculation of blue water availability (such as water allocated to downstream users), and accounting for recharge of the aquifer (or other water resource) under natural vegetation, which may be defined as available blue water.

- Improve grey WF methodology to better understand the nutrient balances of intensive cropping systems on a catchment scale, as well as an improved means of accounting for pesticide / herbicide use and pollution.
- Conduct a catchment scale grey WF assessment to improve understanding on actual water quality impacts and how this can be represented in a simpler way.

10 REFERENCES

ACKOFF RL (1989) From data to wisdom. *Journal of Applied Systems Analysis* **16** (1) 3-9.

AGROCLIMATOLOGY STAFF (2014) ARC-ISCW Climate Information System, Pretoria, South Africa.

ALCAMO J, DÖLL P, HENRICHS T, KASPAR F, LEHNER B, RÖSCH T and SIEBERT S (2003) Development and testing of the WaterGAP 2 global model of water use and availability. *Hydrological Sciences Journal* **48** (3) 317-337.

ALDAYA M and HOEKSTRA A (2010) The water needed for Italians to eat pasta and pizza. *Agricultural Systems* **103** (6) 351-360.

ALDAYA MM, MARTÍNEZ-SANTOS P and LLAMAS MR (2010) Incorporating the water footprint and virtual water into policy: Reflections from the Mancha Occidental Region, Spain. *Water Resources Management* **24** (5) 941-958.

ALEXANDROVA P and DONOV D (2003) Nitrogen content and its uptake by maize as influenced by some meteorological elements and fertilization. *International Agrophysics* **17** (2) 41-46.

ALLIANCE FOR WATER STEWARDSHIP (2012) Water stewardship accounting. Available online. URL: www.allianceforwaterstewardship.org (Accessed 29 November 2013).

ALLEN RG, PEREIRA LS, RAES D and SMITH M (1998) Crop evapotranspiration-Guidelines for computing crop water requirements-FAO Irrigation and Drainage Paper 56. *FAO, Rome* **300** (9) D05109.

ANNANDALE J, BENADE N, JOVANOVIC N, STEYN J and DU SAUTOY N (1999) Facilitating irrigation scheduling by means of the Soil Water Balance model, Water Research Commission (WRC) Report No. 753/1/99, Pretoria, South Africa.

ANZECC and ARMCANZ (2000) Australian and New Zealand guidelines for fresh and marine water quality. *Australian and New Zealand Environment and Conservation Council and Agriculture and Resource Management Council of Australia and New Zealand, Canberra* 1-103 pp.

BACKEBERG GR and REINDERS FB (2009) Institutional reform and modernisation of irrigation systems in South Africa. in *Proceedings of the 5th Asian Regional Conference of ICID*, New Delhi, India.

BARNARD HC (1996) Ondersoek na die afname in vloei van Maloney's Eye, Distrik Krugersdorp. Technical Report GH 3877, Department of Water Affairs and Forestry. Pretoria, South Africa.

BARNARD HC (1997) Geohydrological evaluation of the Maloney's Eye catchment area. MSc Dissertation. University of the Free State, South Africa.

BERGER M and FINKBEINER M (2013) Methodological Challenges in Volumetric and Impact-Oriented Water Footprints. *Journal of Industrial Ecology* **17** (1) 79-89.

BOSIRE CK, OGUTU JO, SAID MY, KROL MS, DE LEEUW J and HOEKSTRA AY (2015) Trends and spatial variation in water and land footprints of meat and milk production systems in Kenya. *Agriculture, Ecosystems & Environment* **205** 36-47.

BREDENKAMP D, VAN DER WESTHUIZEN C, WIEGMANS F and KUHN C (1986b) Groundwater supply potential of dolomite compartments west of Krugersdorp. *Department of Water Affairs Directorate of Geohydrology* Report nr. GH3440, Pretoria, South Africa.

BREDENKAMP DB, VAN DER WESTHUIZEN C, WIEGMANS FE and KUHN CM (1986) Groundwater supply potential of dolomite compartments west of Krugersdorp. Volume 2. Report number GH 3440, Department of Water Affairs: Directorate of Geohydrology. Pretoria, South Africa.

BUNN ES and ARTHINGTON HA (2002) Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. *Environmental Management* **30** (4) 492-507.

BURGESS SS, ADAMS MA, TURNER NC, BEVERLY CR, ONG CK, KHAN AA and BLEBY TM (2001) An improved heat pulse method to measure low and reverse rates of sap flow in woody plants. *Tree Physiology* **21** (9) 589-598.

CHAPAGAIN A and HOEKSTRA A (2011) The blue, green and grey water footprint of rice from production and consumption perspectives. *Ecological Economics* **70** (4) 749-758.

CHAPAGAIN A and HOEKSTRA AY (2004) Water footprints of nations, value of water research Report Series No. 16. in*,* UNESCO-IHE, Delft, The Netherlands.

CHAPAGAIN A and ORR S (2008) UK Water Footprint: the impact of the UK's food and fibre consumption on global water resources. Volume two: appendices. *WWF-UK, Godalming*.

CHAPAGAIN AK and HOEKSTRA AY (2007) The water footprint of coffee and tea consumption in the Netherlands. *Ecological Economics* **64** (1) 109-118.

CHAPAGAIN AK and ORR S (2009) An improved water footprint methodology linking global consumption to local water resources: a case of Spanish tomatoes. *Journal of Environmental Management* **90** (2) 1219-1228.

CHAPAGAIN AK and ORR S (2009) An improved water footprint methodology linking global consumption to local water resources: A case of Spanish tomatoes. *Journal of Environmental Management* **90** (2) 1219-1228.

CLOTHIER B, GREEN S, HERATH I, VAN DEN DIJSSEL C, MASON K and DRYDEN G (2012) The water footprint of export apples from New Zealand., Pipfruit New Zealand Report No. PF11P12. 10. Plant & Food Research, Auckland, New Zealand. 48 pp.

CONLEY DJ, PAERL HW, HOWARTH RW, BOESCH DF, SEITZINGER SP, KARL E, KARL E, LANCELOT C, GENE E and GENE E (2009) Controlling eutrophication: nitrogen and phosphorus. *Science* **123** 1014-1015.

CROP ESTIMATES COMMITTEE (2016) Preliminary area planted and preliminary production forecast - summer crops, Department of Agriculture, Forestry and Fisheries (DAFF). Pretoria, South Africa.

CROP ESTIMATES CONSORTIUM (2015) Agricultural boundaries for crop field areas, Department of Agriculture, Forestry and Fisheries. Pretoria, South Africa.

CSIR (2012) [Series editor KG Kennedy] Final Report: Water use surveillance and ecological economic modelling of agro-ecosystems in the Sandveld region, Western Cape. pp 179.

DAFF (2010) Irrigation Strategy for South Africa, Department of Agriculture, Forestry and Fisheries. Pretoria, South Africa. www.dwaf.gov.za

DE JAGER E (2016) South Africa annual total rainfall general information, South African Weather Services, Pretoria, South Africa. www.weathersa.co.za

DEA&DP (2011) Western Cape IWRM Action Plan: Status Quo Report Final Draft. Prepared by Western Cape Department of Environmental Affairs and Development Planning (DEA&DP). Available online. URL: http://www.westerncape.gov.za/eng/pubs/public_info/P/205596 (Accessed 28 January 2013).

DEPARTMENT OF WATER AFFAIRS (2011) Classification of significant water resources in the Mokolo and Matlabas Catchment: Limpopo Water Management Area (WMA) and Crocodile (West) and Marico WMA: Ecological Water Requirements Report. Report No: RDM/WMA 1,3/00/CON/CLA/0312, Directorate Water Resource Classification. Pretoria, South Africa.

DEPARTMENT OF WATER AFFAIRS (2013) National Water Resource Strategy 2, Pretoria, South Africa.

DEPARTMENT OF WATER AFFAIRS (2014) Water quality data for the Maloney's Eye. Monitoring point ID 90163. Resource Directed Management of Water Quality, Pretoria, South Africa.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (1996) South African water quality guidelines. Edition 2; Volume 7: Aquatic ecosystems, Pretoria, South Africa.

DEPARTMENT OF WATER AFFAIRS AND FORESTRY (1999) General and special limits applicable to discharge of waterwater into a water resource. in, Government Gazette 20526. Pretoria, South Africa.

DEPARTMENT OF WATER AND SANITATION (2014) Long term flow data for the Maloneys' Eye. Available online. URL: https://www.dwa.gov.za/Hydrology/hymain.aspx (Accessed 1 June 2014).

DEPARTMENT OF WATER AND SANITATION (2016) Hartbeespoort Dam background information. URL: Available online: https://www.dwa.gov.za/Dir_WQM/what.asp (Accessed 11 August 2016).

DEPARTMENT OF WATER AND SANITATION (2016) The quaternary drainage regions. URL: Available online: https://www.dwa.gov.za/iwqs/wms/data/000key2data.asp (Accessed 20 November 2015).

DEURER M, GREEN SR, CLOTHIER BE and MOWAT A (2011) Can product water footprints indicate the hydrological impact of primary production? – A case study of New Zealand kiwifruit. *Journal of Hydrology* **408** (3–4) 246-256.

DOMINGUEZ-FAUS R, POWERS SE, BURKEN JG and ALVAREZ PJ (2009) The water footprint of biofuels: A drink or drive issue? *Environmental Science & Technology* **43** (9) 3005-3010.

DOS SANTOS L (2014) Food wastage at retail level. Personal communication., Pretoria, South Africa.

DZIKITI S and SCHACHTSCHNEIDER K (2015) Water Stewardship for stone fruit farmers: Technical report to World Wide Fund for Nature, South Africa. Available online. URL: http://awsassets.wwf.org.za/downloads/wwf_water_stewardshiptechreport_2015.pdf

DZIKITI S, VERREYNNE SJ, STUCKENS J, STREVER A, VERSTRAETEN WW, SWENNEN R, THERON KI and COPPIN P (2011) Seasonal variation in canopy reflectance and its application to determine the water status and water use by citrus trees in the Western Cape, South Africa. *Agricultural and forest meteorology* **151** (8) 1035-1044.

ESKOM (2016) Water Management. URL: http://www.eskom.co.za/OurCompany/SustainableDevelopment/Pages/Reduction_In_Water_Consumption.aspx (Accessed 24 September 2016).

FAO (2013) Food Wastage Footprint: Impact on Natural Resources Summary Report. FOOD AND AGRICULTURE ORGANIZATION, ISBN 978-92-5-107752-8. 63 pp.

FERNÁNDEZ J and CUEVAS M (2010) Irrigation scheduling from stem diameter variations: a review. *Agricultural and Forest Meteorology* **150** (2) 135-151.

FRANKE NA, BOYACIOGLU H and HOEKSTRA AY (2013) Grey water footprint accounting: Tier 1 supporting guidelines, Value of Water Research Report Series No. 65, UNESCO-IHE, Delft, the Netherlands.

GATHINO S (2016) Food wastage at retail level. Personal communication. Pretoria, South Africa.

GERBENS-LEENES P, HOEKSTRA A and VAN DER MEER T (2009) The water footprint of energy from biomass: A quantitative assessment and consequences of an increasing share of bio-energy in energy supply. *Ecological Economics* **68** (4) 1052-1060.

GLEESON T, ALLEY WM, ALLEN DM, SOPHOCLEOUS MA, ZHOU Y, TANIGUCHI M and VANDERSTEEN J (2012) Towards sustainable groundwater use: setting long‐term goals, backcasting, and managing adaptively. *Groundwater* **50** (1) 19-26.

GLEESON T, WADA Y, BIERKENS MF and VAN BEEK LP (2012) Water balance of global aquifers revealed by groundwater footprint. *Nature* **488** (7410) 197-200.

GLOBALG.A.P. (2013) GLOBALG.A.P. Certification. Available online. URL: www.globalgap.org (Accessed 29 November 2013).

GOEDKOOP M, HEIJUNGS R, HUIJBREGTS M, DE SCHRYVER A, STRUIJS J and VAN ZELM R (2013) ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level First edition (revised) Report I: Characterisation. Ministry of Housing, Spatial Planning and Environment (VROM), Den Haag, Netherlands, 133 pp.

GUSH M, DZIKITI S, CLULOW A, MENGISTU M, JARMAIN C, TAYLOR N and EVERSON C (2014) Water use of apple orchards. In: GUSH MB and TAYLOR NJ (Eds). The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling. Water Research Commission, WRC Report 1770/2/14, Section 3, Pretoria, South Africa.

GUSH M and TAYLOR N (2014) The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling. Water Research Commission Report No.1770/2/14, WRC, Pretoria, South Africa.

GUSTAVSSON J, CEDERBERG C, SONESSON U, VAN OTTERDIJK R and MEYBECK A (2011) Global food losses and food waste. *Food and Agriculture Organization of the United Nations, Rome, Italy*.

HERATH I, GREEN S, HORNE D, SINGH R and CLOTHIER B (2013 a) Water footprinting: Assessing impacts of potato production through measurements and modelling. in *WISPAS: a newsletter about soil - plant - atmosphere system.* Plant and Food Research, New Zealand.

HERATH I, GREEN S, SINGH R, HORNE D, VAN DER ZIJPP S and CLOTHIER B (2013) Water footprinting of agricultural products: a hydrological assessment for the water footprint of New Zealand's wines. *Journal of Cleaner Production* **41** 232-243.

HOEKSTRA A (2003) Virtual water trade: Proceedings of the International Expert meeting on virtual water trade. Delft, The Netherlands, 12 – 13 December 2002, value of water research report series no. 12, UNESCO – IHE, www.waterfootprint.org/Reports/Report12.pdf. Delft The Netherlands.

HOEKSTRA AY, ALDAYA MM, CHAPAGAIN AK and MEKONNEN MM (2011) *The water footprint assessment manual: Setting the global standard*, Routledge, London, UK.

HOEKSTRA AY and CHAPAGAIN AK (2011) *Globalization of water: Sharing the planet's freshwater resources*, Blackwell Publishing, Oxford, UK.

HOEKSTRA AY, CHAPAGAIN AK, ALDAYA MM and MEKONNEN MM (2009) Water footprint manual: State of the art 2009, Water Footprint Network. Enschede, The Netherlands.

HOEKSTRA AY, CHAPAGAIN AK, ALDAYA MM and MEKONNEN MM (2011b) *The water footprint assessment manual: Setting the global standard*, Routledge.

HOEKSTRA AY, MEKONNEN MM, CHAPAGAIN AK, MATHEWS RE and RICHTER BD (2012) Global monthly water scarcity: blue water footprints versus blue water availability. *PLoS One* **7** (2) e32688.

HOLLAND M (2016) Personal communication on geohydrology of the Steenkoppies Aquifer, Pretoria, South Africa.

I CANALS LM, CHAPAGAIN A, ORR S, CHENOWETH J, ANTON A and CLIFT R (2010) Assessing freshwater use impacts in LCA, part 2: case study of broccoli production in the UK and Spain. *The International Journal of Life Cycle Assessment* **15** (6) 598-607.

I CANALS LM, CHENOWETH J, CHAPAGAIN A, ORR S, ANTÓN A and CLIFT R (2009) Assessing freshwater use impacts in LCA: Part I—inventory modelling and characterisation factors for the main impact pathways. *The International Journal of Life Cycle Assessment* **14** (1) 28-42.

INGWERSEN WW (2012) Life cycle assessment of fresh pineapple from Costa Rica. *Journal of Cleaner Production* **35** 152-163.

ISO 14046 (2014) Environmental Management Water footprint — Principles, requirements and guidelines. In, Geneva, Switzerland.

JESWANI HK and AZAPAGIC A (2011) Water footprint: methodologies and a case study for assessing the impacts of water use. *Journal of Cleaner Production* **19** (12) 1288-1299.

JONGSCHAAP R, BLESGRAAF R, BOGAARD T, VAN LOO E and SAVENIJE H (2009) The water footprint of bioenergy from Jatropha curcas L. *Proceedings of the National Academy of Sciences of the United States of America* **106** (35) E92-E92.

JOVANOVIC N, ANNANDALE J, BENADÉ N and CAMPBELL G (2003) CLIMGEN-UP: A user-friendly weather data generator. *South African Journal of Plant and Soil* **20** (4) 203-205.

JOVANOVIC N, EHLERS L, BENNIE A, DU PREEZ C and ANNANDALE J (2004) Modelling the contribution of root accessible water tables towards crop water requirements. *South African Journal of Plant and Soil* **21** (3) 171-181.

KATZ B, BERNDT M and CRANDALL C (2014) Factors affecting the movement and persistence of nitrate and pesticides in the surficial and upper Floridan aquifers in two agricultural areas in the southeastern United States. *Environmental Earth Sciences* **71** (6) 2779-2795.

LAKE PS (2003) Ecological effects of perturbation by drought in flowing waters. *Freshwater Biology* **48** (7) 1161-1172.

LAUNIAINEN S, FUTTER MN, ELLISON D, CLARKE N, FINÉR L, HÖGBOM L, LAURÉN A and RING E (2014) Is the water footprint an appropriate tool for forestry and forest products: The Fennoscandian case. *Ambio* **43** (2) 244-256.

LE ROUX C, VAN DER LAAN M, VAHRMEIJER J, BRISTOW K and ANNANDALE J (2016) Estimating water footprints of vegetable crops: Influence of growing season, solar radiation data and functional unit. *Water* **8** (10) 473.

LUNDQVIST J, DE FRAITURE C and MOLDEN D (2008) *Saving water: from field to fork: curbing losses and wastage in the food chain. SIWI Policy Brief*, Stockholm International Water Institute (SIWI), Stockholm, Sweden.

LUO L, VAN DER VOET E, HUPPES G and DE HAES HAU (2009) Allocation issues in LCA methodology: a case study of corn stover-based fuel ethanol. *The International Journal of Life Cycle Assessment* **14** (6) 529-539.

MAHAN LK and ESCOTT-STUMP S (2004) *Krause's food, nutrition, & diet therapy*, WB Saunders, Philadelphia, USA.

MEKONNEN M and HOEKSTRA A (2010) *A global and high-resolution assessment of the green, blue and grey water footprint of wheat*, UNESCO-IHE Institute for Water Education, Delft, the Netherlands.

MEKONNEN MM and HOEKSTRA AY (2011) The green, blue and grey water footprint of crops and derived crop products. *Hydrology and Earth System Sciences* **15** (5) 1577-1600.

MEKONNEN MM and HOEKSTRA AY (2012) A global assessment of the water footprint of farm animal products. *Ecosystems* **15** (3) 401-415.

MENTIS D (2016) Food wastage at retail level. Personal communication, Pretoria, South Africa.

MIDGLEY S and LÖTZE E (2008) *Climate change in the Western Cape of South Africa: Trends, projections and implications for chill unit accumulation*, *Acta Horticulturae* **903** 1127-1134.

MISSTOFVERENIGING VAN SUID AFRIKA (2007) *Bemestingshandleiding*, FSSA-MVSA, Pretoria, Suid Africa.

MITCHELL B (1990) *Integrated water management: international experiences and perspectives*, Belhaven Press, London, UK.

MOSSÉ J, HUET J and BAUDET J (1985) The amino acid composition of wheat grain as a function of nitrogen content. *Journal of Cereal Science* **3** (2) 115-130.

MOSTAFA ME (1977) Water in arid agriculture: salinity and waterlogging in the near-east region. *Ambio* **6** (1) 36-39.

MUCINA L and RUTHERFORD MC (2006) *The vegetation of South Africa, Lesotho and Swaziland.*, Strelitzia 19, South African National Biodiversity Institute, Pretoria, South Africa.

MULTSCH S, PAHLOW M, ELLENSOHN J, MICHALIK T, FREDE H-G and BREUER L (2016) A hotspot analysis of water footprints and groundwater decline in the High Plains Aquifer region, USA. *Regional Environmental Change* **16** (8) 1-10.

NAGAR B, DATTA M and KHAKHAR M (1974) Eutrophication and recovery in experimental lakes: implications for lake management. *Science* **184** 897-899.

NAHMAN A, DE LANGE W, OELOFSE S and GODFREY L (2012) The costs of household food waste in South Africa. *Waste Management* **32** (11) 2147-2153.

NDITWANI T, BASSON T and ROSSOUW J (2009) Water Reconciliation Strategy for the Crocodile (West) River catchment. *Civil Engineering* **17** (5) 14-18.

NIEUWOUDT WL, BACKEBERG GR and DU PLESSIS HM (2004) The value of water in the South African Economy: Some Implications. *Agrekon* **43** (2) 162-183.

NYAMBO P and WAKINDIKI II (2015) Water footprint of growing vegetables in selected smallholder irrigation schemes in South Africa. *Water SA* **41** 571-578.

OELOFSE SH and NAHMAN A (2013) Estimating the magnitude of food waste generated in South Africa. *Waste Management & Research* **31** (1) 80-86.

PAHLOW M, SNOWBALL J and FRASER G (2015) Water footprint assessment to inform water management and policy making in South Africa. *Water SA* **41** (3) 300-313.

PATTIE F, WARD WB and PATTON DR (1985) Effects of Regulated Water Flows on Regeneration of Fremont Cottonwood. *Journal of Range Management* **38** (2) 135-138.

PEGASYS (2012) Water Footprint Analysis for the Breede Catchment, South Africa draft report, Breede Overberg Catchment Management Agency, Cape Town, South Africa.

PERRY C (2014) Water footprints: Path to enlightenment, or false trail? *Agricultural Water Management* **134** 119-125.

PETEK M, CUSTIC MH, NINA T, SLUNJSKI S, LEPOMIR C, PAVLOVIC I, KARAZIJA T, LAZAREVIC B and CVETKOVI S (2012) Nitrogen and crude proteins in beetroot (Beta vulgaris var. conditiva) under different fertilization treatments. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* **40** (2) 215-219.

PFISTER S, BAYER P, KOEHLER A and HELLWEG S (2011) Environmental impacts of water use in global crop production: hotspots and trade-offs with land use. *Environmental Science & Technology* **45** (13) 5761-5768.

PFISTER S, KOEHLER A and HELLWEG S (2009) Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science & Technology* **43** (11) 4098-4104.

PIKE A and SCHULZE RE (2004) Development and evaluation of an installed hydrological modelling system, Water Research Commission (WRC) Report No. 1155/1/04. Pretoria, South Africa.

POSTEL S (1999) *Pillar of sand: can the irrigation miracle last?*, W. W. Norton & Company United States of America.

PRODUCTION REPORT (2016) Daily input and output quantities of carrots, cabbage and lettuce for 2015 - 2016, Steenkoppies Aquifer Packhouse.

RANCHOD N, SHERIDAN CM, PINT N, SLATTER K and HARDING KG (2015) Assessing the blue-water footprint of an opencast platinum mine in South Africa. *Water SA* **41** (2) 287-293.

REBITZER G, EKVALL T, FRISCHKNECHT R, HUNKELER D, NORRIS G, RYDBERG T, SCHMIDT W-P, SUH S, WEIDEMA BP and PENNINGTON DW (2004) Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications. *Environment International* **30** (5) 701-720.

RICHTER BD (2010) Re ‐ thinking environmental flows: from allocations and reserves to sustainability boundaries. *River Research and Applications* **26** (8) 1052-1063.

RIDOUTT BG and PFISTER S (2010) A revised approach to water footprinting to make transparent the impacts of consumption and production on global freshwater scarcity. *Global Environmental Change* **20** (1) 113-120.

RIDOUTT BG and PFISTER S (2013) A new water footprint calculation method integrating consumptive and degradative water use into a single stand-alone weighted indicator. *The International Journal of Life Cycle Assessment* **18** (1) 204-207.

RODRIGUEZ C, DE GALARRETA VR and KRUSE E (2015) Analysis of water footprint of potato production in the pampean region of Argentina. *Journal of Cleaner Production* **90** 91-96.

ROSENZWEIG C and PARRY ML (1994) Potential impact of climate change on world food supply. *Nature* **367** (6459) 133-138.

ROUNTREE M (2014) Information on aquatic impacts due to changes in river flows. Personal communication, South Africa.

ROWLEY JE (2007) The wisdom hierarchy: representations of the DIKW hierarchy. *Journal of Information Science* **33** (2) 163-180.

SABMILLER and WWF (2009) Water footprinting: identifying & addressing water risks in the value chain. URL: from http://awsassets.panda.org/downloads/sab0425_waterfootprinting_text_artwork.pdf (Accessed Accessed on 13 October 2016).

SANBI (2009) Updating National Land Cover, South African National Biodiversity Institute, Pretoria, South Africa.

SCANLON BR, JOLLY I, SOPHOCLEOUS M and ZHANG L (2007) Global impacts of conversions from natural to agricultural ecosystems on water resources: Quantity versus quality. *Water Resources Research* **43** (3).

SCHAU EM and FET AM (2008) LCA studies of food products as background for environmental product declarations. The *International Journal of Life Cycle Assessment* **13** (3) 255-264.

SCHEEPERS ME and JORDAAN H (2016) Assessing the blue and green water footprint of lucerne for milk production in South Africa. *Sustainability* **8** (1) 49.

SCHINDLER D and FEE E (1974) Experimental lakes area: whole-lake experiments in eutrophication. *Journal of the Fisheries Board of Canada* **31** (5) 937-953.

SCHINDLER DW (2006) Recent advances in the understanding and management of eutrophication. *Limnology and Oceanography* **51** (1) 356-363.

SCHULZE RE (2000) Modelling hydrological responses to land use and climate change: a southern African perspective. *Ambio* **29** (1) 12-22.

SCHULZE RE (2007) South African Atlas of Climatology and Agrohydrology. WRC Report 1489/1/06., Water Research Commission, Pretoria, South Africa.

SHUTTLEWORTH WJ and WALLACE J (1985) Evaporation from sparse crops ‐ an energy combination theory. *Quarterly Journal of the Royal Meteorological Society* **111** (469) 839-855.

SIMS JT, SIMARD RR and JOERN BC (1998) Phosphorus loss in agricultural drainage: historical perspective and current research. *Jounal of Environmental Quality* **27** 277-293.

SMAKHTIN V, ASHTON P, BATCHELOR A, MEYER R, MURRAY E, BARTA B, BAUER N, NAIDOO D, OLIVIER J and TERBLANCHE D (2001) Unconventional water supply options in South Africa. *Water International* **26** (3) 314-334.

SMOLDERS AJ, LUCASSEN EC, BOBBINK R, ROELOFS JG and LAMERS LP (2010) How nitrate leaching from agricultural lands provokes phosphate eutrophication in groundwater fed wetlands: the sulphur bridge. *Biogeochemistry* **98** (1-3) 1-7.

SONG X, WANG S, WANG Y, ZHAO Z and YAN D (2016) Addition of Fe 2+ increase nitrate removal in vertical subsurface flow constructed wetlands. *Ecological Engineering* **91** 487-494.

SORENSEN J (1998) Nitrogen effects on vegetable crop production and chemical composition. International Workshop on Ecological Aspects of Vegetable Fertilization in Integrated Crop Production 506, International Society of Horticultural Sciences (ISHS), Belgium.

SOUTH AFRICA YEARBOOK (2015), Pretoria, South Africa.

STARR RC and GILLHAM RW (1993) Denitrification and organic carbon availability in two aquifers. *Groundwater* **31** (6) 934-947.

STATISTICS SOUTH AFRICA (2016) Average prices used to calculate the Consumer Price Index from 2008 - 2015, Pretoria, South Africa.

SUN S, WU P, WANG Y and ZHAO X (2013) Temporal variability of water footprint for maize production: The case of Beijing from 1978 to 2008. *Water Resources Management* **27** (7) 2447-2463.

TAYLOR N, MAHOHOMA W, VAHRMEIJER J, SAAIMAN H, GUSH M, MENGISTU M, ANNANDALE J and EVERSON C (2014) Water use of citrus orchards. In: GUSH MB and TAYLOR NJ (Eds) The water use of selected fruit tree orchards (Volume 2): Technical report on measurements and modelling. Water Research Commission Report No 1770/2/14, Section 4., Pretoria, South Africa

THE COCA COLA COMPANY (2010) Sustainability Review 2009/2010.

TSHWANE FRESH PRODUCE MARKET (2014) Data on vegetables from the Steenkoppies Aquifer, Pretoria, South Africa.

UNILEVER (2012) Our water footprint. URL: www.unilever.com/sustainable-living/water/footprint/ (Accessed 22 November 2013).

UNITED NATIONS (1948) Universal Declaration of Human Rights, UN General Assembly, Resolution 217 A (III) of 10 December 1948, , Paris, France.

UNITED NATIONS (2010) 'The human right to water and sanitation', UN General Assembly, 64th session, Agenda item 48, UN, New York, US.

UNITED STATES DEPARTMENT OF AGRICULTURE (2015) National Nutrient Database for Standard Reference. Available online. URL: http://ndb.nal.usda.gov/ (Accessed Accessed on 2 June 2015).

VAHRMEIJER J (2016) Improved management of groundwater in irrigated catchments under stress (Unpublished doctoral thesis) University of Pretoria, South Africa.

VAHRMEIJER J, ANNANDALE J, BRISTOW K, STEYN J and HOLLAND M (2013) Drought as a catalyst for change: A Case Study of the Steenkoppies Dolomitic Aquifer. In *Drought in Arid and Semi-Arid Regions,* Chapter 14, Springer 251-268 pp.

VAN DER LAAN M, JUMMAN A and PERRET S (2015) Environmental Benefits of Improved Water and Nitrogen Management in Irrigated Sugar Cane: A Combined Crop Modelling and Life Cycle Assessment Approach. *Irrigation and Drainage* **64** (2) 241-252.

VAN HEERDEN P, CROSBY C, GROVÉ B, BENADÉ N, THERON E, SCHULZE R and TEWOLDE M (2009) Integrating and updating of SAPWAT and PLANWAT to create a powerful and user-friendly irrigation planning tool. Water Research Commission (WRC) Report No. TT 391/08 Pretoria, South Africa.

WADA Y, BEEK LPH and BIERKENS MFP (2012) Nonsustainable groundwater sustaining irrigation: A global assessment. *Water Resources Research* **48** (6) http://onlinelibrary.wiley.com/doi/10.1029/2011WR010562/full.

WALTON G (1951) Survey of literature relating to infant methemoglobinemia due to nitrate-contaminated water. *American Journal of Public Health and the Nations Health* **41** (8_Pt_1) 986-996.

WEIDEMA BP, THRANE M, CHRISTENSEN P, SCHMIDT J and LØKKE S (2008) Carbon footprint: a catalyst for life cycle assessment? *Journal of Industrial Ecology* **12** (1) 3-6.

WETZEL RG (2001) *Limnology: Lake and River Ecosystems. Third Edition*, Elsevier Academic Press., San Diego, US.

WICHELNS D (2010) Virtual water and water footprints offer limited insight regarding important policy questions. *International Journal of Water Resources Development* **26** (4) 639-651.

WICHELNS D (2011) Assessing water footprints will not be helpful in improving water management or ensuring food security. *International Journal of Water Resources Development* **27** (3) 607-619.

WICHELNS D (2011) Virtual water and water footprints. Compelling notions, but notably flawed. *GAIA-Ecological Perspectives for Science and Society* **20** (3) 171-175.

WIEGMANS F, HOLLAND M and JANSE VAN RENSBURG H (2013) Groundwater Resource Directed Measures for Maloney's Eye Catchment, Water Research Commission (WRC) Report No KV 319/13, Pretoria, South Africa.

WITTHUESER K, LEYLAND R and HOLLAND M (2009) Vulnerability of dolomite aquifers in South Africa. in Xu Y and E Braunes (eds), *Sustainable Groundwater Resources in Africa: Water supply and sanitation environment,* UNESCO Paris and CRC Press/Balkema, Taylor & Francis Group, pp. 119-131.

WORLD ECONOMIC FORUM (2016) The Global Risks Report 2016; 11th Edition, Geneva, Switzerland. Web adres: http://www3.weforum.org/docs/GRR/WEF_GRR16.pdf.

WU M, CHIU Y and DEMISSIE Y (2012) Quantifying the regional water footprint of biofuel production by incorporating hydrologic modeling. *Water Resources Research* **48** (10).

XU Z, WANG Y and LI H (2015) Stoichiometric determination of nitrate fate in agricultural ecosystems during rainfall events. *PloS One* **10** (4) e0122484.

ZHUO L, MEKONNEN M and HOEKSTRA A (2014) Sensitivity and uncertainty in crop water footprint accounting: a case study for the Yellow River basin. *Hydrology and Earth System Sciences* **18** (6) 2219-2234.

ZILBERMAN D, CHAKRAVORTY U and SHAH F (1997) Efficient Management of Water in Agriculture. in Parker DD and Y Tsurs (eds), *Decentralization and Coordination of Water Resource Management,* Springer US, Boston, MA, pp. 221-246.

Data storage

All raw and processed data are stored at:

Department of Plant and Soil Sciences
University of Pretoria
Hatfield
0028

CSIR, Natural Resources and Environment (NRE)
11 Jan Cilliers Street
Stellenbosch
7600
South Africa

APPENDICES

Appendix A – Capacity building

Mrs Betsie le Roux

In 2014 Mrs le Roux commenced with her PhD focusing on water footprint assessments for vegetable crops grown on the Steenkoppies Aquifer. Her work has included collecting commercial field data and managing crop water use field trials, interacting with farmers, acquiring data from various other stakeholders, modelling water dynamics from field to catchment scale, and investigating the usefulness of water footprint information at these various scales. Amongst other things, Mrs le Roux is now an expert crop modeller.

Mrs le Roux attended several local conferences and workshops as part of this work, including as an invited speaker. Mrs le Roux also played a key role in the administration of the WRC project, for example, taking minutes and presenting results at Reference Group meetings.

In 2016, Mrs le Roux manuscript to the open-access journal water was awarded a fee waiver to the value of approximately R17 000.

Mrs le Roux plans to submit her PhD thesis for examination in early 2017, and thereafter aims to remain at the University of Pretoria in a post-doctorate position continuing to do research on important water issues.

Mr Theunis Smit

Mr Smit's research included testing the ability of the Cosmic Ray Probe (CRP) to measure soil water content in potato fields at relatively large footprints of approximately 30 ha. In addition to the CRP, neutron probes and capacitance sensors were used to monitor soil water content, and the soil water balance was also modelled using the SWB model.

During his studies, Mr Smit was also appointed as a Teaching Assistant for Dr van der Laan's courses 'Sustainable Production Systems' (PPK251) and 'Introduction to Agroclimatology' (LKM260).

Mr Smit achieved 73% for his MSc dissertation, and was also awarded a scholarship from the South African Society for Crop Production.

Mr Smit has taken up a position in the Macadamia Industry with MayoMacs and is based in Nelspruit. Mr Smit commenced his PhD study at the University of Pretoria in 2016 on another WRC project studying the water use of macadamia trees.

Miss Sibongile Manamathela

Under the guidance of Dr. Dominic Mazvimavi (UWC) and Dr. Mark Gush (CSIR), conducted her research on the WF of important crops grown within the Olifants-Doorn WMA. Miss Manamathela submitted her dissertation for external examination in December 2014, and was awarded a final mark of 69% for the study. Her MSc study was entitled 'The water footprint of selected crops within the Olifants/Doorn Catchment, South Africa'.

Miss Manamathela currently works for Shell Downstream and the Department of Water and Sanitation.

Miss Nosey Matlala

Miss Matlala's research study required collecting data on the Hatfield Experimental Farm and Tarlton Greenway Farm, and worked on the carrots and Swiss chard.

Miss Matlala was also appointed as a Teaching Assistant for Dr van der Laan's courses 'Sustainable Production Systems' (PPK251) and 'Introduction to Agroclimatology' (LKM260).

Miss Matlala expects to hand in her dissertation by March 2017.

Mr Jerry Dlamini

Mr Jerry Dlamini joined the project from May 2015. Mr Dlamini was originally based at the Agricultural Research Council in Roodeplaat, before taking up a position with North-West University as a lecturer in crop and soil science. From 2017, Mr Dlamini will be joining the University of the Free State as a lecturer, where he will continue to pursue his PhD studies.

Appendix B – Knowledge Dissemination and Technology Transfer

Scientific articles

Le Roux, C.E., van der Laan, M., Vahrmeijer, T., Annandale, J.A. & K.L. Bristow. 2016. Estimating water footprints of vegetable crops: Influence of growing, solar radiation data and functional unit. *Water, 8, 473; doi:10.3390/w8100473.*

Le Roux, C., van der Laan, M., Vahrmeijer, T., Annandale, J.A. & K.L. Bristow. A Water Footprint Sustainability Assessment of an Aquifer under Stress. *Science of the Total Environment*, accepted.

Gush, M., Dzikiti, S, Maherry, A., Steyn, M., van der Laan, M., Manamathela, S., Pienaar, .H. Estimating the water footprint of apple orchards at field and catchment scales. Agricultural and Forest Meteorology, submitted.

Dissertations/Theses

Smit, T.G. 2015. Assessing the application of cosmic-ray enutron probes in irrigated agriculture. MSc(Agric) dissertation, University of Pretoria, South Africa.

Manamathela, S.A. 2014. The water footprint of selected crops within the Olifants/Doorn Catchment, South Africa. MSc dissertation, University of the Western Cape, South Africa.

Popular press articles

Le Roux, C.E; van der Laan, M. and Gush, M. Water footprints: The story of our fruit and vegetables. Water Wheel, March/April 2015.

Conference presentations

Van der Laan, M., Annandale, J.G., Vahrmeijer, J.T. and K.L. Bristow. 2013. Estimating the Blue, Green and Grey Water Footprint of Crop Production in South Africa using SWB and DSSAT. Combined Congress, Durban, 21-24 January 2013.

Le Roux, C.E., van der Laan, M., Annandale, J.G., Bristow, K.L. 2014. Water footprinting: Improving water resources management for a water scarce South African aquifer. Invited presentation presented at the Water Footprint Symposium, Bloemfontein. 3-4 September 2014.

Van der Laan, M., Annandale, J.G., Le Roux, C.E. 2014. Making sense of the grey water footprint concept. Invited presentation presented at the Water Footprint Symposium, Bloemfontein. 3-4 September 2014.

Gush, M.B. and Dzikiti, S. 2014. The importance of accurately quantifying water-use when determining the water footprint of agricultural crops. *Invited presentation delivered at the Water Footprint Symposium*, University of the Free State, Bloemfontein, South Africa, 3 September 2014.

Manamathela, S., Mazvimavi, D. and Gush, M.B. 2014. The blue water footprint and the water use efficiency of Potato (*Solanum tuberosum*): A case study of the Sandveld region, South Africa. *SANCID Symposium*, Muldersdrift, 18-20 November.

Manamathela, S., Mazvimavi, D. and Gush, M.B. 2014. Water footprint of selected crops within a semi-arid area: A case study of Olifants/Doring WMA, South Africa. *Presentation delivered at the 17th SANCIAHS Symposium*, University of the Western Cape, Belleville, 1-3 September.

Le Roux, C.E., van der Laan, M., Vahrmeijer J.T., Annandale, J.G., Bristow, K.L. 2016. Water footprinting to improve agricultural water use management on a water-stressed aquifer. First Conference of the Water Footprint Research Alliance, Cape Town. 4-7 April 2016.

Gush, M.B., Manamathela, S., Maherry, A., Steyn, M., Jarmain, C. and Goudriaan, R. 2016. Water resource management from field to catchment: Scaling up water footprint assessments in the Olifants / Doorn WMA. *Presentation delivered at the inaugural Water Footprint Research Alliance (WFRA) Conference: Cape Town*, 4-7 April, 2016.

Le Roux, C.E., van der Laan, M., Vahrmeijer J.T., Annandale, J.G., Bristow, K.L. 2016. Water footprinting to improve agricultural water use management on a water stressed aquifer. Combined Congress, Bloemfontein. 18-21 January 2016.

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