WATER RESEARCH COMMISSION

THE APPLICABILITY OF HYDRODYNAMIC RESERVOIR MODELS FOR WATER QUALITY MANAGEMENT OF STRATIFIED WATER BODIES IN SOUTH AFRICA

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REPORT DESCRIBING A JOINT RESEARCH PROJECT CARRIED OUT BY NINHAM SHAND INC. AND THE DEPARTMENT OF CIVIL ENGINEERING (WATER RESOURCES AND PUBLIC HEALTH ENGINEERING), UNIVERSITY OF CAPE TOWN.

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EXECUTIVE SUMMARY

BACKGROUND AND OBJECTIVES

Water quality is an increasingly important consideration in river system management and planning in South Africa. Many of South Africa's rivers are already highly regulated by impoundments, which, in response to the strong seasonality of the climate, stratify on a cyclical basis. Water quality patterns in these impoundments are significantly influenced by stratification. This impacts on treatment (and cost thereof) of water abstracted from such reservoirs, while water quality patterns downstream of such reservoirs are impacted by releases from such impoundments. The interaction of processes and driving forces which determine water quality patterns in reservoirs is complex; consequently, there has for some time been a growing awareness of the need for a greater range of decision support tools for water quality management and planning in South Africa.

In response to this need the Water Research Commission appointed Ninham Shand Inc. in association with the Department of Civil Engineering, University of Cape Town, in January 1990 to conduct an investigation into the applicability of hydrodynamic reservoir models for water quality management of stratified water bodies in South Africa. The research had the following objectives:

(1) *Investigation of the predictive ability of selected existing hydrodynamic reservoir models by verification on selected water bodies in South Africa for which reasonable water quality depth profile data and associated hydrometeorological records were available.*

(2) *Adaptation of the selected models for application under South African conditions. This was expected to involve any or all of the following activities:*

- *(a)* *Model process modifications to improve verification success.*
- *(b)* *Model augmentations to include additional water quality controlling processes.*
- *(c)* *Model structure modifications to allow testing of specific water quality management options, for example, destratification by air bubble plumes, or salinity reduction by saline layer scouring, etc..*
- *(d)* *Model input/output modifications to streamline model usage by greater user-friendliness.*

(3) *Application of the selected models to specific water quality management and planning problems in South African reservoirs.*

GENERAL COMMENTS ON MODELS AND THEIR REQUIREMENTS

In line with their mechanistic nature, the type of reservoir models under discussion typically require hydrometeorological input data of a *daily time-series* variety to represent the driving forces on the impoundment. Usually a certain number of water quality depth profiles that overlap with the time-series data are also required in the reservoir of interest for calibration or verification of the models. Certain physical and water quality process representations in the models are typically augmented by coefficients or parameters of a site-specific nature. Calibration refers to the trial-and-error process by which values for such coefficients/parameters are determined by comparison of simulated and observed water quality depth profiles. Modelling spatial resolution can be either uni- or multi-dimensional.

Typical input data requirements are as follows:

+ mean daily wind-speed series
+ daily shortwave radiation series
+ daily longwave radiation series
+ daily sunlight hours series
+ mean daily air temperature series
+ daily rainfall series
+ mean daily relative humidity or vapour pressure
+ daily inflow volume series
+ daily abstraction/release volume series
+ daily inflow water quality concentration series
+ physical dimensions of dam wall and dam basin

+ physical dimensions of outlet/ spill configuration

+ physical dimensions of inflowing stream channels.

METHODOLOGY

Data sets

No field work or field gathering of data were intended under this project and all modelling data bases were assembled from existing raw data sources, which are listed in the Report. As available data sets were not in a readily usable format, assembling and finalising appropriate data bases for the study consumed a major portion of the first 15 months of the project. Ultimately, four reservoirs were selected for inclusion in the study, on the combined grounds of their available data bases and their inherent water quality management challenges. These reservoirs were as follows:

- *Roodeplaat Dam on the Pienaars River*

- *Inanda Dam on the Mgeni River*

- *Vaal Barrage on the Vaal River*

- *Hartbeespoort Dam on the Crocodile River.*

In the cases of Roodeplaat Dam and Hartbeespoort Dam a large degree of data capturing, either directly from recorder charts or from photostat copies of raw records, were required - a laborious process, but useful, because it revealed the inadequate nature of the data base. Only river flows and river chemistry data were available in computerised format at these two sites, the in-dam data being poorly organised. The Vaal Barrage in-dam data base was better organised, but still required a fair degree of processing to be modelling-compatible. The Inanda in-dam data set supplied by Umgeni Water was well organised and computerised and required the least manipulation of the four.

In all instances time series records of most input variables listed above required various degrees of infilling to deal with periods of missing records or values indicated as suspect during our data screening exercises. These infilling approaches are described at relevant points in the Report.

Model Applications

After a survey of international literature on the subject, four models were selected for investigation in this study:

+ *DYRESM*, a one-dimensional model developed at the University of Western Australia.

+ *MINLAKE*, a one-dimensional model developed at the University of Minnesota.

+ *CE-QUAL-W2*, a multi-dimensional model developed by the Corps of Engineers in the USA.

+ *WASP4*, a multi-dimensional model developed by the US Environmental Research Laboratory in Athens, Georgia.

In all cases the relevant software, as well as supporting documentation, were obtained directly from the custodians of the respective models. New versions of DYRESM and WASP4 became available during the course of the project and were implemented in the place of earlier versions already under study. A great deal of supporting software development took place during the study to enhance both the input side and the ouput side of particular models, with a strong accent on computer screen graphics. In a number of instances, described at relevant points in the Report, modifications and improvements were required to individual process formulations in the model software.

For application purposes, models were matched to reservoirs both in terms of their particular data needs and in terms of their appropriateness to deal with a likely water quality management challenge. Table EX.1 gives an overview of all the model applications, as well as details about the models themselves.

Apart from the required calibration/verification exercises in the case of each model, the scope of the study allowed only two illustrative water quality management-related case studies, i.e. the hypothetical destratification of Roodeplaat Dam and the blending of Vaal Barrage contents by low-salinity releases from Vaal Dam.

GENERALISED CONCLUSIONS

The purpose of this section is to draw together and generalise the detailed conclusions from the individual model application chapters. For this integration process we have used the original project objectives presented above as a guide, but we also kept general modelling interests in focus. For detailed conclusions on a particular model or reservoir application the reader is referred to the respective chapters. It must also be stressed that, owing to the explorative and non-exhaustive nature of this study, our stated conclusions are necessarily of a provisional nature.

Predictive Ability

In this sub-section the term "predictive ability" is used in the context of iterative comparisons between model simulation outputs and observed in-dam data. It should be noted that conventional split-sample tests consisting of calibration followed by independent verification of predictive ability was not possible given the explorative nature of the study.

(i) Water Balance

Against a background of variable degrees of effort for calibration and interpretation, all four models implemented - DYRESM, MINLAKE, CE-QUAL-W2, WASP - maintained appropriate mass balances in their respective case studies.

(ii) Thermal and Hydrodynamics

Against a background of variable degrees of effort for calibration and interpretation the following three models showed acceptable predictive ability of the thermal and hydrodynamics (in terms of profiles) in their respective case studies : DYRESM, MINLAKE, CE-QUAL-W2.

(iii) Conservative Water Quality

The following two models were verified successfully for TDS profiles : DYRESM and CE-QUAL-W2. (This feature was not investigated in depth in the MINLAKE component of the project as the focus of this component lay elsewhere.)

(iv) Non-conservative Water Quality

The only model that displayed reasonable verification success for non-conservative water quality parameters - suspended solids, phosphate, algal biomass - was CE-QUAL-W2. This finding might be an artefact of the available database, as the case study for MINLAKE was based on synthetic suspended solid time series for the inflowing streams to Roodeplaat Dam and might not be an adequate test for MINLAKE's capability. (See conclusions below regarding respective calibration efforts required for this purpose.)

(v) **Role of Calibration**

Calibration requirements vary in concert with the range of processes that a particular model is geared to simulate :

- DYRESM - thermal and hydrodynamics : no calibration
- MINLAKE - thermal and hydrodynamics : no calibration
  - water quality : extensive calibration
- CE-QUAL-W2 - thermal and hydrodynamics : modest calibration
  - water quality : extensive calibration
- WASP - hydrodynamics : modest calibration.

No conclusions could be drawn regarding the transferability of model parameter values from one reservoir to another.

(vi) **Hydrometeorological Database**

Hydrometeorological databases for the three impoundments studied - Roodeplaat Dam, Hartbeespoort Dam and Inanda Dam - were found to suffer from a range of inadequacies and extensive use had to be made of data collected at stations remote from the dams. Provisionally, it appears that, of all the input data types concerned, the highest requirement for accuracy and representativeness of data lies with daily wind-run, daily inflow quantity and daily inflow quality data.

(vii) **In-reservoir Database**

Three requirements are relevant for the in-reservoir database which serves to verify a model's adequacy for water quality management :

- observations of a suitable range of water quality variables at weekly to quarterly intervals : at least temperature, electrical conductivity, suspended solids, phosphates, nitrates, algal indices, total dissolved solids, ammonia;

- observations of the chosen variables at a number of representative points across the reservoir basin : at least three points chosen to expose longitudinal variation and to include the main body of water; and

- observation of the chosen variables at a suitable number of depths at each observation point : at least three depths at each point - one each in the epilimmion, the metalimmion and the hypolimmion.

Of the three impoundments studied, only the data set for Inanda Dam met all three requirements adequately. The Vaal Barrage data set was adequate in terms of the particular goals of that investigation, but not in the general terms stated above.

Adaptation of Selected Models

(i) **Algorithm Modifications**

All four models required various degrees of modification to certain process algorithms and/or to improve their versatility. Details are provided in the specific model chapters. Some of the modifications that appear to be required fell outside the scope of this study and/or the expertise of the project team.

(ii) **Model Structure Modifications**

An important modification to DYRESM by the model's developers became available and was successfully implemented during the course of the study : the bubble plume dynamics utility, useful for testing destratification options.

(iii) **Input/output Modifications**

In terms of user-friendliness for both input preparation and output display/manipulation the models can be ranked as follows, from high friendliness to low friendliness : DYRESM; MINLAKE; CE-QUAL-W2; WASP.

On the input side, much effort had to be expended during this project to improve the CE-QUAL-W2 and WASP input framework. On the output side, friendly specialist output display software was developed during this project for each of DYRESM, MINLAKE and CE-QUAL-W2. Details appear in the respective model application chapters.

Case Studies of Water Quality Management

Although each model application can be viewed as a "case study" in its own right and has led to detailed conclusions as reported in each relevant chapter, this sub-section deals only with the two cases where a water quality management action was simulated, namely :

- hypothetical destratification of Roodeplaat Dam by air bubble plume action; and
- blending of Vaal Barrage contents by low-salinity releases from Vaal Dam.

(i) Destratification

The technical feasibility of destratification by aeration of a typical dam in the summer rainfall zone, Roodeplaat Dam, has been demonstrated and broadly quantified by simulation with DYRESM. Optimisation approaches for both layout design and operation of the aerator have also been indicated.

(ii) **Blending**

The two-dimensional nature of the translation of the low-salinity release water through the Vaal Barrage has been demonstrated by simulation with CE-QUAL-W2. The consequent distribution of non-conservative water quality constituents throughout the Barrage has also been highlighted.

GENERALISED RECOMMENDATIONS

Highly detailed recommendations conclude the respective model application chapters, which, for reasons of economy, are not repeated here. Instead, this section offers a broad overview to give the reader a sense of the nature of the detailed recommendations. We also emphasise certain crucial aspects relating to this level of modelling and databases in general, for notice by the research planning/funding and water management fraternity in South Africa.

Specific to This Project

The generalised conclusions stated above and the detailed conclusions in the respective model application chapters confirm that this project has largely succeeded in its goal to explore the "applicability of hydrodynamic reservoir models for water quality management in stratified water bodies in South Africa". Time and budget constraints meant that certain research tasks could not be exhaustively completed. We therefore recommend extensions to this project to complete the following research tasks:

- Implementation of the new versions of the DYRESM model, ie. DYRESM-2D and DYRESM-WQ, with the present project databases to evaluate these models and their application.
- Further study of the water quality aspect of MINLAKE, to evaluate its predictive capacity, incorporate sediment-phosphorous interaction and pH simulation, and verify the formulations for nitrogen limited growth in order to simulate algal succession.
- Definitive sensitivity analyses of all selected models to identify the significance of model parameters and processes.
- Use of CE-QUAL-W2 and the DYRESM suite for specific water quality management studies on Inanda Dam, Vaal Barrage and Hartbeespoort Dam.

Modelling in General

The data intensity of physically-based, time series-driven models, such as those investigated in this project, is often of concern to water resource managers because of the consequent cost and time implications. We believe that our elementary case studies on destratification of Roodeplaat Dam and freshening releases into Vaal Barrage illustrate the worth of this level of modelling. This work confirms the promise shown in earlier simulation studies by Ninham Shand Inc. (1989) on salinity management of Laing Dam. It is unlikely that the detailed findings which such water quality management studies are required to yield could be achieved with steady-state models or rule-based approaches.

In recognition of water resource managers' legitimate concerns about data intensity on the one hand and the shortcomings of South African monitoring systems for this purpose on the other hand, we recommend that the selected models should be tested under reduced data input, such as smoothed weekly, monthly or seasonal values for the hydrometeorological input data. Such a study should assist in:

- establishing whether the intensity of data requirements of the models can be reduced without serious loss of performance,

- establishing if site-specific hydrometeorological data are essential, or whether regional data will suffice for certain input requirements, and

- identifying the significance of model variables, parameters and processes.

Data in General

We recommend that a shortlist of reservoirs be compiled where intensive water quality management is expected in the future and that a monitoring strategy be devised to accommodate the primary input requirements of hydrodynamic models such as those implemented in this project. In such a strategy particular attention should be accorded to the following:

- **Wind data** : Since the wind speed is of major significance in all the selected models, careful attention should be given to the placement of wind measuring stations where possible. Periods of wind measurement should be undertaken at a height of 10 metres in order to evaluate the theoretical conversion of wind speed, measured at different heights, to a height of 10 metres. Similarly, over water wind speeds should be measured, again to evaluate the theoretical conversion formulation. It is therefore recommended that further research be undertaken into the over land to over water and height conversions of wind speeds.

- **In-reservoir profiles** : Key water quality variables which should be given high priority include:

  - suspended solids (and occasional fall velocities)
  - Phosphorous (soluble ortho and total)
  - Nitrogen-species (nitrate and ammonia)
  - Algal biomass and chlorophyll-a
  - Dissolved oxygen and water temperature
  - Total coliform
  - TDS and electrical conductivity

Ideally, such variables should be measured regularly at discrete intervals throughout the depth profile. However, as a minimum data requirement, samples should be taken at the surface, mid-depth (metalimnion) and bottom waters (hypolimnion) at weekly to quarterly intervals, depending on the season. The sampling points should be positioned along the length of a water body so that longitudinal gradients in water quality can be evaluated. Single measurements taken of the surface water at the dam wall provide no useful information on longitudinal and vertical gradients. The sampling methods used in Inanda Dam by Umgeni Water represent a near ideal water quality monitoring system.

- **Water quality of inflowing streams** : Key requirements here are daily to weekly measurements of:
  - temperature
  - TDS/EC
  - nutrients
  - suspended solids.

- **Reservoir modelling databank** : The establishment of such a databank at an appropriate institution, linked to the Computing Centre for Water Research (CCWR), should be part of the monitoring strategy.

TABLE EX1 : SUMMARY OF MODEL APPLICATIONS

MODEL	DIMENSIONALITY	NUMERICAL STRUCTURE	WATER QUALITY OUTPUTS	RESERVOIRS APPLIED	SIMULATION PERIOD	COMMENT
DYRESM	1-D	Lagrangian layers	Only TDS and temperature	(i) Roodeplaat	Apr. 1980 to Apr. 1982	Verification Destratification study
				(ii) Hartbeespoort	Jan. 1984 to Jan. 1985	Verification
MINLAKE	1-D	Lagrangian layers	Extensive	(i) Roodeplaat	Apr. 1980 to Apr. 1982	Calibration
				(ii) Hartbeespoort	Jan. 1984 to Jan. 1985	Abandoned
CE-QUAL-W2	2-D	Finite difference	Extensive	(i) Inanda	Jan. 1990 to Dec. 1990	Calibration & Verification
				(ii) Vaal Barrage	Jul. 1990 to Nov. 1990	Calibration
WASP4	2-D	Links (channels) and nodes (junctions) and segments	Extensive	(i) Inanda	Jul. 1990 to Nov. 1990	Only hydrodynamics Water qual. abandoned
				(ii) Roodeplaat	Nov. 1980 to Feb. 1981	Only hydrodynamics Water qual. abandoned

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> Applicability of hydrodynamic reservoir models for water quality management in stratified water bodies in South Africa.

The Steering Committee for this project consisted of the following persons:

Mr HM du Plessis	Water Research Commission (Chairman)
Mr H Maaren	Water Research Commission
Mr FP Marais	Water Research Commission (Secretary)
Mr G Quibell	Department of Water Affairs and Forestry
Prof G Ekama	University of Cape Town
Mr N Rossouw	CSIR
Mr I Reid	Ninham Shand Inc.
Dr H Furness	Umgeni Water

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ABBREVIATIONS AND UNITS

WRC	Water Research Commission
DWAF	Department of Water Affairs and Forestry
HRI	Hydrological Research Institute (Directorate of DWA&F)
UW	Umgeni Water
RWB	Rand Water Board
ISCOR	Iron and Steel Corporation
ESCOM	Electricity Supply Commission

NTU	Nephelometric turbidity units
SS	Suspended solids (units: mg/l)
EC	Conductivity (units: mS/m)
TDS	Total dissolved salts concentration (units: mg/l)
Phosphate	Soluble orthophosphate (units: mg-P/l)

km	kilometre
mm	millimetre
m^3	cubic metre
10^6	million
°C	degree centigrade
W/m^2	watt per metre squared
m^3/s	cubic metre per second (≡ cumec, see below)
cumec	cubic metre per second
μg/l	microgram per litre
mg/l	milligram per litre

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CHAPTER 1
INTRODUCTION

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1.1 BACKGROUND

In general, water quality models for reservoirs are developed for two main reasons. Firstly, models are used as research tools to establish an understanding of the complex interactions between physical, chemical and biological processes. Secondly, models are used as management and planning tools to provide the necessary information for decisions on the abatement of water quality problems.

The development and application of water quality models in different countries largely depends on the waste water management policy adopted. Some countries use a best technical means (BTM) policy. In this case, management decisions are based on effluent standards for the discharged water (i.e uniform effluent standard approach). When the BTM approach is adopted, there is little demand for models which describe the water quality processes in the receiving water body. In other countries, a receiving water quality policy is adopted where a set of water quality objectives are set for a receiving water body. The water quality objective then forms the background for defining the quality of effluent which can be released into the water body. The definition of an effluent discharge condition, or standard, is based on a deterministic method which calculates the influence of that effluent quality on the receiving water quality. The deterministic method may be either a simplified empirical approach such as a surface load ratio or a more advanced approach such as a hydrodynamic eutrophication model.

The uniform effluent standard approach controls the input of contaminants to the aquatic environment by maintaining that effluent comply with uniform standards. In South Africa, the uniform effluent standard approach has been applied for more than two decades and has been reasonably effective (Van der Merwe and Grobler, 1990). The uniform effluent standard has: (1) limited the rate of deterioration in water quality, (2) focused attention on pollution, and (3) resulted in improvements to wastewater treatment technology and water management. In South Africa, despite the implementation of uniform effluent standards, the BTM policy has been ineffective at preventing the deterioration in water quality. A new approach to water pollution control in South Africa is being used which involves the use of receiving water quality objectives (Van der Merwe and Grobler, 1990).

The receiving water quality objective (RWQO) approach to the management of water quality involves (1) defining the water quality objectives in the receiving waters and (2) control of point and nonpoint sources of contamination to comply with the water quality objectives. The receiving water quality objective approach is based on the basic principle that receiving waters are capable of assimilating pollutants without having a detrimental influence on the users of the water. In the United Kingdom (UK) and United States of America, the management of water quality is based on the receiving water quality objective approach. In the UK, the approach uses the following methods:

(1) the users of a water body are identified,
(2) the concentrations of water quality variables in the water body which must not be exceeded are specified, and
(3) the point sources are then controlled by setting site specific effluent standards which take into account the role of nonpoint sources and the receiving water quality objective.

Van der Merwe and Grobler (1990) state that the receiving water quality objective approach has several advantages over the uniform effluent standard approach. The receiving water quality objective approach (1) is used to manage the quality of the water so that the users are least affected, (2) it considers both point and nonpoint sources of contaminants, and (3) considers the assimilative capacity of the receiving waters for a particular contaminant.

The receiving water quality objective approach, however, requires a thorough investigation and understanding of the fate of contaminants in the aquatic environment and the influence of contaminants on the users of the water. This approach also results in the development of site specific effluent standards being developed which entails more detailed investigation compared with the uniform effluent standard approach.

The concept of waste load allocation (WLA) is central to the receiving water quality objective approach to water pollution control. The waste load allocation approach involves the assignment of allowable discharges to a waterbody so that the water quality objectives of the waterbody are met. The waste load allocation method involves determining the water quality objectives for the water uses, and determining the relationship between pollutant load and the receiving water quality. Unfortunately, the whole waste load allocation methodology is hampered by the lack of locally tested models for simulating the response of receiving waters to discharges of pollutants (Van der Merwe and Grobler, 1990) signalling an important research need.

Equally compelling motivations for research into reservoir modelling technology include the use of these models in the following applications:

- Short term operational decisions to provide water quality and hydrological information. For example, the Vaal Dam/Barrage where the system is operated to maintain the TDS concentration within specified limits.
- In-lake management techniques which use destratification and aeration. These management methods are being investigated in Hartbeespoort and Inanda Dams.
- Long term planning/design decisions where information is required on influence of catchment transfer and blending options. Such information has been derived using hydrodynamic reservoir modelling at Laing Dam.
- In some instances, information is required on the biochemical and physical processes governing the quality of a reservoir. At Swartwater and Fika Patso Dams, hydrodynamic water quality models are being used to provide detailed information on water quality processes which will in turn be used in the design of water treatment facilities and assist in the development of a catchment management policy.

1.2 DEVELOPMENT OF RESERVOIR MODELS

Internationally the work on reservoir models has focused on two primary approaches. One approach uses the input-output orientated model, which is based on measurements of the loadings of a lake with phosphorus and nitrogen, to calculate some lake parameters (i.e retention coefficient) on a statistical or empirical basis. The values of these parameters are then used for calculating the consequences of changed loadings on the concentrations of interest. The classic models of this type are Vollenweider (1969) and latter extended versions by Dillon and Rigler (1974).

These empirical models are limited by a number of factors. The models are steady-state in that they are unable to account for daily or hourly variations of loadings and parameter values. Secondly, the models do not describe the complex interaction between the biological, chemical and physical processes which have direct influence on the water quality of a water body. Thirdly, the models do not describe the biological processes in any way and can not account for important processes and interactions between phytoplankton limiting factors, light, phosphorus and nitrogen. The only advantage of the steady-state models is that the modelling structure is simple and the models may be applied using the minimum input data for calibration and provide adequate information.

The other type of model which has been developed is the hydrodynamic eutrophication model which includes time dependent variations and also takes into account the main biological, chemical and physical processes. Pioneers of these models are Chen (1970), Di Toro *et al.* (1971) and Scavia and Park (1976). Chen and Di Toro have both used their models for management purposes. Scavia developed the model for research purposes. One stated disadvantage was the data requirements needed to calibrate and verify these models. Since the mid-seventies, researchers have made progress with this type of model. Models chosen for investigation in this project conform to this approach. Figure 1.1 shows the two general types of reservoir simulation model available - empirical and mechanistic. Figure 1.2 shows a schematic of the different structured approaches used in the mechanistic hydrodynamic reservoir simulation models chosen for this study.

In South Africa, simple steady-state input-output type models have been developed for the management of eutrophication in a number of sensitive catchments (Grobler and Silberbauer, 1984). These models have been used to determine the necessity of implementing the phosphate standard for effluents. Such models were developed from the Vollenweider and OECD modelling approach and included a number of modifications resulting in the reservoir

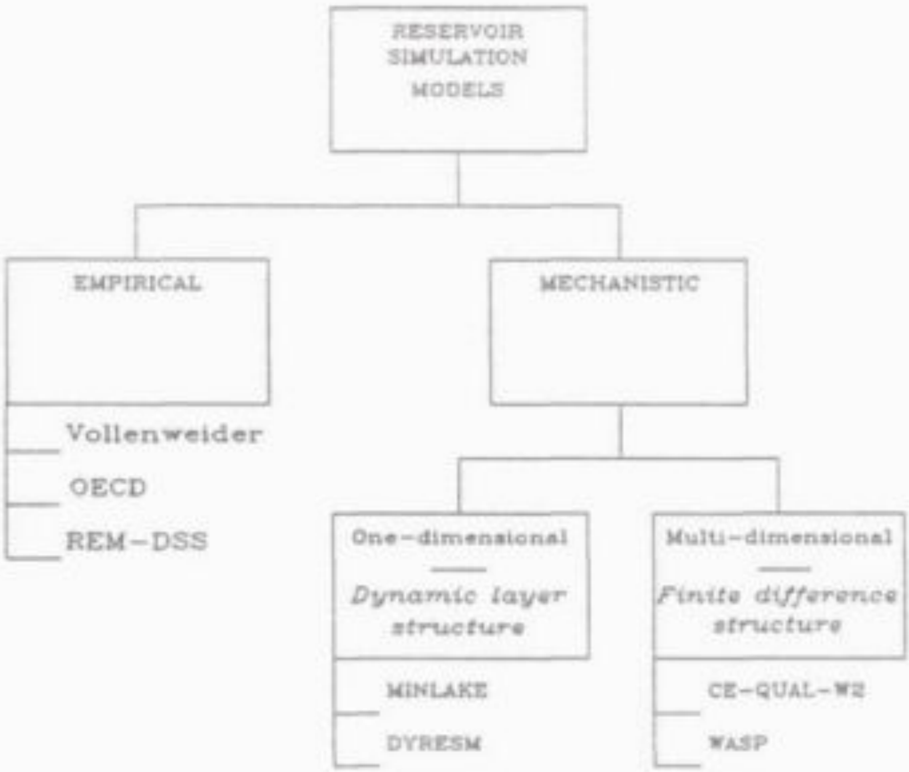


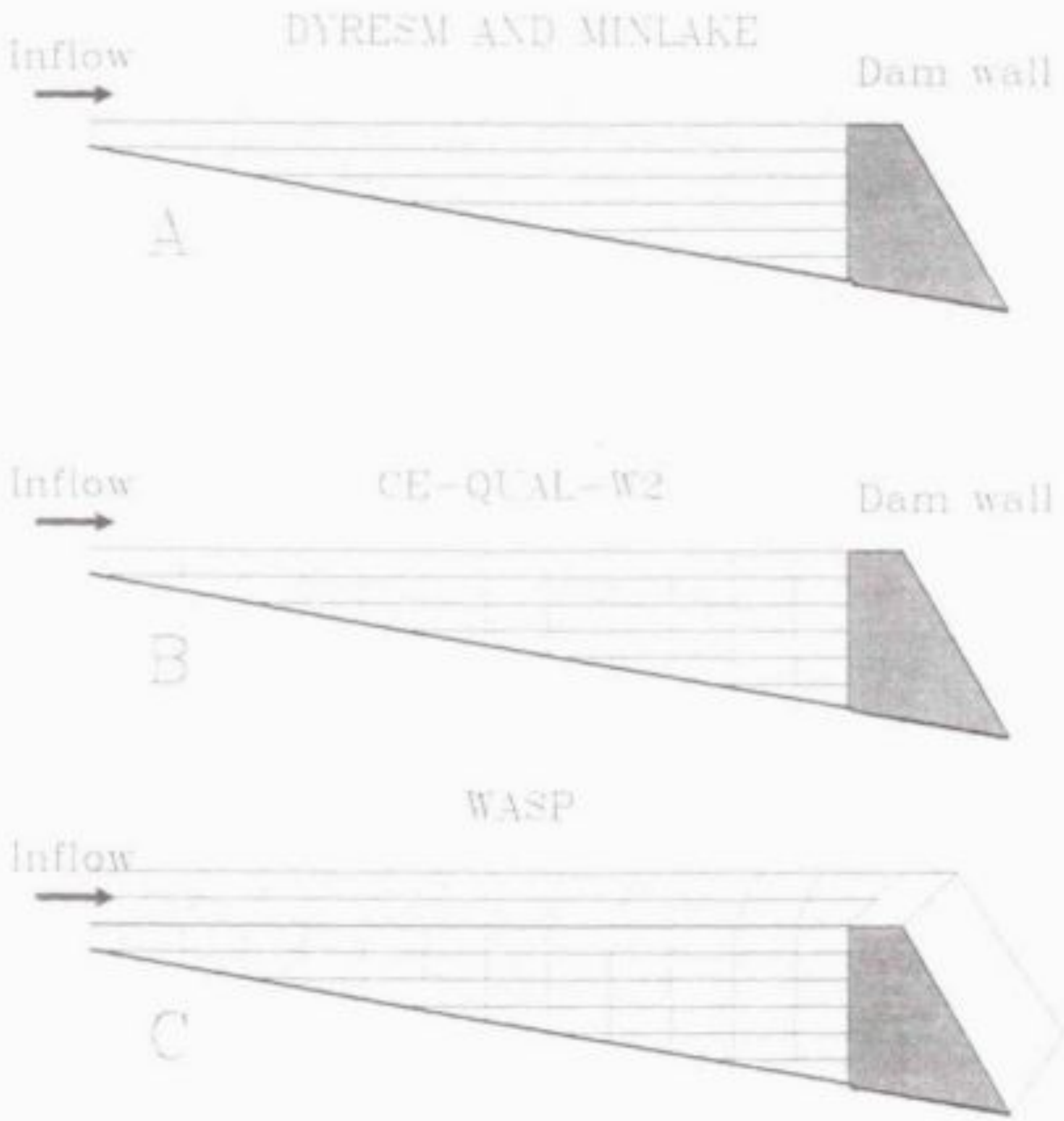
Figure 1.1 General characteristics of reservoir simulation models.

eutrophication model decision support system known as REMDSS (Rossouw, 1990). Hitherto, steady-state models have been widely used in South Africa, while a hydrodynamic eutrophication modelling approach has been used only in research settings (NIWR, 1985).

1.3 ROLE OF RESERVOIR MODELS IN THE MANAGEMENT OF WATER QUALITY

As stated previously, the concept of receiving water quality objectives (RWQO) is being implemented in South Africa to control the contamination of non-hazardous substances from point and nonpoint sources and thereby control the quality of water bodies. The main problems experienced in South African water bodies include:

1. **Eutrophication** describes the development of a water body into a state in which the aerobic microbial decomposition of organic matter consumes more oxygen than is introduced into the system, resulting in an oxygen deficit. This definition extends beyond the early concepts of eutrophication as a phenomenon of increasing



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Schematic of the different modelling approaches used in (A) DYRESM and MINLAKE, (B) CE-QUAL-W2, and (C) WASP.

FIGURE 1.2

phytoplankton growth caused by enrichment with mineral nutrients. Increased nutrient loading remains the main cause of the massive growths of phytoplankton and water plants (Codd and Bell, 1985). Eutrophication results in increased water treatment costs, aesthetic problems, interference with recreation, taste and odour problems, problems for livestock watering, and clogging of irrigation canals (Walmsley and Butty, 1980). Eutrophication therefore has an adverse influence on all water use sectors including domestic, agricultural, industrial and recreation (Bath, 1989). The economic implications of eutrophication have not been determined in South Africa but the cost is expected to be high (Bruwer, 1979).

2. **Salinization** related problems occur through the increased loading of dissolved salts to a water body. Salinization results in problems for domestic, agricultural and industrial users of the water. Salinization has a direct influence on the industrial water users through scaling and corrosion of water reticulation systems. Salinization also influences the agricultural sector through damage to crops and soil.

3. **Microbiological** related problems are caused by the addition of runoff containing bacteriological contaminants. Microbiological contamination has most influence on the informal water user who takes water directly from a reservoir without treatment. The microbiological quality is important for the recreational use of the water body.

4. **Turbidity** related problems caused by the influx of suspended solids derived from surface erosion and riverine sources. High turbidity has a detrimental influence on all user groups as well as the aquatic environment. High turbidity in rivers reduces the operational life of the reservoirs to which they flow.

5. In a few water bodies, problems are caused by dissolved organic compounds and trace metal contaminants. However, the occurrence of organic and metal contamination is comparatively infrequent compared with the four groups described above. The presence of iron and manganese in the hypolimnion is generally linked to eutrophication of a water body, refer to (1) above.

The RWQO approach entails an integrated approach to the management of water quality and quantity, where water quality objectives are developed for each catchment. In the application of the RWQO approach, the Department of Water Affairs and Forestry has produced a protocol for the development of catchment water quality management plans. The protocol for the development of catchment management plans requires that the investigation contains three sections, see Figure 1.3. Van der Merwe and Grobler (1990) state that in terms of the RWQO approach, water quality models play an important role in providing the necessary information for water quality management. For example:

- **In the situation analysis:** Hydrodynamic models can be used to firstly identify, assess and rank the sources of pollution draining into a water body, and secondly determine the assimilative capacity of a water body.

- **In the development of catchment management objectives:** The hydrodynamic models can be used to assess the influence of both (1) catchment and (2) in-lake management strategies on the quality of water bodies.

- **In the development of management information systems:** The hydrodynamic models can be used to assist in the design of the water quality monitoring system by identifying critical water quality variables, critical positions in a water body, and optimize sampling frequency.

Figure 1.3 Schematic showing three sections of the integrated catchment management approach.

1.4 ROLE OF RESERVOIR MODELS IN THE OPERATIONS OF WATER BODIES

Models may be used to provide information on the operational management of reservoirs. The following are examples of such applications

- Evaluation of salinity operational management in reservoirs by saline layer scouring, timing of freshwater imports, timing of downstream releases and choice of withdrawal level (NSI, 1989).

- Evaluation of optimum location in a reservoir for offtake points and withdrawal level to avoid abstraction of poor water quality associated with (1) high algal biomass in the epilimnion, and (2) high organic/deoxygenated water in the hypolimnion.

- Evaluating and design of bubble plume aeration systems for reservoirs. These aerators will be used to destratify the reservoirs and thereby improve water quality. Models have been specifically designed to provide information on the design and operation of aerators. Prototype studies include Hartbeespoort and Inanda Dam.

1.5 ROLE OF RESERVOIR MODELS IN THE PLANNING OF WATER BODIES

Hydrodynamic eutrophication models have been shown to play an essential role in the planning of water bodies, this includes the following

- Inter-catchment transfer schemes involve the conveyance of raw water from one catchment to another. Such transfers may resolve water supply problems but result in changes in water quality in the recipient catchment and reservoir system. Hydrodynamic models have been used successfully as planning tools to determine the influence of catchment transfer schemes on the salinity, an example being the Laing Dam on the Buffalo River (NSI, 1989).

- In the United States, the design of cooling ponds for thermoelectric power plants has necessitated the use of hydrodynamic models to provide detailed information on the heat exchange characteristics of a water body (Edinger *et al.*, 1974). The design of the water body is governed by the (1) size, depth and surface area of the water body, (2) the local meteorological conditions and (3) heat input from the thermoelectric power plant.

- Aiding the site selection of salt-gradient solar ponds in Western Australia (Schladow, 1988) and design of in-channel river purification lakes on the River Tame in England (Thompson, 1986).

1.6 ROLE OF RESERVOIR MODELS IN UNDERSTANDING IN-LAKE PROCESSES

Hydrodynamic reservoir models have been used to provide information on the interaction of chemical, biological and physical processes in water bodies.

- Use of CE—QUAL—W2 in the management of anaerobic conditions in a lake in Arkansas, USA (Martin, 1988). Use of DYRESM on Laing Dam (NSI, 1989) and Bathurst Dams (NSI, 1987) have demonstrated the value of understanding the salinity dynamics of both water bodies.

- In the case of Swartwater and Fika Patso Dams (NSI, 1992), the hydrodynamic models are being used to provide information on the governing processes and their influence on water quality. Such information will ultimately be used to provide information on the design of a water treatment works at Fika Patso Dam, and design operational and management guidelines for the reservoirs and their associated catchment areas.

1.7 DETAILED AIMS OF THIS PROJECT

1. *Investigation of the predictive ability of selected existing hydrodynamic water quality reservoir models by verification on selected water bodies in South Africa for which reasonable water quality depth profile data and associated hydro-meteorological records are available.*

2. *Adaptation of the selected models for application under South African conditions. This would typically involve any or all of the following activities:*

    - *model process modifications to improve predictive abilities.*

    - *model augmentations to include additional water quality controlling processes.*

    - *model structure modifications to allow testing of specific water quality management options, e.g. destratification.*

- *model input/output modifications to streamline model usage.*

3. *Application of the selected models to specific water quality management and planning problems in South African reservoirs.*

1.8 CHOICE OF MODELS

The objective of this investigation was to determine the applicability of a selection of models used overseas. These models were chosen in order to cover a range of deterministic models being used for both research and management purposes. It was decided that the models would range from one-dimensional through to multi-dimensional approaches. The choice of model to be used in this investigation was based on:

- a study of the most prominent reservoir models that are in active use internationally, and
- a review of case studies in which these models have been implemented.

The models selected and their capabilities are as follows

- **One-dimensional**:

  - DYRESM (Imberger and Patterson, 1981) incorporates advanced hydrodynamics but only simulates water temperature and electrical conductivity.

  - MINLAKE (Riley and Stefan, 1988) simplified hydrodynamics and fairly advanced chemical and biological processes.

- **Multi-dimensional**:

  - CE-QUAL-W2 was chosen as the multi-dimensional model. The model features extensive mathematical descriptions of the chemical and biological processes and has relatively advanced hydrodynamics based on the Navier-Stokes flow theory. The model provides a three-dimensional description of a water body with dendritic layout of branches.

  - WASP (Ambrose *et al.*, 1988) was chosen as a model which can be used to describe water quality variation in both the longitudinal, vertical and lateral axis. The model has sophisticated water quality prediction capabilities.

Figure 1.2 shows the conceptual design of the models used in this investigation. MINLAKE and DYRESM are one-dimensional models which divide the water body into a series of stacked layers. CE-QUAL-W2 divides the water body into a series of vertical segments and horizontal layers so that the model simulates vertical and longitudinal gradients in water quality. The model WASP may be used to divide a water body into a series of vertical segments which may be further divided longitudinally and laterally. Detailed descriptions of all models follow in the relevant chapters.

1.9 FORMAT OF REPORT

The report is divided into seven chapters:

Chapter 2 — Application of the one-dimensional model DYRESM. The chapter describes the provisional simulation of the hydrodynamic behaviour of Roodeplaat and Hartbeespoort Dams. The model is used to provide preliminary information on the evaluation of bubble plume aeration techniques.

Chapter 3 — Application of the one-dimensional model MINLAKE. This chapter describes (1) application, and (2) modification of the model and (3) initial calibration of the water quality components on Roodeplaat Dam.

Chapter 4 — Application of the multi-dimensional water quality model CE-QUAL-W2. The chapter describes the calibration, verification and testing of the model on Inanda Dam and the Vaal Barrage.

Chapter 5 — Application of the multi-dimensional model WASP. This chapter describes the preliminary application of the model on Roodeplaat Dam and the Vaal Barrage. Problems were experienced in the application of the model resulting in incomplete evaluation of the predictive capabilities of the model.

Chapter 6 — Conclusions are specified under two headings, general conclusions relating to the use of hydrodynamic water quality simulation models, and specific conclusions relating to the use of each of the four models.

1.10 GENERAL COMMENTS

This project was executed as a two-year contract on a fixed budget. As the relevant sections of the report show, the task of assembling the hydrometeorological and water quality data bases for the various reservoirs was extremely time consuming. In certain instances, this resulted in decisions to curtail modelling applications or to accept that our investigations had to be non-exhaustive.

The research was carried out as a joint program between Ninham Shand Inc. (Cape) and the Department of Civil Engineering (Water Resources and Public Health engineering), University of Cape Town.

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CHAPTER 2

APPLICATION OF A ONE-DIMENSIONAL HYDRODYNAMIC RESERVOIR SIMULATION MODEL : DYRESM

by

K O de Smidt and A H M Görgens

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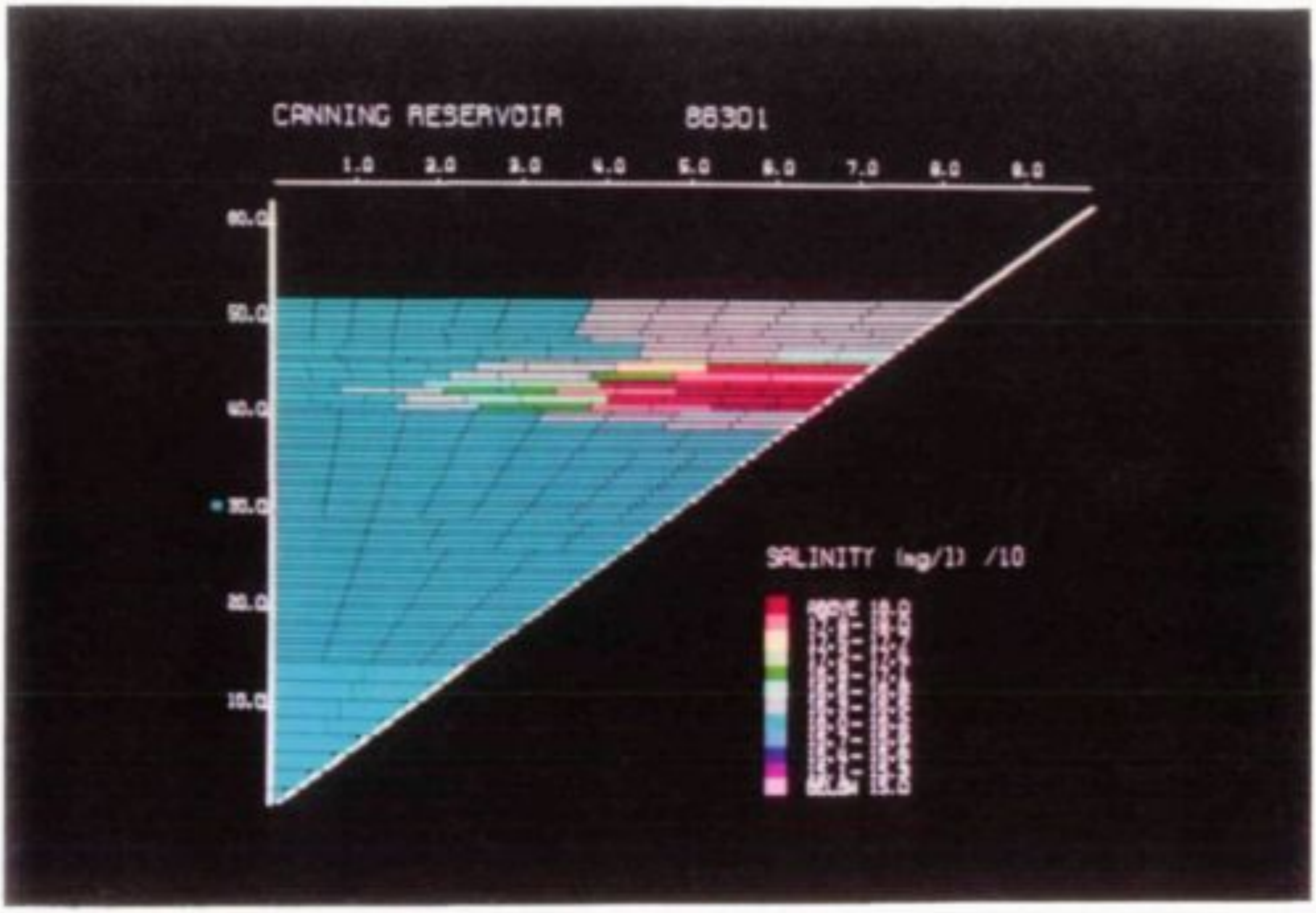
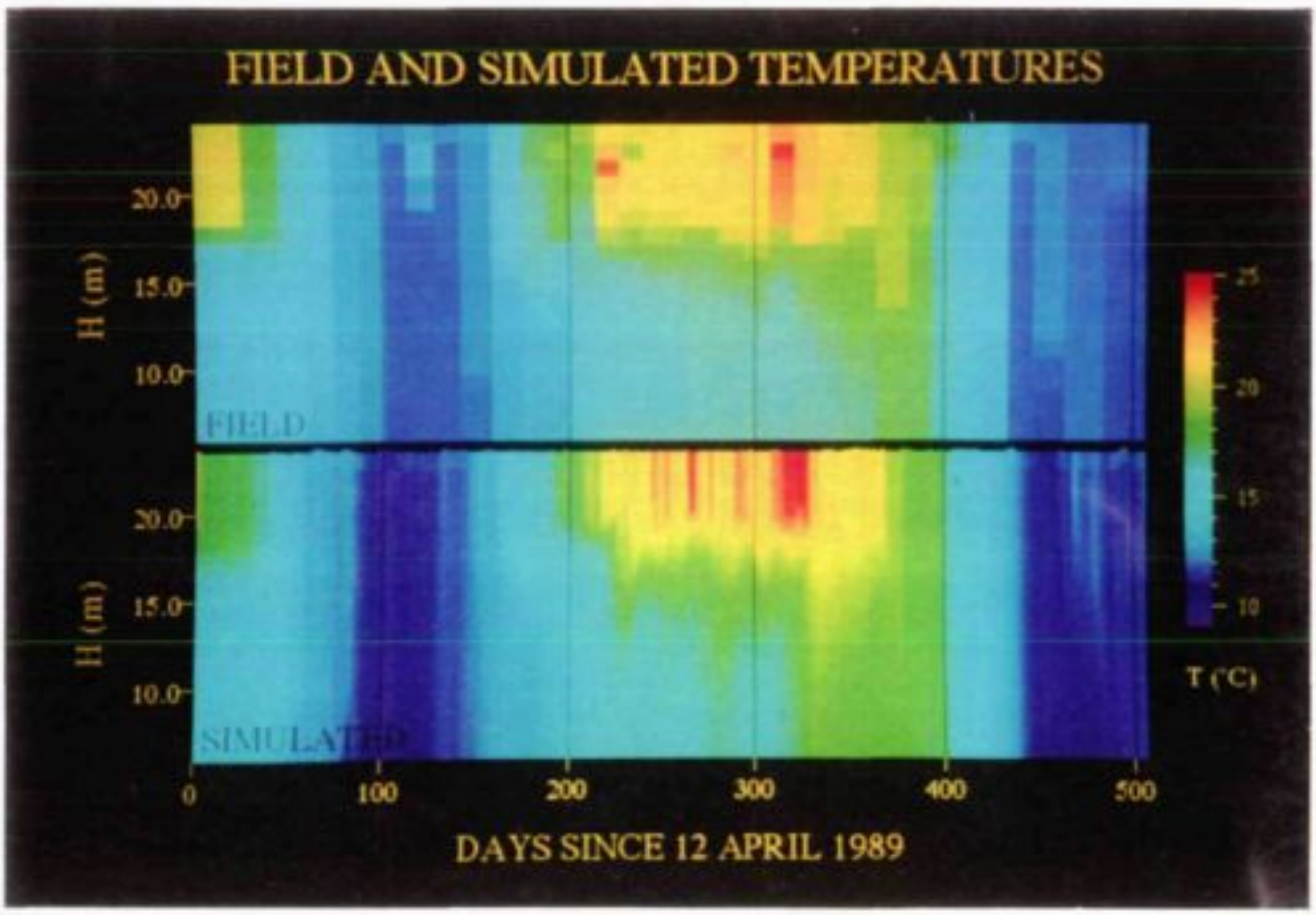
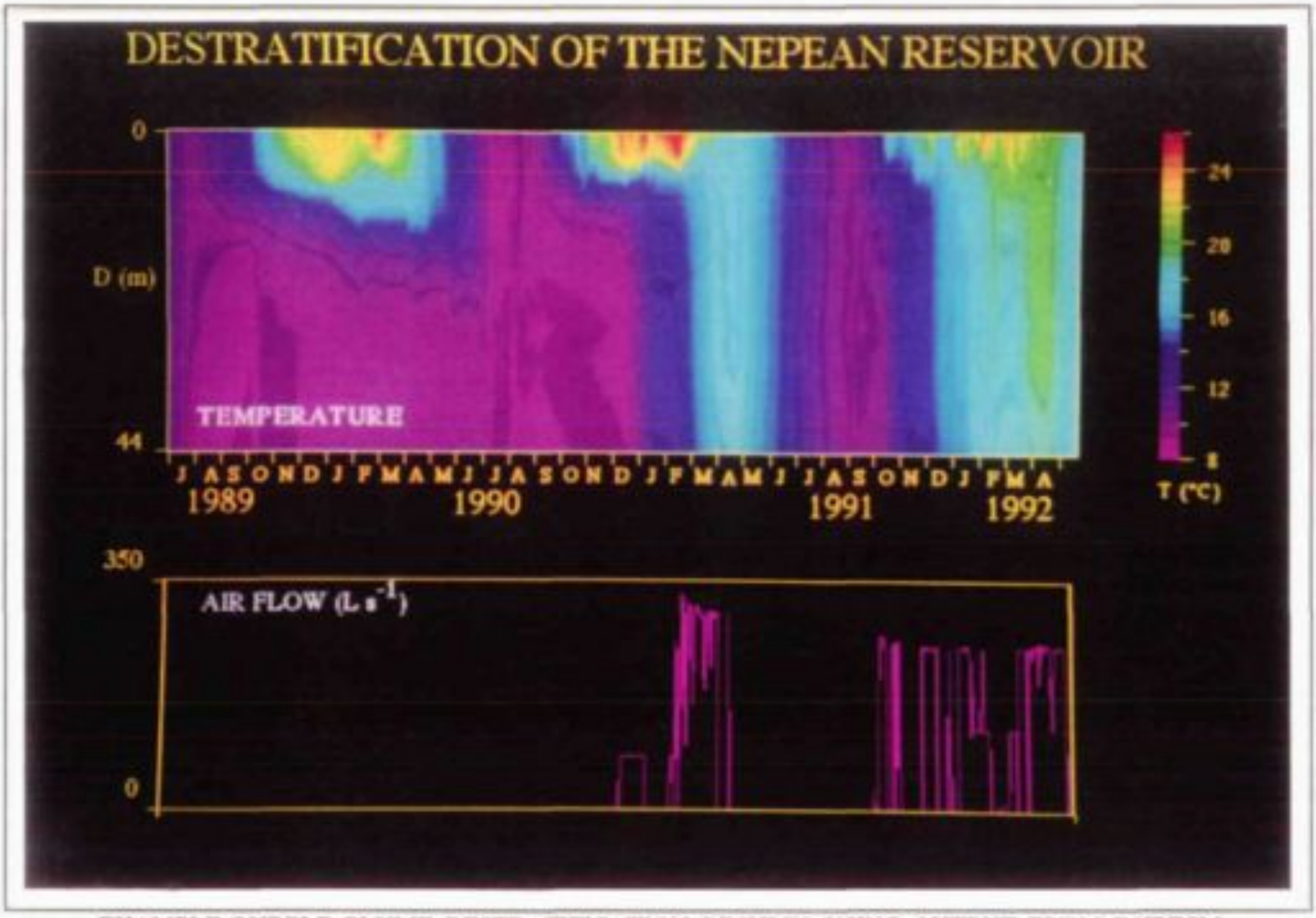
APPENDICES



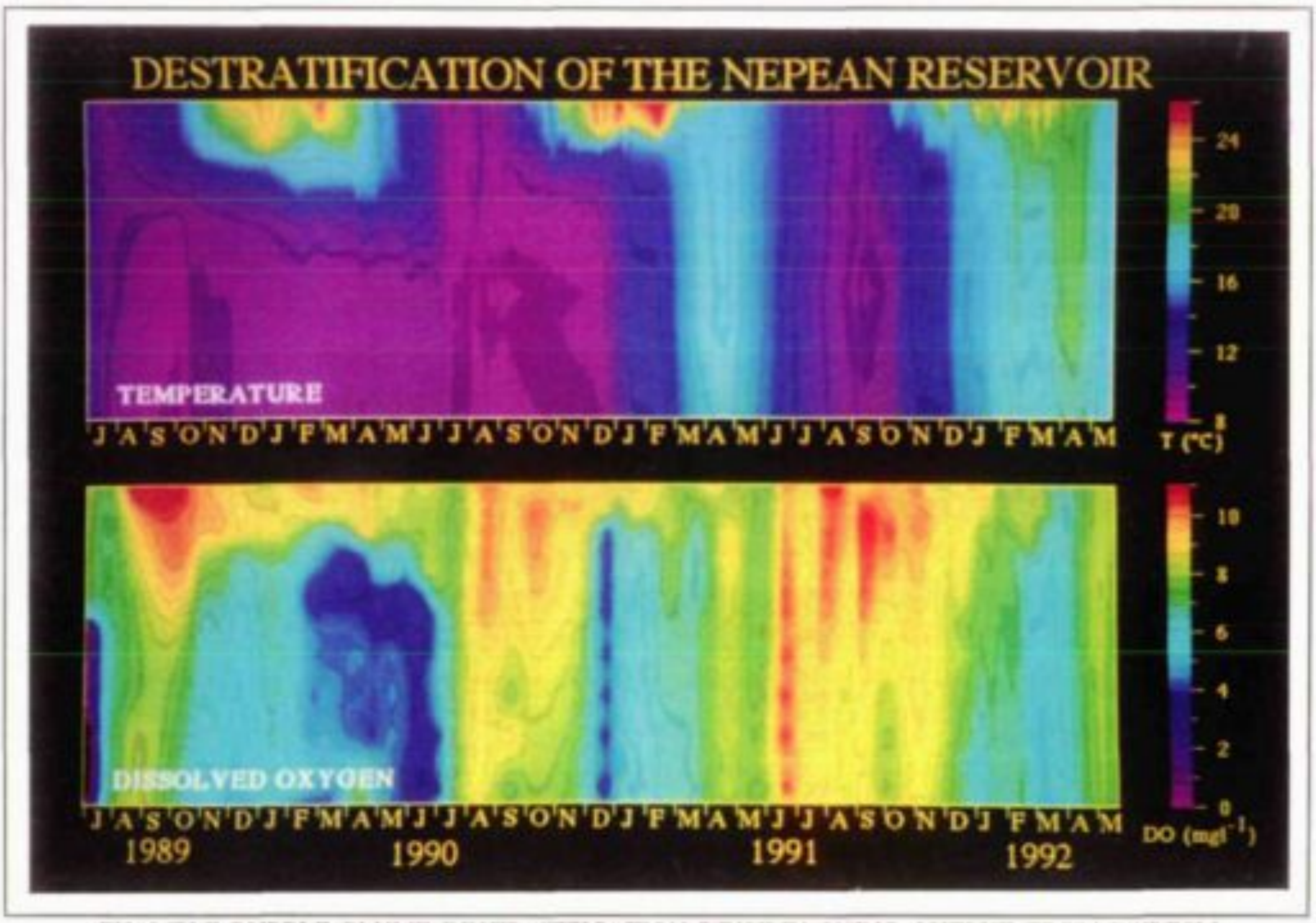
DYRESM -2D: EXAMPLE OUTPUT SCREEN FIGURE A2.1



EXAMPLE COMPARISON OF SIMULATED vs. OBSERVED TEMPERATURE DATA USING OUTPUT FROM DYRESM (NEPEAN RESERVOIR, AUSTRALIA) FIGURE A2.2



EXAMPLE BUBBLE PLUME DESTRATIFICATION RESULTS USING OUTPUT FROM DYRESM (NEPEAN RESERVOIR, AUSTRALIA) FIGURE A2.3



EXAMPLE BUBBLE PLUME DESTRATIFICATION RESULTS USING OUTPUT FROM DYRESM (NEPEAN RESERVOIR, AUSTRALIA) FIGURE A2.4

2.1 INTRODUCTION

2.1.1 Background

The DYRESM-1D model was developed in 1978 as a one-dimensional hydrodynamic reservoir simulation model for the prediction of the vertical temperature and salinity distribution in small to medium size lakes and reservoirs. The model was designed as a tool to be used in the management of the quality of stored water. Its continuing development and the processes incorporated in the model are well documented in the literature (Imberger *et al.*, 1978; Spigel and Imberger, 1980; Imberger and Patterson, 1981; Imberger, 1982; Patterson *et al.*, 1984; Hocking *et al.*, 1988; Imberger and Patterson, 1990). Specific applications to South African reservoirs include those by Allanson (1983) and Görgens and Forster (1989). The latter study represented the first published application of DYRESM in a PC environment with friendly graphics support.

Sections of the description of the model and the processes incorporated in it, that follow, have been paraphrased from the DYRESM-1D User's Manual (Centre for Water Research, 1991).

The DYRESM-1D model is based on the one-dimensional assumption that the density stratification found in lakes and reservoirs inhibits vertical mixing while lateral and longitudinal variations in density are quickly removed by horizontal convection occurring on time scales faster than vertical advection. This results in lateral density variations being considerably smaller in comparison with those in the vertical direction. The vertical density structure of a lake or reservoir is, however, the result of a complex set of interactive processes which are often incompletely understood. Many earlier models relied heavily on the calibration of a diffusivity model and were thus unsuitable for the basis of water quality modelling over a range of conditions outside of the original calibration. This method also gave little insight into the relationship between the different processes and hydrodynamics at work in the water body. The DYRESM approach has been to utilise parameterisations of the individual processes that contribute to the generation of a stratified profile. The success of any model requires the inclusion of all relevant processes and that the descriptions and algorithms associated with these processes are accurate. Any simulation based on these descriptions will reveal deficiencies in both the combination of processes represented and the process descriptions themselves. A model such as DYRESM is therefore both an operational and a research model which is continually being improved and refined.

The processes included in the basic model are :

- Surface heat, mass and momentum exchanges
- Surface mixed layer deepening
- Inflow
- Outflow
- Mixing in the hypolimnion

These processes are linked in the framework of a Lagrangian layer structure. A schematic diagram showing the layout of these processes is given in Figure 2.1. Mixing is modelled by the amalgamation of layers, with the layer thickness being contained within a specified limit. As a layer becomes too thick, either from amalgamation or inflow, to resolve a particular process, it is split into two or more layers which will satisfy the required resolution, whilst thin layers are amalgamated with their neighbour. The computational time step within the daily loop of the model is similarly determined by limitations on heat and momentum flux at the surface. The result of the above limitations gives spatial resolutions down to a few centimetres and time steps as short as 1 minute, but only where and when the hydrodynamics require it, whilst at other times the layer thickness may reach a few metres and the time step several hours. This Lagrangian layer and time step approach has resulted in the DYRESM model being computationally efficient.

The use of process descriptions as the basis for the model also allows a quantitative method of evaluating the applicability of the one-dimensional assumption (described in Section 2.2.1). Patterson *et al*. (1984) evaluated criteria for this assumption based on the Wedderburn number, the inflow and outflow Froude number and the Rossby radius. These were later represented in terms of the Lake number L_N (Imberger and Patterson, 1990) which incorporates the disturbing influences such as surface wind, inflow or outflow. For an L_N >> 1 the deflection caused by these disturbing influences on a density field in which the isopleths are horizontal is small compared with the vertical length scales. The model is appropriate for stratified conditions when the Wedderburn number and L_N are large. For winter conditions of weak stratification, with both a small Wedderburn number and small L_N, the assumption of one-dimensionality may be invalid. However, the error made by a vertical mixing model compared to a model based on upwelling is small. On the other hand, if L_N is large but the Wedderburn number is small, upwelling from the hypolimnion may occur at the upwind end of the lake or reservoir, under which conditions the one-dimensional model may not be appropriate.

The DYRESM-1D model has recently been enhanced by the inclusion of a bubble plume destratification algorithm (Imberger and Patterson, 1989) which enables both the design, testing and optimisation of potential destratification systems and the modelling of existing bubble plume installations. The use of this feature of the DYRESM model has resulted in the successful design and implementation of bubble plume destratification systems in a number of Australian reservoirs by the Centre for Water Research, University of Western Australia, Perth.

2.1.2 Current Developments

The basic DYRESM model structure has formed the basis for a number of specialist developments and applications which include :

- Large lake simulations
- Solar pond modelling
- Ice and snow cover simulations
- Water quality (simulation of chemical and biological components, including dissolved oxygen and chlorophyll-a) [DYRESM-WQ]
- Quasi two dimensional reservoir simulations [DYRESM-2D]

The two new versions of DYRESM, viz. DYRESM-2D and DYRESM-WQ are operational but are only being used on a research and development basis on projects in which the Centre for Water Research has a significant involvement. Since the verification and further extension of the models are still underway, they have not as yet been released and so could not be included in this research contract. These two models are, however, discussed in more detail in Section 2.4 below.

2.2 DYRESM-1D MODEL DESCRIPTION

2.2.1 One-dimensional Assumption

The assumption of one-dimensionality greatly simplifies the modelling task, however, its application means that the model is restricted to those lakes for which it is appropriate. A set of criteria is therefore required to determine the applicability of the assumption.

2.2.1.1 Lake Number

The Lake number L_N is defined in terms of the stability of the stratification and the disturbing influence of the wind. Thus, for a particular stratification being acted upon by a wind field there is a resulting force acting tangential to the water surface. This force will act to overturn the density structure of the lake and will be resisted by a restoring force generated by the rotation of the centre of mass about the centre of volume. The Lake number L_N is defined as the ratio of these two moments. If $L_N >> 1$, then the restoring force is greater than the disturbing force and the deflection of the centre of mass is small. This means that the density structure will be approximately horizontal and the one-dimensional assumption is valid. If $L_N << 1$, the disturbing force is greater and significant deflections may occur. The criterion for one-dimensionality is therefore $L_N >> 1$. A similar criterion $L_{N,I}$ may be developed for disturbances due to inflows where the disturbing force is the action of the inflow, resulting in another criterion for one-dimensionality being $L_{N,I} >> 1$.

2.2.1.2 Outflow Froude Number

A Lake number formulation for the effects of outflow is not obvious, however, an appropriate condition for the one-dimensional assumption has been found to be $F_o << 1$, where F_o is the outflow Froude number. Essentially this condition compares the speed at which disturbances are carried by the outflow velocity to the speed at which gravity will even them out. For $F_o << 1$, the structure will be maintained in a horizontal configuration by gravity.

2.2.2 Model Design

The basic model is constructed around the five process descriptions listed in Section 2.1.1 above and these processes are discussed in more detail below. A schematic diagram of the layout of these processes and their components that act on the water body is given in Figure 2.1.

2.2.2.1 Surface heat, mass and momentum exchange

The surface inputs of mass, heat and momentum play a major role in determining the vertical distribution of properties in the reservoir. Usually only single point measurements of the meteorological variables are available and the model relies on the bulk aerodynamic formulae for stress, sensible heat and evaporative heat to calculate these transfers.

Radiative heat transfers are also an important component of the heat budget at the surface. In this instance the model assumes that there are two components of radiation, viz. short wave and long wave. Short wave radiation is usually measured directly, while long wave radiation can either be measured directly or estimated from cloud cover, air temperature and humidity. Back radiation from the water surface is given by the Stefan-Boltzmann black body radiation law.

The incoming long wave radiation is all absorbed in the first few millimetres of the water column. Some of the incoming short wave radiation is reflected from the surface with a reflection coefficient determined by the angle of the sun, the colour of the water surface or the water surface state. The remainder of the incoming short wave radiation penetrates the water surface and is absorbed by the water column and, in general, this absorption is determined by an extinction coefficient which is dependant on the radiation wavelength and water clarity and colour. In DYRESM, this absorption is modelled by Beer's Law and the required extinction coefficient may be related to Secchi disk depth measurements.

The heat budget in the DYRESM layer structure as seen in the "radiation and energy fluxes" part of Figure 2.1 results in only the top layer being affected by evaporative heat losses, sensible heat losses or gains and long wave radiation input and emission. Short wave radiation both enters and leaves the top layer and provides a source of heat for lower layers, following Beer's Law. All the above fluxes are used to calculate the net temperature increase of the top, or surface layer for the time step in question.

The model is based on a daily time step (outer loop) but also internally selects sub-daily time steps (inner loop) which are determined in two ways. Firstly, the time step is chosen so that the upper layer temperature does not increase or decrease by more than 3°C, and secondly, it is chosen such that the increase in mean shear velocity is limited to 0,1 m/s. The minimum of the above two sub-daily time steps is chosen, with an absolute minimum of one minute and a maximum which brings the time of day to the first of either noon or midnight.

2.2.2.2 Surface mixed layer deepening

The algorithm which describes the deepening of the surface layer is based on an integral model of the turbulent kinetic energy budget. Here, a certain fraction of the energy made available at the surface and at the interface between the mixed layer and the underlying water is made available to lift and accelerate the quiescent and relatively heavy water below the interface into the mixed layer. This may be achieved in several ways.

Convective overturn: After a single time step the temperature structure will change as a result of the surface heat exchanges with, typically, the increase in temperature of the first few layers and in particular the surface layer. After cooling, however, the surface layer becomes cooler than the underlying layer leaving the temperature profile in an unstable state. This cold surface water will, in reality, plunge in a turbulent plume mixing with the water beneath. This process is modelled in DYRESM by simply adjusting the profile by comparing the density of the surface layer with that of the layer below and mixing the two layers if instability exists. This process is repeated until the profile is stable.

Wind stirring: Some fraction of the energy input to the surface by the surface wind is available at the interface for mixing. The surface stress provides a means of calculating this energy input using the overwater wind speed at a height of 10 metres.

Shear production: The action of the surface wind field, in addition to providing energy for deepening of the mixed layer, generates a shear velocity at the interface. As the interface deepens the conservation of momentum requires that a new shear velocity becomes applicable and in this change the total kinetic energy is reduced making more energy available for mixing. To operate the shear production mechanism a value for the shear velocity is required, which is dependant on whether or not the time after which shear production is no longer effective has been reached. This cut off time may extend beyond one model time step and the wind stress may change over the period when shear production is effective. These effects result in the calculation of shear production being a complex matter.

Billowing: The presence of shear at the interface or thermocline may lead to a shear instability providing additional mixing. The effect of this is the formation of Kelvin-Helmholtz billows which smear out the sharp interface generated by stirring and shear production.

Energy balance: The energy available for mixing, expressed as the rate of available turbulent kinetic energy, is calculated from that produced by convective overturn, wind stirring, shear production and billowing and is used to deepen the mixed layer. This means lifting relatively heavy water and accelerating stationary water, both of which require energy. The former energy requirement is that of the potential energy change required to mix two neighbouring layers of lower density on top and higher density below, resulting in a combined layer of uniform density. The latter energy requirement is that of the kinetic energy required to accelerate the stationary fluid below the mixed layer to the turbulent velocity scale. The presence of billows provides both a source and sink for energy which therefore appears on both sides of the energy balance. The simplest mixed layer model thus balances the energy requirement with the available energy and, in general, this balance provides an equation for the rate of deepening of the mixed layer. In the DYRESM model, where the time step is determined elsewhere and the incremental amount of mixing is in each case constrained to complete layers, the following procedure is adopted :

In each time step the available energy is calculated, based on the existing mixed layer after adjustment of the profile following surface cooling. The energy required to mix in the next layer is then calculated. If the available energy is greater than the required energy, the layer is mixed in and the mixed layer properties adjusted. The available energy is then reduced by the required energy amount and the next layer is considered. When the available energy is less than the required energy, mixing ceases and the remaining available energy is stored for use in the following time step. As the model takes each process in turn, the actual procedure is slightly more complex, but follows essentially the same path.

2.2.2.3 Inflow

The inflow process may be divided into three parts. As the stream enters the reservoir it pushes the reservoir water ahead of itself until buoyancy forces, due to the difference in density between reservoir and stream water, arrest the flow. At this point the stream either flows over the reservoir surface (if the stream density is less) or plunges beneath the surface (if the stream density is greater). Once submerged, the stream flows down the drowned river valley, entraining reservoir water, until a level is reached at which its density equals that of the reservoir. At this depth the stream intrudes horizontally into the reservoir in a relatively narrow intrusion.

Downflow: The time of downflow may be several days in length and to account for this a separate stack structure has been implemented in the DYRESM model. The stack is two dimensional, with each column corresponding to an individual inflowing river and the elements of each column corresponding to a particular day's inflow for that river. In each element all the parameters associated with a particular time step's flow are stored, including the volume, temperature, salinity and its depth. Each inflow retains its identity until it reaches the level of insertion, even though several elements may be at the same depth. The day's inflow is placed on the top of the downflow stack and also begins in a particular model layer. As each element flows down the drowned river valley it entrains water from the reservoir. The initial and final flowing depth, distance travelled, entrainment, velocity, etc., for the element to traverse the model layers are calculated from the geometry, drag coefficient, day's inflow and principles of conservation of volume and momentum. The travel time of the inflow is compared with the model time step, and if permissible, the process is repeated until either the time step is exhausted or the element reaches the level of neutral buoyancy. This process is repeated for all elements in the stack for each river and those elements due for insertion are flagged.

Insertion: Once the elements have reached the level at which their density equals that of the reservoir water, they are inserted in relatively thin layers, the thickness of which may be estimated from simple force balances. The thickness of the intrusion layer is inversely proportional to the degree of local reservoir stratification and directly proportional to the flow volume, while the length of intrusion is directly proportional to both the degree of local reservoir stratification and the flow volume. The hydrostatic pressure difference across the intrusion thickness drives the horizontal intrusion and the resultant horizontal force is balanced by either the retarding viscous force or the inertia of the intrusion. The ratio of the inertial to viscous terms (R) determines which of the formulae for intrusion layer thickness and length are appropriate, with the assumption that the inflow is two dimensional and uniform across the width of the reservoir. For the inertial term to be greater than the viscous term the value of R must be greater than unity, where R is directly proportional to flow volume and inversely proportional to the degree of local stratification, reservoir length and kinematic viscosity. Once the thickness and length have been determined, the volume of the element in the stack being inserted is distributed over the model layers encompassed by the intrusion thickness using a cosine intrusion velocity distribution.

2.2.2.4 Outflow

When water is drawn from a submerged offtake in a stratified reservoir most of the water comes from a narrow layer approximately centred at the offtake level. The thickness of the layer is determined by the stratification, the discharge and the nature of the offtake (line or point sink). For a line sink, with the withdrawal being uniformly distributed across the reservoir, the scaling described above for intrusions is valid. Thus equivalently, the ratio of the inertial to viscous terms (R) determines the nature of the withdrawal layer and an appropriate withdrawal thickness may be calculated.

While the two dimensional assumption may be reasonable for inflow intrusions, it is not valid near the offtake for withdrawal. The withdrawal layer thickness is established within a distance approximately equal to the layer thickness itself.

Consequently, if the side boundaries are further away than the height of the withdrawal layer, they should have little influence on the layer formation, and the outlet will behave as a point sink. On the other hand, if the layer thickness is greater than the distance to the boundaries, the behaviour will be like that of a line sink, at least for the region away from the sink itself. Consequently, three dimensional point sink formulations of the layer thickness are required to complete the model (see Hocking *et al.*, 1988).

Independently of the way the thickness of the withdrawal layer is calculated, the flow upstream is assumed to have no lateral variation, consistent with the one-dimensional assumptions. To properly model the region of withdrawal, however, the withdrawal velocity must be allowed to vary longitudinally and this velocity profile is assigned a cosine distribution. It is then possible to calculate the vertical velocities resulting from this flow and the resulting streamlines. Integrating backwards along the streamlines from the offtake enables the initial location of all particles which reach the offtake after some time step to be determined. This means that an envelope from which all water withdrawn in a particular time step originates may be drawn. It is evident from these envelopes that although the horizontal velocity is zero outside of the withdrawal layer, some of the fluid withdrawn in fact comes from outside the layer. The DYRESM model procedure for daily withdrawal is therefore to calculate the withdrawal layer thickness appropriate for the R value calculated for a point sink. This thickness is then compared with the reservoir's lateral dimension and, if greater, the line sink calculation is invoked. Using the withdrawal layer thickness the withdrawal envelope is calculated and the water from the layers encompassed by the envelope is withdrawn.

2.2.2.5 Mixing in the hypolimnion

Mixing in the hypolimnion of reservoirs due to internal wave breaking and wave interactions, mixing on the boundaries, billowing, etc., is patchy and sporadic with individual events occupying relatively small volumes and occurring relatively quickly. In the context of all models of the DYRESM type these events are modelled by a diffusive-like process with the actual events being parameterised by an eddy diffusivity. The formulation in DYRESM follows the premise that the diffusivity is proportional to the dissipation of turbulent kinetic energy and is inversely proportional to the degree of stratification.

2.2.2.6 Bubble plume destratification

Bubble plume destratification systems are modelled in DYRESM as simple buoyant plumes with the plume density being the density of the air-water mixture. This model is applicable for the case of very fine bubbles and the usual parameters for buoyant plumes apply, with the entrainment coefficient set at 0,083 (Patterson and Imberger, 1989). The model uses the usual equations of conservation of volume, momentum and buoyancy which are integrated over the cross section of the plume, with an additional buoyancy source term due to the expansion of the bubbles as they rise through the water column. These equations are solved using a 4th order Runge Kutta scheme. At the level of the aerator the local water density is reduced by the presence of air and the plume rises. As it rises it entrains water from each layer that it passes, increasing the density of the mixture and decreasing the centreline velocity of the plume. At some level the centreline velocity becomes zero, the plume stops and the water component is ejected. At this level the water component is relatively heavy and falls. Since the water component contains water from above the plume origin its density is less than the original density and the level to which it falls is therefore above that of the plume origin, resulting in a net vertical exchange. The bubble component of the plume continues to rise and as a result a new buoyant plume begins.

The whole process of plume rise and the ejection of the water component may be repeated several times depending on the air flow rate, the degree of stratification and the water depth, however, in the case of multiple plumes (and therefore intrusions) the net vertical transport is small. The height that the plume rises before ejection of the water component is inversely proportional to the degree of stratification and directly proportional to the supply of buoyancy, ie. the air flow rate. If the air flow rate is sufficiently large, the ejection of the water component will not occur before the surface is reached and may even be sufficient to carry the plume further than the available depth. Although this is not possible, it reflects a situation in which an excess of energy is being supplied and the overall efficiency is reduced. Similarly, a situation in which the air flow rate is so low that multiple intrusions form, reflects poor mixing and again low efficiency. An optimum value of the air flow rate for a given configuration and stratification therefore exists.

The efficiency of the process is represented as the ratio of the change in potential energy of the reservoir to the work required to produce the air flow via a compressor. The basic plume form is that arising from a point source of buoyancy. This is appropriate for single plumes or those which are sufficiently far apart to justify the assumption that the plumes do not interact. In many applications the diffuser holes are closely spaced and the individual plumes interact strongly to form a sheet. To account for this mode, as the plumes rise, the model checks for the possibility of adjacent plumes interacting and if this is the case the formulation switches to a line source model with the total air flow rate distributed over the length of the aerator.

2.2.3 Model Software Package

2.2.3.1 Hardware requirements

The following computer configuration is required to run DYRESM :

- An 80386 or 80486 processor based PC
- A maths co-processor
- At least 2 Mbytes of total system memory
- MS-DOS Version 3.0 or higher
- An Expanded Memory (EMS) Manager
- Preferably a high resolution colour graphics card and monitor

Run times of approximately one second or less per day for normal operation and up to approximately one minute per day during bubble plume operation have been experienced using a 25 MHz Mecer 80386 machine. This results in the modelling of one year's data running for approximately 4 to 6 minutes under normal operations with an appreciable increase in run time during periods of bubble plume destratification (eg. a few hours run time for several months of bubbler simulation). This model is therefore computationally efficient with relatively short simulation run times, when compared to other models, allowing more scenarios to be investigated in any particular period. It should also be noted that the model runs considerably faster when using an 80486 machine, with run times of several simulated days per second for normal operation and much reduced run times for bubble plume operations.

2.2.3.2 Software Description

The DYRESM model has been written in the FORTRAN computer programming language and has recently been converted to the Personal Computer environment. The source code is compiled using the F77L EM/32 Lahey 32-bit compiler with the OS/386 DOS extender. Although the source code is provided with the model, the model is supplied by the Centre for Water Research in a compiled form. The Lahey compiler is therefore only required if code changes that incorporate pre-processor type changes to the data presented to the model to adjust for specific South African conditions, are necessary. A flow chart showing the layout of the DYRESM subroutines, decision structure and main loops, and a brief description of each subroutine and function is given in Appendix A2.1.

The conversion of the model software to the PC environment included the introduction of a user friendly interface, with menus, input data screens, etc. This enhancement greatly simplifies the selection of data files and run parameters, the execution of the model and the viewing of model output. Examples of user interface screens showing typical menus, an input table and run time information are given in Figures 2.2 and 2.3 and an organogram showing the hierarchy of the user interface screen modules and their functions is given in Figure 2.4. The use of free format input files is also significant in making the preparation of input data an easier task.

The viewing/plotting facility allows two or three output data sets to be compared with each other or against observed temperature and salinity profiles, with a choice of plotting the profiles at selected fixed intervals or only those common to all the selected data sets. The user is given control over both the plot scaling and the colours to be used either via an input screen or plot definition file in the working directory. Hard copies of typical observed versus simulated profile plots are given in Section 2.3 below.

In the early stages of the project user friendly screen-graphics software, known as DYPLOT, was developed by Ninham Shand to view, plot and manipulate profiles and isoline values for both temperature and salinity. Much of the MINLAKE results shown in Chapter 3 were produced with DYPLOT. Unfortunately, DYPLOT is not compatible with the latest version

[DATAPREP] LIST FILE **INPUT DATA** CREATE DPO

Enter of revise input data files

Reservoir : GLENNIES CREEK

Simulation range : 90218 91101

Inflow :	GLEN90.INF
Outflow :	GLEN90.OUT
Meteorological :	GLEN90.MET
Field :	GLEN90.FLD
Morphometric :	GLENN.TAB
Physical :	GLENN.FIZ

[F1] = HELP [↑↓] = MOVE BAR [↵] = SELECT [Esc] = BACKUP

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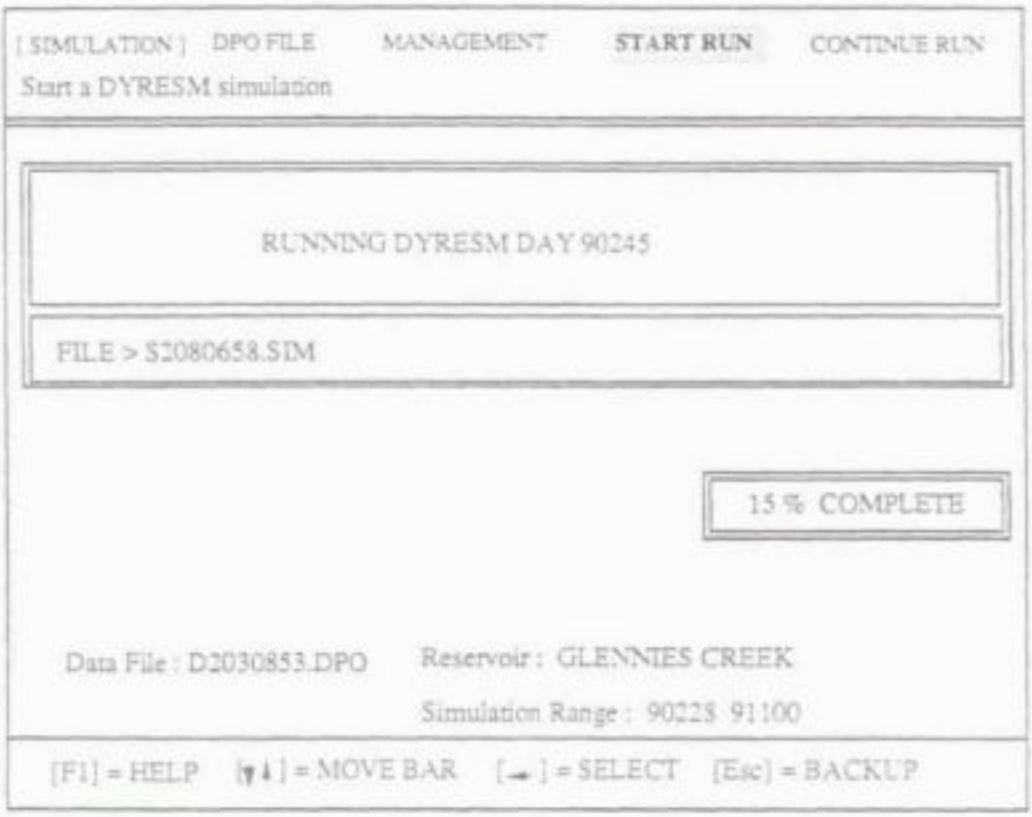
DYRESM - 1D: Example user interface screen showing typical menu and input table

FIGURE 2.2



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	DYRESM - 1D: Example user interface screen showing typical menu and run time information	FIGURE 2.3

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Organogram of DYRESM - 1D user interface menus

FIGURE 2.4

of DYRESM and the exhaustion of the project budget and time did not allow the necesssary conversions.

2.2.4 Model Data Requirements

DYRESM-1D requires that data from the following six sources be used to create free format ASCII input data files for use by the model :

- Lake or reservoir morphometry
- Lake or reservoir physical data
- Meteorological data
- Inflow data
- Withdrawal data
- Observed temperature and salinity profile data

A description of the data required for each input file is given below :

2.2.4.1 Lake morphometry

This file contains the following basin characteristics required for modelling :

- Reservoir name.
- Base elevation and full supply level (m).
- Basin width and length at full supply level (m). The width should be a representative width since inflow insertion takes place over this width. The length should be the basin length following the major stream and is also used by the inflow insertion routine.
- Depth of hole (m). Used when a depression in the basin upstream of the dam wall has a lower base than the base elevation at the dam wall.
- Minimum layer volume. This is expressed as the ratio of this volume over the total volume of the reservoir and should not be less than 0,02.
- Minimum and maximum layer thickness (m). The minimum thickness should be greater than 1% of the total depth of the reservoir. A typical range of layer thicknesses would be 0,65 - 2,00m for a 50 - 60m deep reservoir.

- Cumulative basin area and volume versus depth values at various levels within the reservoir from the base to above full supply level.

2.2.4.2 Physical data

This file contains the coefficients and constants of the various physical processes incorporated in the model and the user is advised not to change the values from those given in the user's manual, with the exception of the light extinction exponent. This value, for any particular reservoir, can be approximated from Secchi disk depths where the extinction exponent is equal to between 1,44 to 2,30 (typically 1,7) divided by the Secchi disk depth (m), or alternatively, calculated from measurements of light attenuation at depth. In the latter case, the extinction exponent is taken to be equal to the change in the natural log of the light intensity over the change in depth.

The molecular diffusivity (m^2/s) of both heat and salt is given in this file, however, if the diffusivity of salt is omitted then only temperature profiles are calculated. It should also be noted that the variable PERCW has recently been removed from the source code and therefore, although assigned a value in this file, has no effect on model simulations.

2.2.4.3 Meteorological data

This file contains the total or daily average meteorological data required to run the model. Each day's data includes the following :

- Julian day.
- Total daily short wave radiation ($kJ/m^2/day$). This can be selected to be net short wave radiation where the reflection has been precalculated and subtracted, or total incoming short wave radiation where the reflected component is calculated within the model. Total incoming short wave radiation is also called total global radiation and encompasses wave lengths in the range 0,1 to 4,0 micrometres. Incoming short wave radiation can also be approximated by 2 x the photosynthetic active radiation (PAR).
- Total daily incoming long wave radiation ($kJ/m^2/day$). This encompasses wave lengths in the range 4,0 to 100,0 micrometres, and can be input in one of three ways. Firstly, net long wave radiation where the outgoing radiation

is subtracted from the incoming, secondly, incoming long wave radiation, and thirdly, sunshine ratio (1,0 - cloud cover ratio) where the incoming radiation is calculated using the daily average cloud cover ratio and daily average absolute air temperature (°K).

- Average daily air temperature (°C). This can be approximated by the average of the daily maximum and minimum daily air temperatures.
- Average daily vapour pressure (mbar). This can be approximated using daily average wet and dry bulb temperatures, or daily average relative humidity and daily average air temperature.
- Average daily wind speed (m/s). This is extremely important as many of the model processes are significantly affected by the wind speed. The wind speed should be calculated as an average over the entire day or computed from a total daily windrun. The model requires the wind speed entered into this file to be over water wind speed adjusted to 10m height. The adjustment for height is most commonly done using a natural log relationship with a good theoretical basis and well established value for the surface roughness of water. If the wind, however, is not measured as over water wind speed, but is measured as over land wind speed, then a land surface roughness is required. It can be seen from Addendum 2, Table 2.2 that this value can vary considerably. The adjustment of the overland wind speed to a 10m height is none the less possible using the natural log relationship, however, in certain cases a further adjustment from over land wind speed to over water wind speed is required. The available methods to make this adjustment are dependant on predominant wind directions, over water wind fetches, etc., and include those given in the MINLAKE model user's manual (Riley, 1988) and the Shore Protection Manual (United States Army Corp of Engineers, 1984) (see also Addendum 2 of this report). The model allows the wind speed to be adjusted to take account of the above by the use of a wind factor which is entered via the user interface before a model simulation is run. This wind factor is simply applied to all the wind speeds and is not the same as the wind coefficient in the MINLAKE model. It should also be noted that in cases where the wind includes a significant degree of high speed gusts, the cubed root of the daily mean of the cubes of short duration (eg. 6 minute or 1 hour)

wind data should be used for the daily average wind speed.

- Total daily rainfall (mm). As measured at the nearest (or most appropriate) station.

2.2.4.4 Inflow data

This file contains the following inflow data for each stream :

- Stream name.
- Stream half angle (degrees). This is half the angle between the average slope of each side of the stream bed in cross section. The cross section being a typical one for the drowned river channel within the basin below full supply level.
- Stream bed slope (degrees). This is the average slope of the drowned river channel within the basin below full supply level.
- Stream bed drag coefficient. This is taken to be approximately equal to 0,015 for drowned river channels within the basin below full supply level that have a Manning n value of approximately 0,05. Refer to Imberger and Patterson (1981) for C_D values associated with other roughnesses.
- Daily total inflow volume for each Julian day (m^3x10^3). This may be calculated from either gauged inflows or estimated from a water balance.
- Daily average inflow temperature (°C). This may be calculated from continuously measured data, synthesized/patched data (using for example regression techniques on weekly observed data) or estimated from average air temperatures (using for example the average air temperature for the 14 days prior to the day in question).
- Daily average salinity (NaCl ppm). Since total dissolved salts (TDS in mg/l) and/or electrical conductivity (EC in mS/m) are most commonly measured in South Africa, the daily average salinity in (NaCl ppm) has to be calculated using regression techniques or the relationship between water density, temperature and TDS or EC must replace the NaCl relationship in the source code.

2.2.4.5 Outflow data

This file contains the following outflow data for each outlet from the dam :

- Outlet elevation (m).
- Basin width and length at outlet elevation (m). The width should be a representative width and is used for withdrawal mode determination. The length should be the basin length following the major stream and is also used by the withdrawal routine.
- Daily total outflow volume for each Julian day (m^3x10^3). In most cases this is calculated from gauged outflows.

2.2.4.6 Temperature and salinity profiles

This file contains the observed field profiles. A model simulation may only be started on a day with field profile data. The data for each profile includes the Julian day, reservoir elevation, number of observed points and the depth, water temperature (°C) and salinity (NaCl ppm) for each measurement point in the profile. The depths are input relative to the bottom of the lake or reservoir with increasing depth. It should also be noted that the simulated profile for a particular Julian day is that calculated for approximately 07h00. This should be kept in mind when comparing simulated and observed profiles.

In most cases the observed field profiles entered should be the average of all the profiles measured at the various sampling points within the dam basin, however, care should be taken to avoid profiles that appear incorrect or non-representative for a particular reason. Should profiles from particular sampling points vary considerably separate observed profile files should be created or various profiles entered into the file offset by a day or two from the actual sampling date, in order to facilitate comparison of the observed and simulated profiles.

2.3 DYRESM-1D MODEL APPLICATION

At the outset of this section we need to stress that, due to time and budget constraints, only a provisional and non-exhaustive application of DYRESM could be completed as part of this project.

2.3.1 Roodeplaat Dam

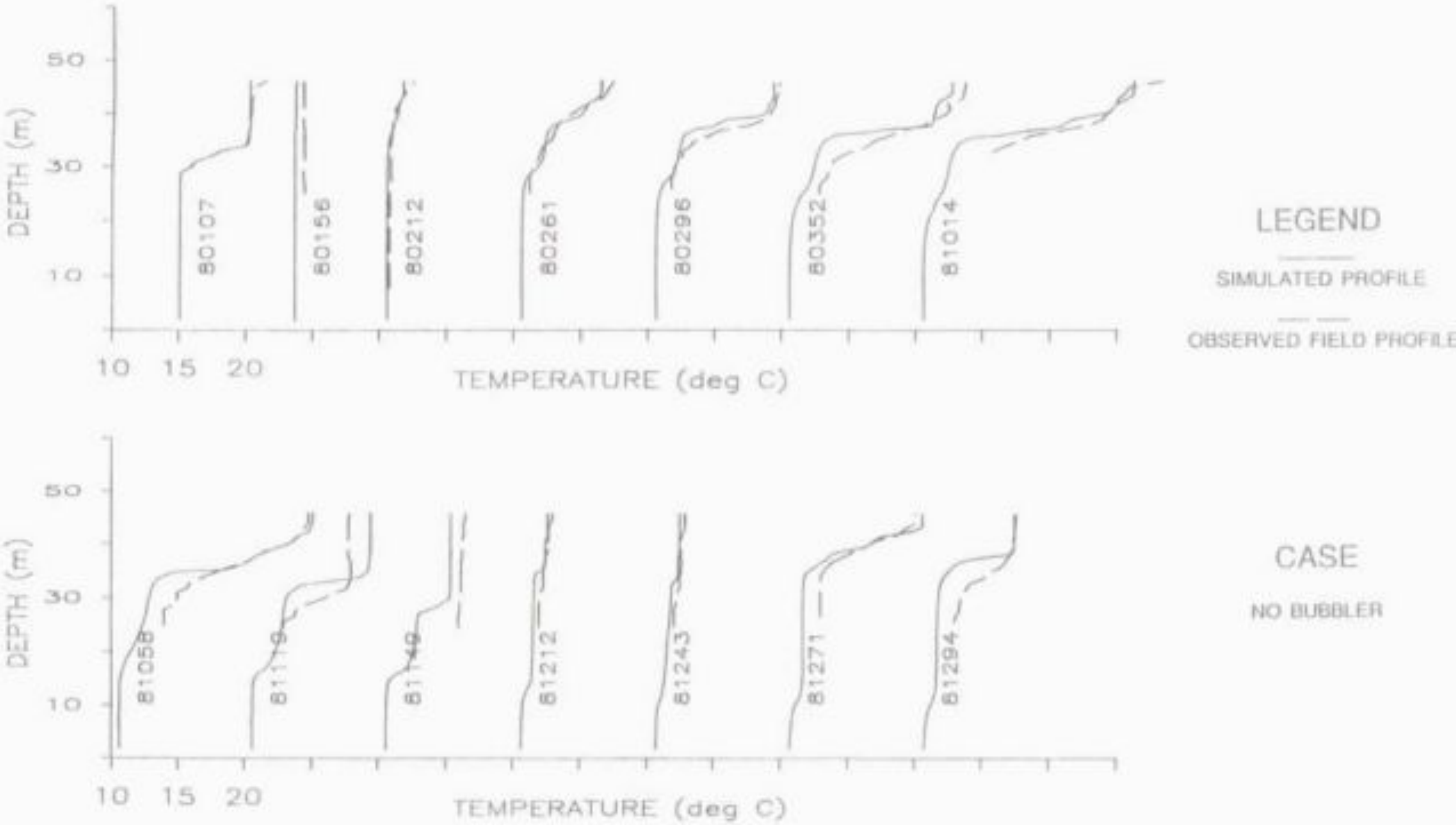
2.3.1.1 Model input data

The data set used in the DYRESM simulation of Roodeplaat Dam was taken from the MINLAKE data set as described in Chapter 3. The available data allowed for a simulation period of 1355 days, from 16 April 1980 to 31 December 1983, however, the last available observed field profile was on 7 April 1982, giving a workable simulation period of 722 days (approximately two years). The data set was converted for DYRESM input via a set of computer programs written specifically for this purpose. Data specific to DYRESM and not available in the MINLAKE data set, was obtained from the following sources :

- Reservoir basin lengths and widths at full supply level and outlet levels, and inflow stream half angles and slopes were estimated from appropriate contour mapping.
- The light extinction exponent was estimated from the average of observed secchi disk depth measurement data.
- Daily average vapour pressure was estimated using relative humidity and air temperature data.
- Daily average inflow and observed profile salinities (NaCl ppm) were estimated from TDS (mg/l) using a logarithmic regression.

2.3.1.2 Simulations and model results

Since no observed salinity profile data was available the runs were limited to simulating temperature profiles within the dam. The wind data used for Roodeplaat Dam is measured at the Hydrological Research Institute (HRI) which is situated near the dam wall. The wind



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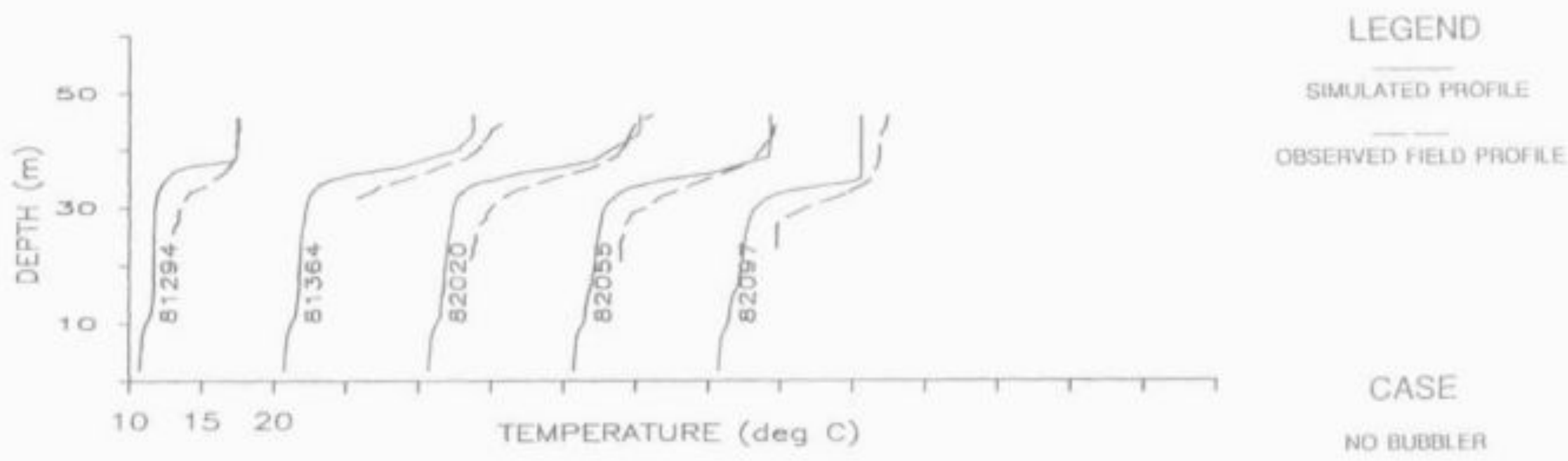
ROODEPLAAT DAM: DYRESM TEMPERATURE PROFILES
Julian Day 80107 - 81294 (No calibration)

FIGURE 2.5



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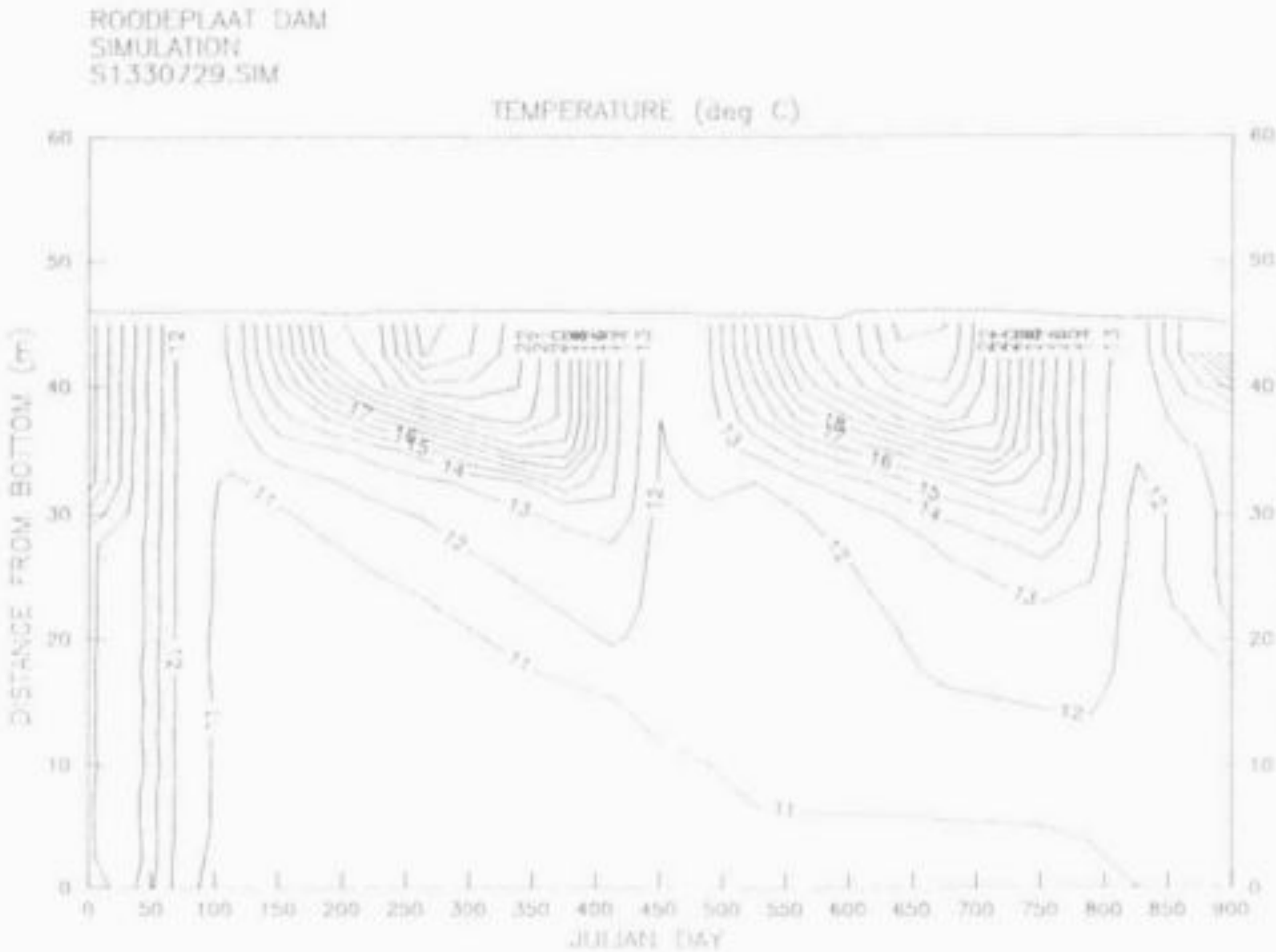
ROODEPLAAT DAM: DYRESM TEMPERATURE PROFILES
Julian Day 81294 - 82097 (No calibration)

FIGURE 2.6



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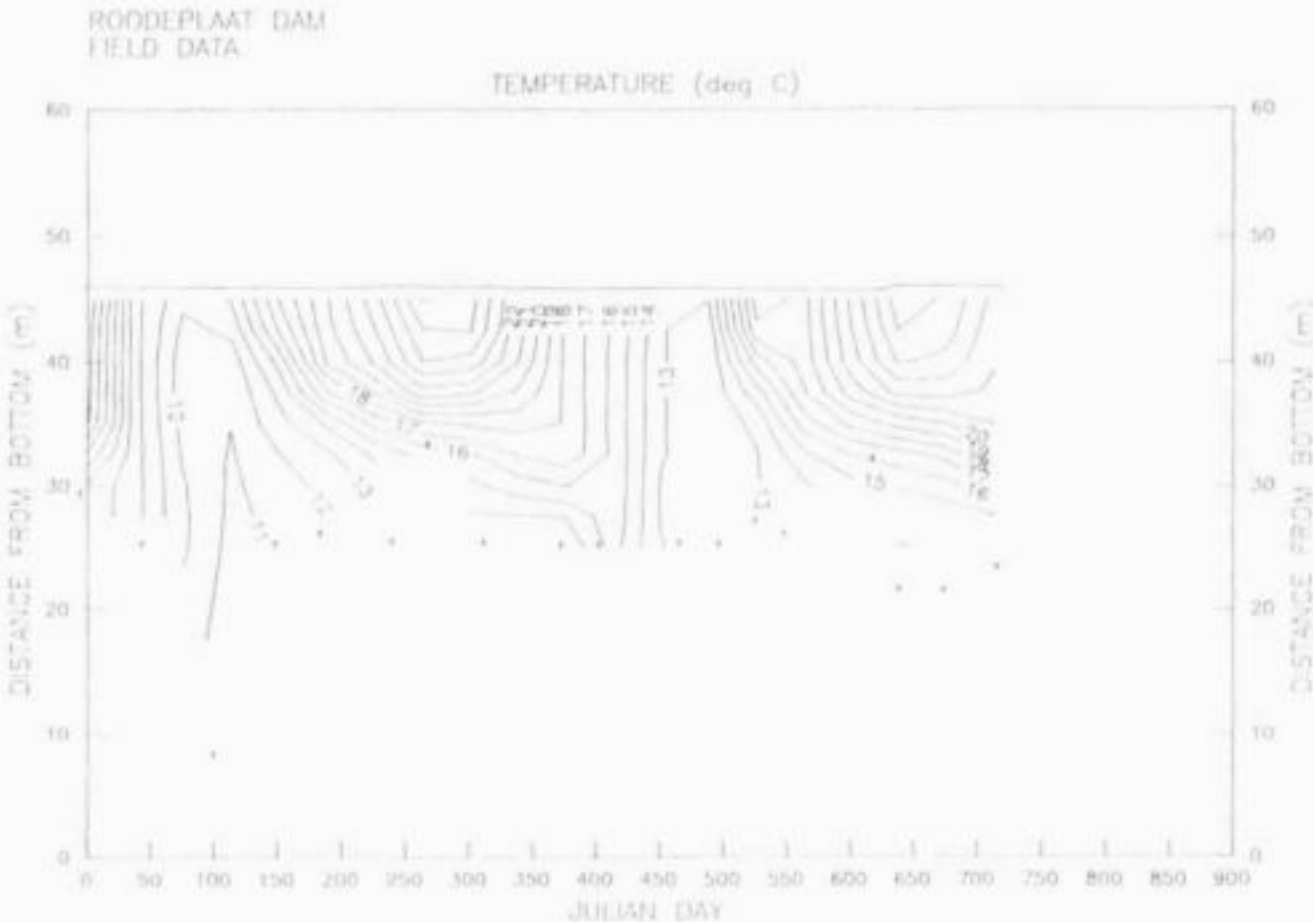
ROODEPLAAT DAM:
DYRESM - 1D simulated temperature isolines

FIGURE 2.7



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RODDEPLAAT DAM:
Temperature isolines based on observed field profiles

FIGURE 2.8

speed is measured by cup anemometer at the height of 1,8 metres. For the initial model run the wind speed was converted to a height of 10 metres using the power law with a power of 0,34 (overland wind speed). The resulting wind conversion factor was found to be 1,78. This was later found to be equivalent to using the natural log relationship to convert from 1,8m height to 10,0m height with the land surface roughness taken as 0,2 and with no over land to over water conversion. It can be seen from Addendum 2, Table 2.2 that this surface roughness corresponds to the low end of the sparsely built up suburbs scale.

Figures 2.5 and 2.6 show the DYRESM simulated temperature profiles for the initial run versus the observed field temperature profiles for the 722 day simulation period. It can be clearly seen that the initial model run simulated the reservoir hydrodynamics very well. In particular the onset and degree of stratification, the depth of the surface mixed layer and the mixing/overturning of the reservoir were well predicted. In most cases the simulated temperature was within one or two degrees of the observed with the main discrepancy lying in the prediction of the hypolimnion temperature which appears to be under predicted by up to a few degrees. A further comparison of the simulated versus observed hydrodynamics for the initial simulation can be seen in Figures 2.7 and 2.8 where temperature isolines are plotted against time over the simulation period. Unfortunately the temperature measurements making up the observed profiles (the locations of which are shown by the small arrows in Figure 2.8) were not made over the entire depth of the dam, however, the goodness of fit can still be clearly seen.

Since DYRESM is a physical process based model which does not require fundamental calibration, each adjustment made to the input data and parameters to obtain a better fit between the simulated and observed profiles should be justifiable and should represent a possible scenario or encompass feasible data measurement/extrapolation/translation anomalies.

2.3.1.3 Sensitivity checks

In order to test the sensitivity of the simulated profiles to the various model parameters and input data a number of simulations were undertaken with the following results :

- The minimum layer thickness to be used by the model was varied. This had only a minimal effect on the simulated profiles but did affect the computation time slightly.
- The light extinction exponent (ET1) was set to that calculated from :
  a) The average Secchi disk depth of available measurements (ET1=0,88).
  b) The average of all the ET1 values calculated from each available Secchi disk depth (ET1=1,11).
  c) The minimum of all the ET1 values calculated from each available Secchi disk depth (ET1=0,46).
  d) The maximum of all the ET1 values calculated from each available Secchi disk depth (ET1=2,33).

  The initial runs were done using a) above. The results using a) and b) were very similar showing relative insensitivity to this parameter, however, the use of c) caused an increase in the depth of the surface mixed layer that created a significant difference between the simulated and observed profiles. The use of d) above caused more energy to be available to the hypolimnion resulting in a more accurate prediction of the hypolimnion temperatures but with a worse simulation of the surface mixed layer temperature. This parameter can therefore affect the simulation to some extent and should be investigated using a range of ET1 values from within the range calculated from the observed Secchi disk depths or light intensity measurements.
- The reservoir basin length at full supply level was varied. The model was found to be relatively insensitive to this parameter which should just be chosen rationally.
- The reservoir basin width at full supply level was varied. The model was found to be relatively sensitive to this parameter with an increase in effective width resulting in a marginally less defined thermocline. Over the range of

feasible effective widths the sensitivity of the model to this parameter is not great, however, this effect should be kept in mind as the estimate of effective width is a subjective one.

* In order to test the effect of the inflow temperature on the simulated temperature of the hypolimnion, runs were done with the inflow temperatures first increased by 3 °C and then decreased by 3 °C. The effect of these changes on the simulated profiles did, however, not provide a better fit between simulated and observed profiles and the initial data was still seen to provide the best overall fit.
* The effect of increasing and decreasing the wind velocity by 10% was evaluated bearing in mind the uncertainty in the over land to over water and wind height adjustment factors. The results showed that the model is highly sensitive to wind velocity and all of the simulated profiles were affected to some degree. In the case of the increase in wind speed, a cooling and deepening of the surface mixed layer as more energy was available for mixing, was observed. A slightly cooler hypolimnion was also observed. The decrease in wind speed caused the opposite effect with the surface mixed layer being warmer than the initial simulation and with a sharper thermocline visible. In this case a slightly warmer hypolimnion was observed. Neither case represented a better overall fit of the simulated profiles to the observed field profiles when compared to the original run; however, the importance of wind measurement, calculation and transformation was highlighted.

The results of the various hydrodynamic simulations of Roodeplaat Dam showed that no significant improvement to the already good fit between the simulated and observed profiles, as seen in Figures 2.5, 2.6, 2.7 and 2.8, was possible at this level of investigation and within the boundaries of justifiable adjustments to the model input data/parameters, as discussed in paragraph three of this section. The results also show that the one-dimensional DYRESM model is capable of a good hydrodynamic simulation using a data set originating from reservoirs that belong to the upper end of the range of monitoring configurations in South Africa. The sensitivity of the model to the wind data indicates the necessity of maintaining a good wind measuring network and database for all dams that may require an analysis of this nature. The necessity of regular and accurate measurement of the various aspects of inflow, outflow, meteorological and observed field profile data has, however, been highlighted.

2.3.2 Hartbeespoort Dam

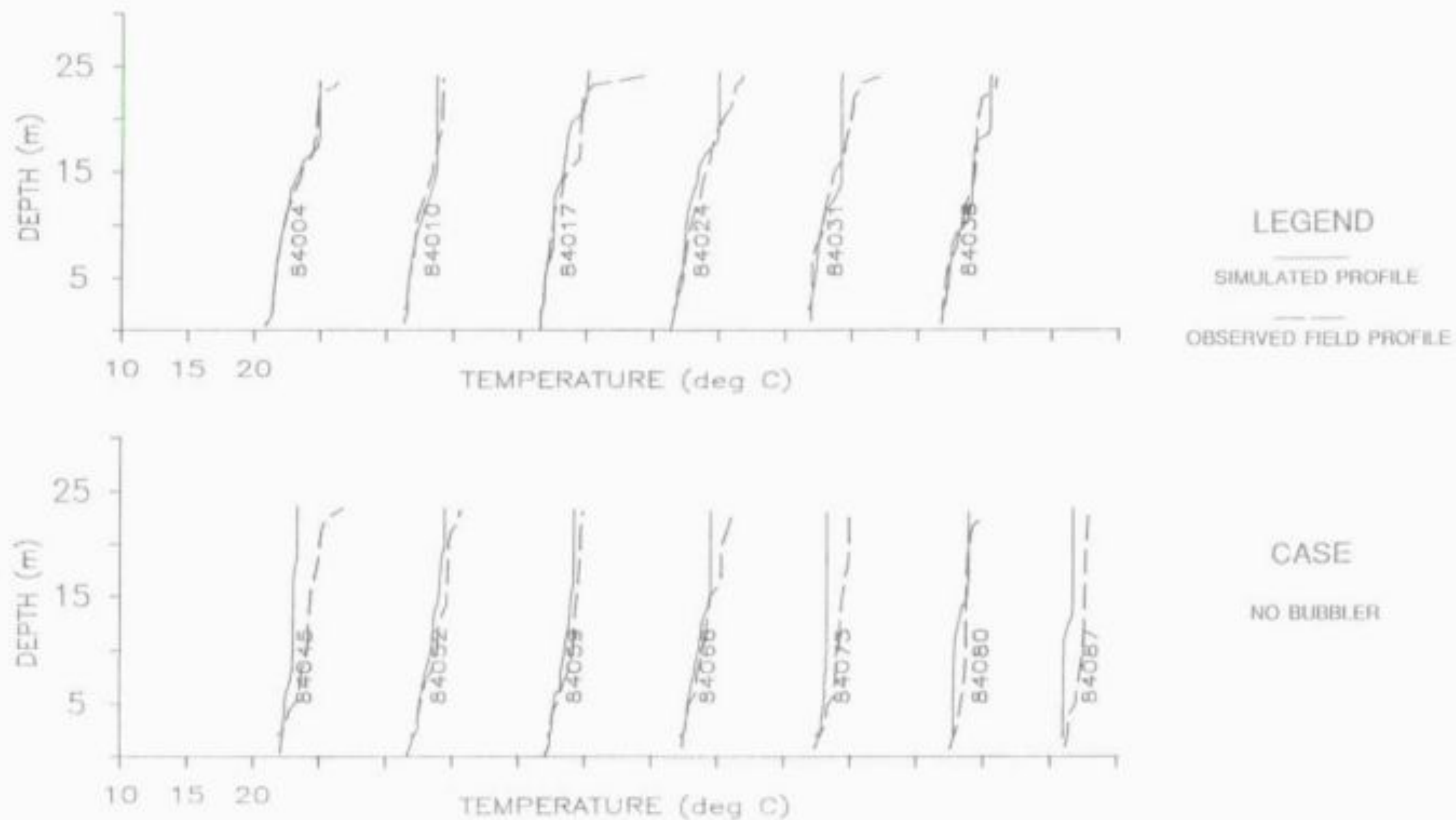
2.3.2.1 Model input data

As in the case of Roodeplaat Dam, the data set used in the DYRESM simulation of Hartbeespoort Dam was taken from a data set prepared for MINLAKE application (see Chapter 3). This data set was converted for DYRESM input via the set of computer programs written for this purpose. The data available covered the period from 4 January 1984 to 31 December 1986. Data specific to DYRESM and not available in the MINLAKE data set was obtained from similar sources as for the Roodeplaat Dam simulation.

It was soon discovered that the inflow volumes were too low for the first few years of available data and that a factor of approximately 1,45 was required to allow for a reasonable mass balance. This factor is partly explained by the 10% difference between the total catchment area of the dam and the collective catchment area of the inflow gauging stations on the Crocodile and Magalies Rivers. Problems with the inflow records of these gauges and the outflow records in general have been encountered in the past (Bosman, personal communication, 1991). Further investigation into this matter is required, which was unfortunately not possible within the scope of this study, and therefore only preliminary model runs were undertaken as described below.

2.3.2.2 Simulations and model results

Figures 2.9 to 2.12 show the DYRESM simulated temperature profiles for the initial run (with an inflow factor of 1,45) versus the observed field temperature profiles for the period from 4 January 1984 to 8 January 1985. With the exception of Julian day 84143, the model has simulated the observed profiles fairly well. The shape and temperatures of the simulated profiles fit the observed profiles in the first part of 1984 quite well. However, the simulated profiles at the onset of stratification towards the end of 1984 display a sharper thermocline, more completely mixed surface layer and under predicted lower hypolimnion temperatures, possibly due to wind and inflow temperature anomalies, when compared with the observed



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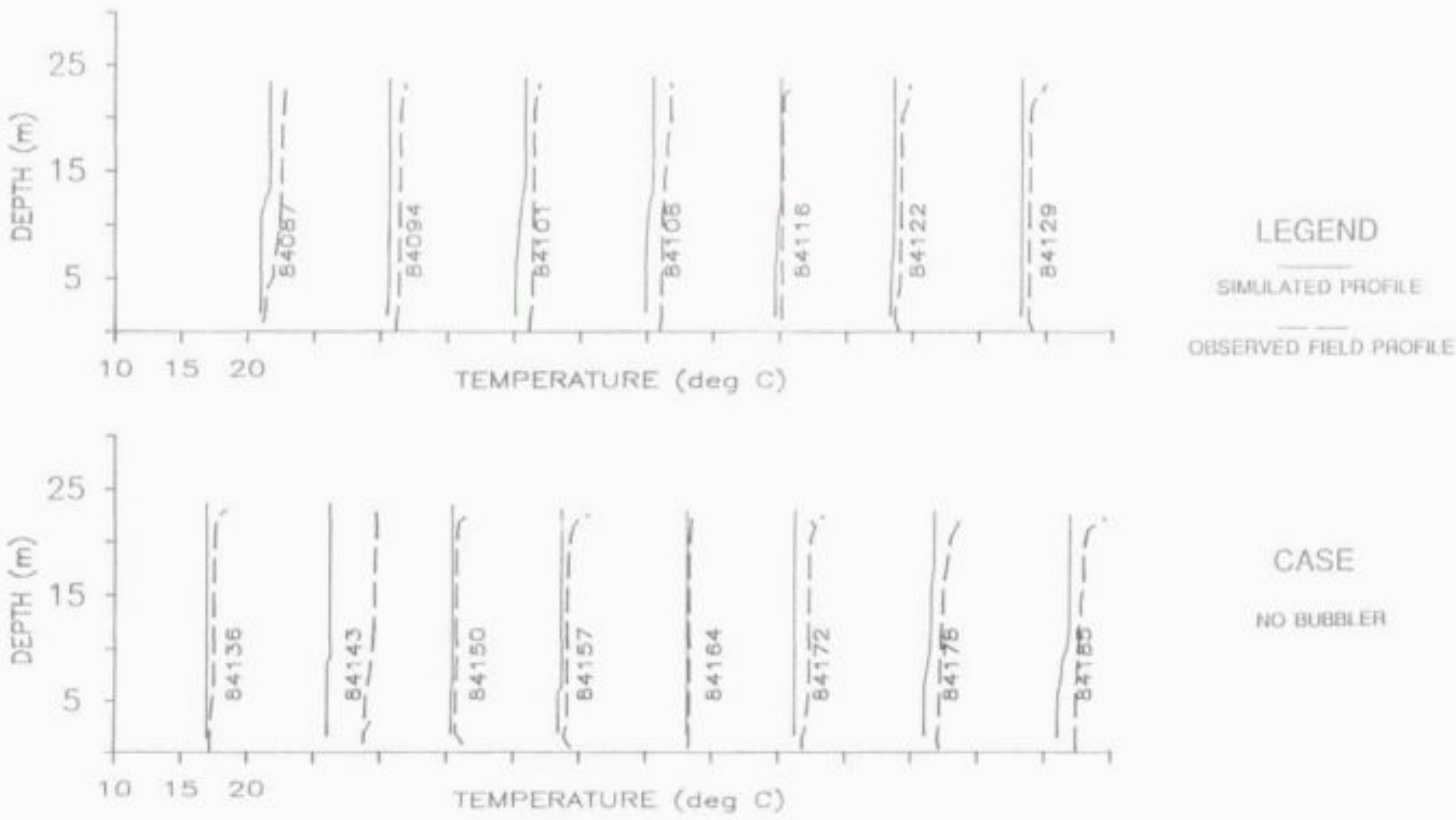
HARTBEESPOORT DAM : DYRESM TEMPERATURE PROFILES

Julian Day 84004 - 84087

FIGURE 2.9



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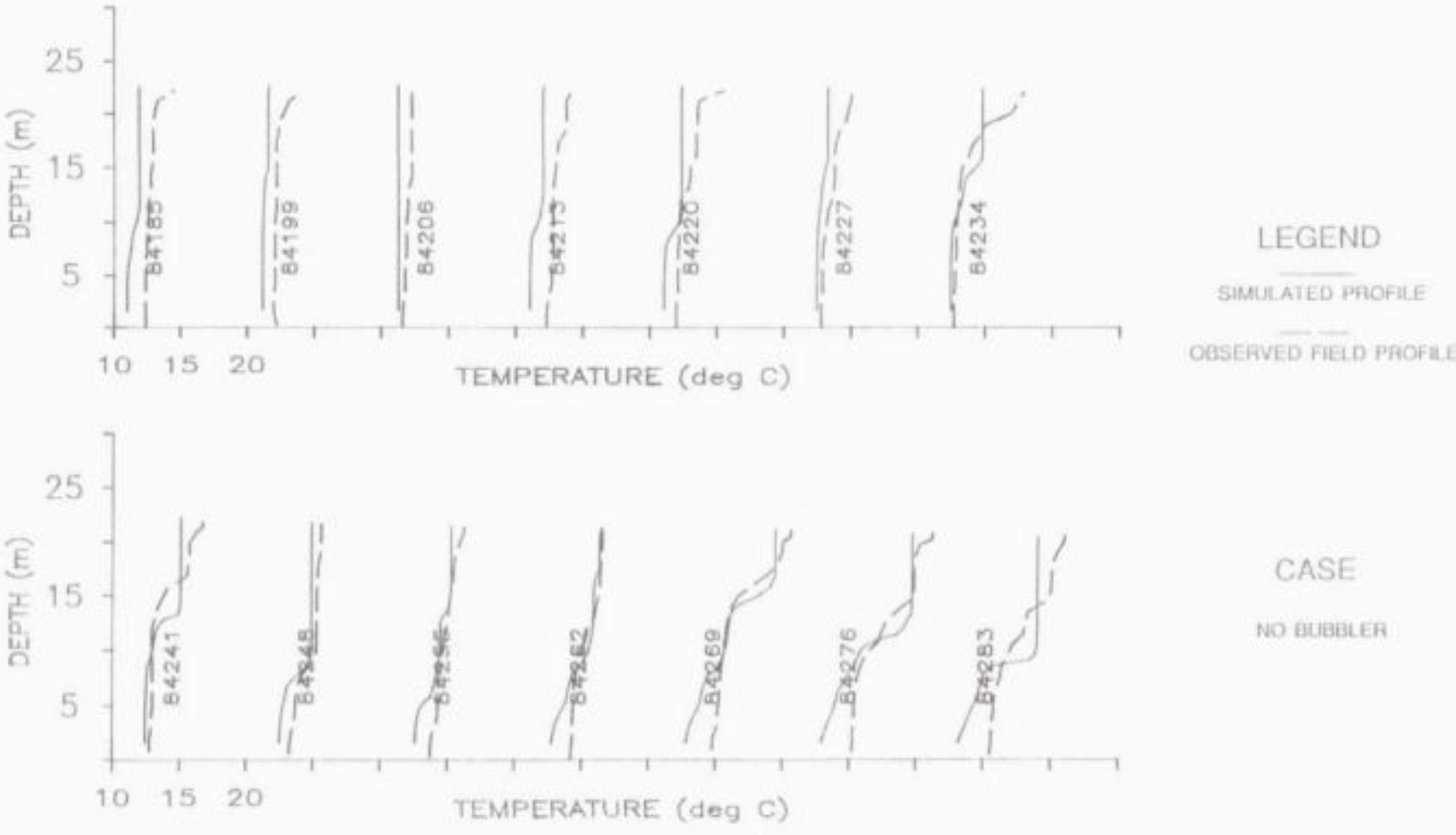
HARTBEESPOORT DAM : DYRESM TEMPERATURE PROFILES
Julian Day 84087 - 84185

FIGURE 2.10



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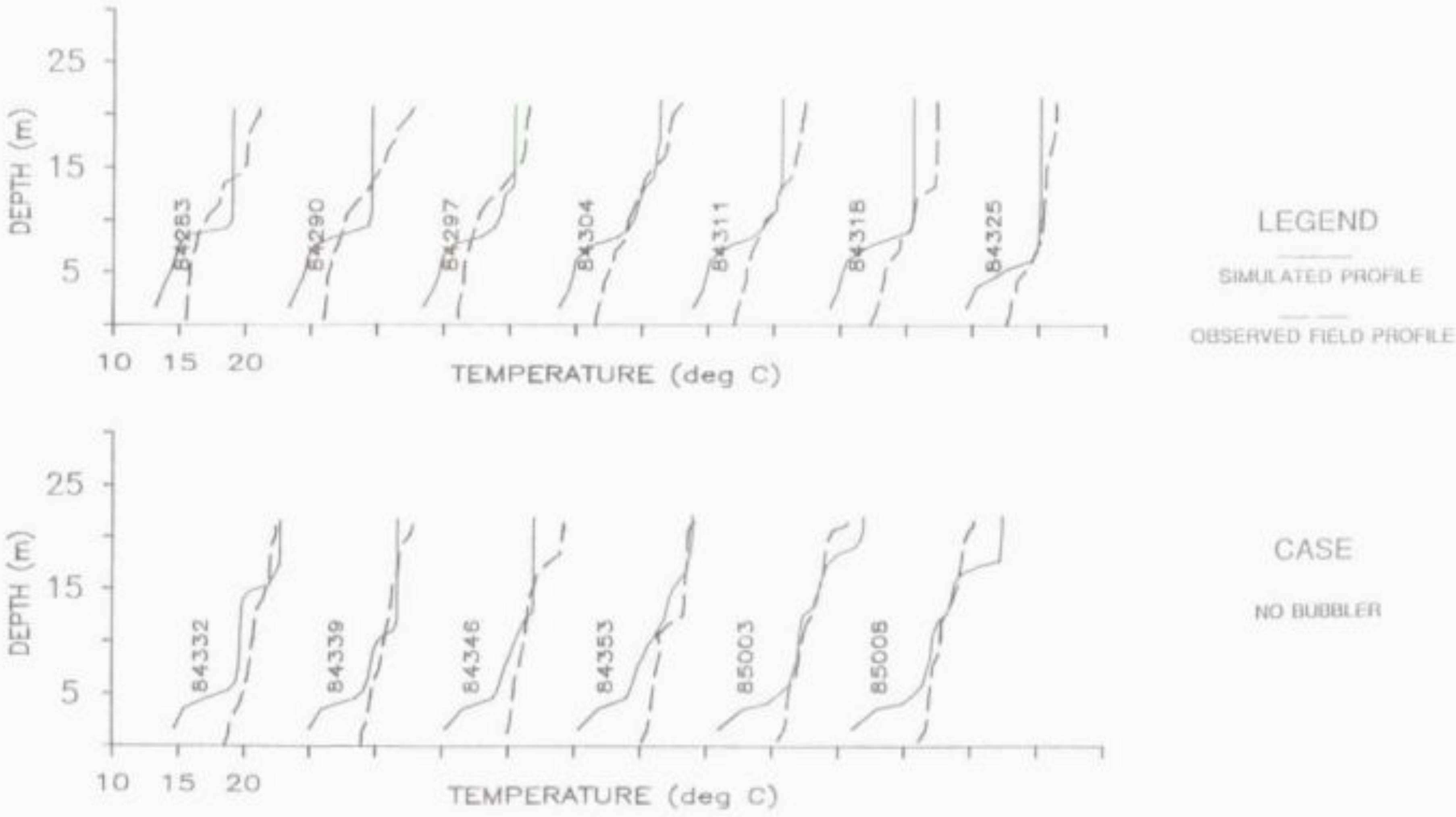
HARTBEESPOORT DAM : DYRESM TEMPERATURE PROFILES
Julian Day 84165 - 84283

FIGURE 2.11



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HARTBEESPOORT DAM : DYRESM TEMPERATURE PROFILES
Julian Day 84283 - 85008

FIGURE 2.12

profiles. It should also be remembered that small errors in the predicted profile in the lowest region of the reservoir is of less significance due to the minimal volumes involved.

When considering the above profile plots it should be kept in mind that the observed profiles are based on only one field sampling point in the dam basin and that this point is unfortunately situated at the start of the narrowing which leads to the dam wall (see Figure 3.17). This location appears to be largely sheltered and could experience local effects. It is therefore possibly unrepresentative of the main body of the reservoir. These phenomena may well be able to be better modelled by DYRESM-2D, however, the input data problems mentioned in the above paragraph, should first be investigated. The need for several representative observed field profile sampling points throughout the main body of the dam is, however, highlighted. It should be noted that, although there are other sampling points in Hartbeespoort Dam (National Institute for Water Research, 1985), at the time of this study only data for sampling point one was available.

2.3.3 Bubble Plume Destratification

2.3.3.1 General considerations

One of the unique features of the DYRESM model is the inclusion of the bubble plume destratification routine. In the light of the success of the Roodeplaat Dam simulation we decided to use that simulation to test and demonstrate the application of this method of destratification. It is important to stress that the analysis is not to be viewed as a full design of a bubbler system for Roodeplaat Dam but rather as a demonstration of the feasibility of a bubbler required for adequate destratification in a typical reservoir in the summer rainfall region.

The bubbler design philosophy as laid out in by Schladow (1991) was used to calculate the required air flow rate and bubble plume configuration. The first step was to determine the degree of stratification that would have to be broken down. This was done by calculating the equivalent linear stratification that has the same potential energy as a typical stratified observed field profile. Julian day 80014 (see Figure 2.5) of the Roodeplaat observed record was chosen since it represents an extreme case of stratification. The equivalent linear stratification for this profile was found to be approximately 0,5 °C/m.

Schladow (1991) shows that the mechanical efficiency of a bubbler system is related to the air flow rate through each bubble source, the total pressure head at the bubble source (water head plus atmospheric pressure head) and the equivalent linear stratification. Schladow (1991) also shows that efficiency peaks exist that are related to the number of whole plumes that form between the bubble source and the water surface (see Section 2.2.2.6 above). It is recommended that, since the efficiency drops off dramatically for single plumes with an air flow rate that could carry the plume further than the available depth, the "second efficiency peak" associated with an optimal case with only two whole plumes forming, should be strived for in bubbler design.

It is important at this point to discuss the two cases for which reservoir destratification is required. Firstly, there is the case of the destratification of an already strongly stratified water body in which a relatively large air flow rate is required to remove the stratification over a period of a few weeks. In the second case, the bubbler is used to prevent the onset of stratification and maintain the reservoir in a mixed state, which requires a smaller air flow rate. In the practical implementation of a bubble plume destratification system, however, both air flow rates are often required. For example, should the compressor system be out of action for whatever reason for a long enough period, strong stratification may result, requiring an air flow rate to destratify the reservoir greater than that available from a prevention/maintenance system alone. It was therefore decided that although the Roodeplaat Dam simulation shows that stratifications of approximately 0,5 °C/m are possible, bubbler configurations for stratifications of 0,25 °C/m and 0,20 °C/m would also be tested.

2.3.3.2 Quantified details

The air flow rate for individual bubble sources and the associated efficiencies for the "second efficiency peak" were calculated from the theory (Schladow, 1991) for each of the three stratifications. The efficiencies ranged between approximately 6,5 % and 10,0 %. The total air flow rate required for the case of the 0,5 °C/m stratification was determined, using the change in potential energy required to mix the reservoir, the calculated efficiency of 10 % and a time for destratification of three weeks, and was found to be 855 l/s.

At this point it was deemed necessary to determine the approximate feasibility in terms of costs of a bubbler system of this nature. A local compressor supplier indicated that a 55 kW compressor is capable of supplying an air flow rate of 150 l/s at a 50 metre depth. The aforementioned 0,5 °C/m stratification requirement for an 855 l/s air flow rate implies a need for six such compressors. At a capital cost of R 80 000 each, this requirement is clearly very costly and more favourable options need to be sort by optimisation. It was therefore decided to test the effect of air flow rates of 900, 300 and 150 l/s.

Three scenarios based on the above findings were chosen and the appropriate number of bubble sources calculated for each case. The length of each bubble plume system was calculated based on the number of sources and the rule-of-thumb that the diameter of a bubble plume increases at the rate of 0,2 times the height of rise, assuming non-interacting plumes. The three scenarios selected are given in Table 2.1 below.

TABLE 2.1 : BUBBLE PLUME DESTRATIFICATION SYSTEM SCENARIOS

Scenario	1	2	3
Degree of stratification (°C/m)	0,50	0,25	0,20
Total air flow rate (l/s)	900	300	150
Individual bubble source air flow rate (l/s)	18,0	8,5	4,2
Number of bubble sources	50	35	35
Length of bubbler system	500	350	350
Number of compressors	6	2	1
Total power requirement (kW)	330	110	55

2.3.3.3 Simulation results

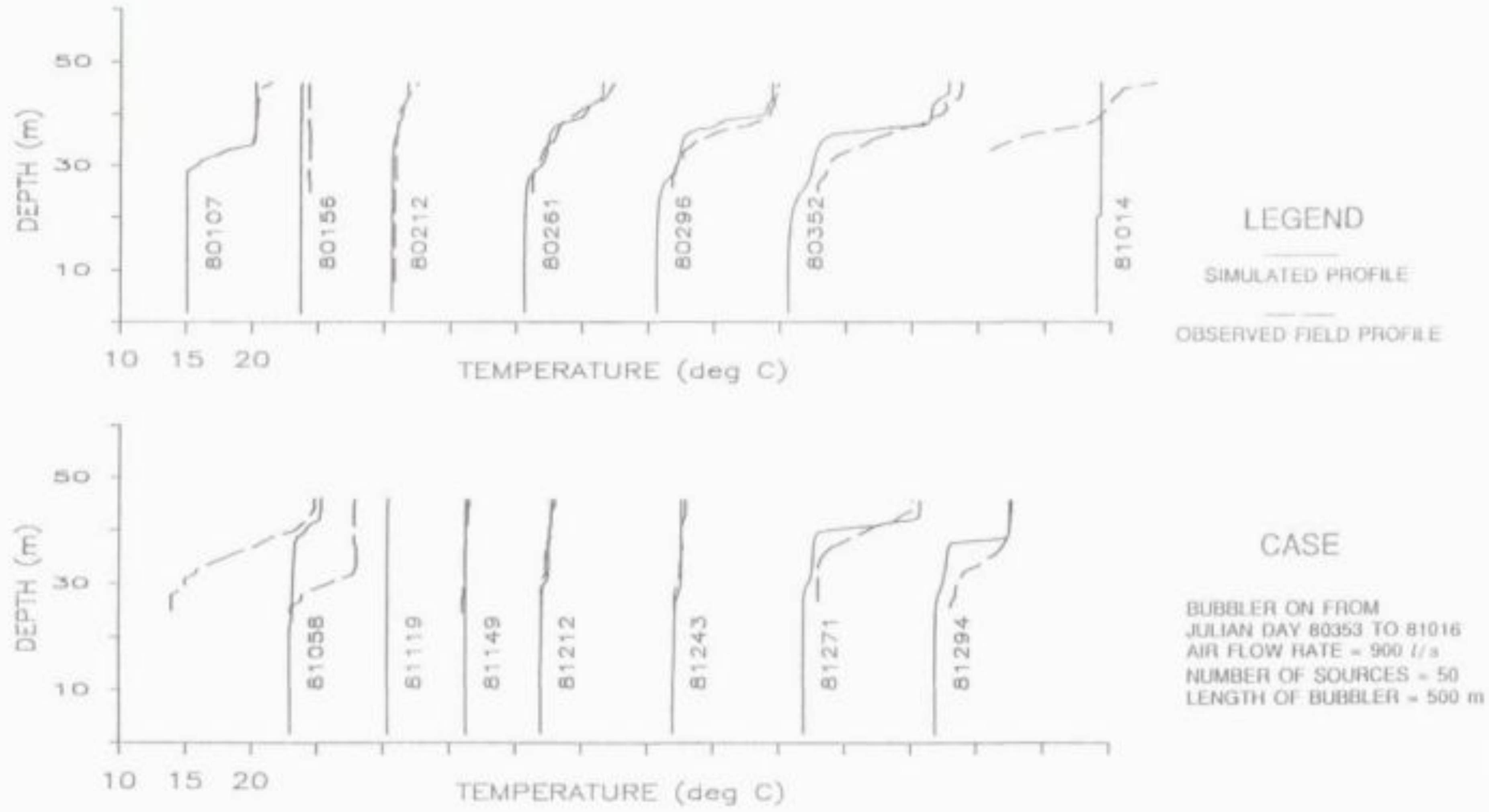
Figure 2.13 shows the results for Scenario 1 (severe destratification) with the bubbler in operation from Julian day 80353 to 81016, a period of 30 days. The effect of the bubbler can be clearly seen in that the bubbler simulation profile for Julian day 81014 shows a completely mixed reservoir when compared with both the simulated and observed profiles without bubble plume operation. This scenario can therefore be seen to be capable of mixing the severely stratified Roodeplaat Dam within a period of a few weeks. It is also of interest to note that, upon closer inspection of the daily simulated profiles, the reservoir begins to restratify within three to four weeks after the bubbler operation ceases. This indicates the need for the destratification process to be sustained during most of the spring and summer period.

Since the capital cost of Scenario 1 is high, the effect of using Scenario 2 over the same period was tested. The results in Figure 2.14 show that the Scenario 2 bubbler configuration (one-third the size of Scenario 1) is capable of sufficiently mixing the reservoir and highlights the need for an in depth analysis to accompany the design of a bubble plume destratification system. Simulations can yield a significant capital cost saving as opposed to designs based purely on the above theory.

Simulations using the Scenario 3 bubbler (prevention/maintenance) system were firstly done with the bubbler in operation from Julian day 80214 (1 August 1980) to Julian day 81060 (1 March 1981), a period of 213 days. The effect of the bubbler in a prevention/maintenance mode can be clearly seen in Figure 2.15, in that the simulated profiles, with the bubbler operational, show a completely mixed reservoir when compared with both the simulated and observed profiles without bubble plume operation (Figure 2.5). This scenario can therefore be seen to be capable of preventing the onset of stratification and maintaining Roodeplaat Dam in a continually mixed state during spring and summer. The running and maintenance costs of Scenario 3 must, however, be considered when contemplating the benefits of destratification. Typically, if the electricity supply costs for a dam site such as Roodeplaat Dam are of the order of 20c/kWh, the running cost of one 55 kW, 150 l/s compressor for a continuous seven month period would be in the region of R 55 000.

It was decided to try the Scenario 3 bubbler system on a one week on and one week off basis to determine whether or not there would be scope for cost saving. Simulations were carried out with the bubbler in such intermittent operation from Julian day 80201 (19 July 1980) to Julian day 81031 (31 January 1981). This represents a period of 197 days (28 weeks), for which the bubbler was operational for 99 days (14 weeks). Figure 2.16 shows the effect of this type of bubbler operation, wherein it can seen that although the reduction in bubbler operation time has an effect on the degree of reservoir mixing, the dam remained in a relatively mixed condition throughout the summer of 1980/81. A considerable saving in running costs would none the less have been achieved.

The above results show that the use of the bubble plume destratification modelling routine within DYRESM allows the relatively easy testing of existing bubbler systems and the optimisation of the design of feasible systems for the destratification and hydrodynamic management of a typical South African reservoir. Further investigation of this facility using data sets from other dams, eg. Inanda Dam, would enable a more clear understanding of the potential of bubble plume destratification as a management tool in South African reservoirs. Example bubble plume destratification output for Nepean Reservoir (Australia), as provided by the Centre for Water Research, using third party graphics presentation software, is given in Appendix A2.2.



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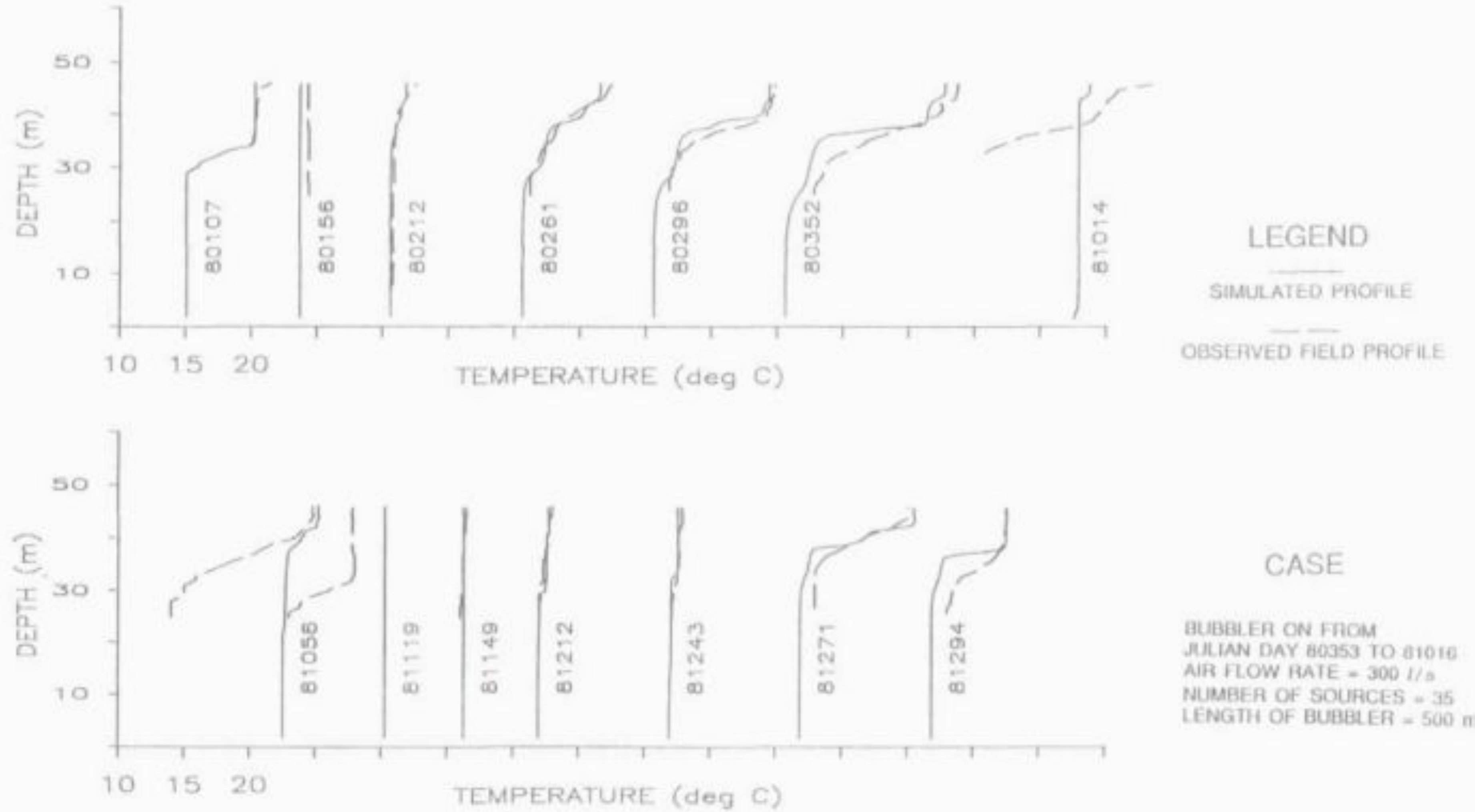
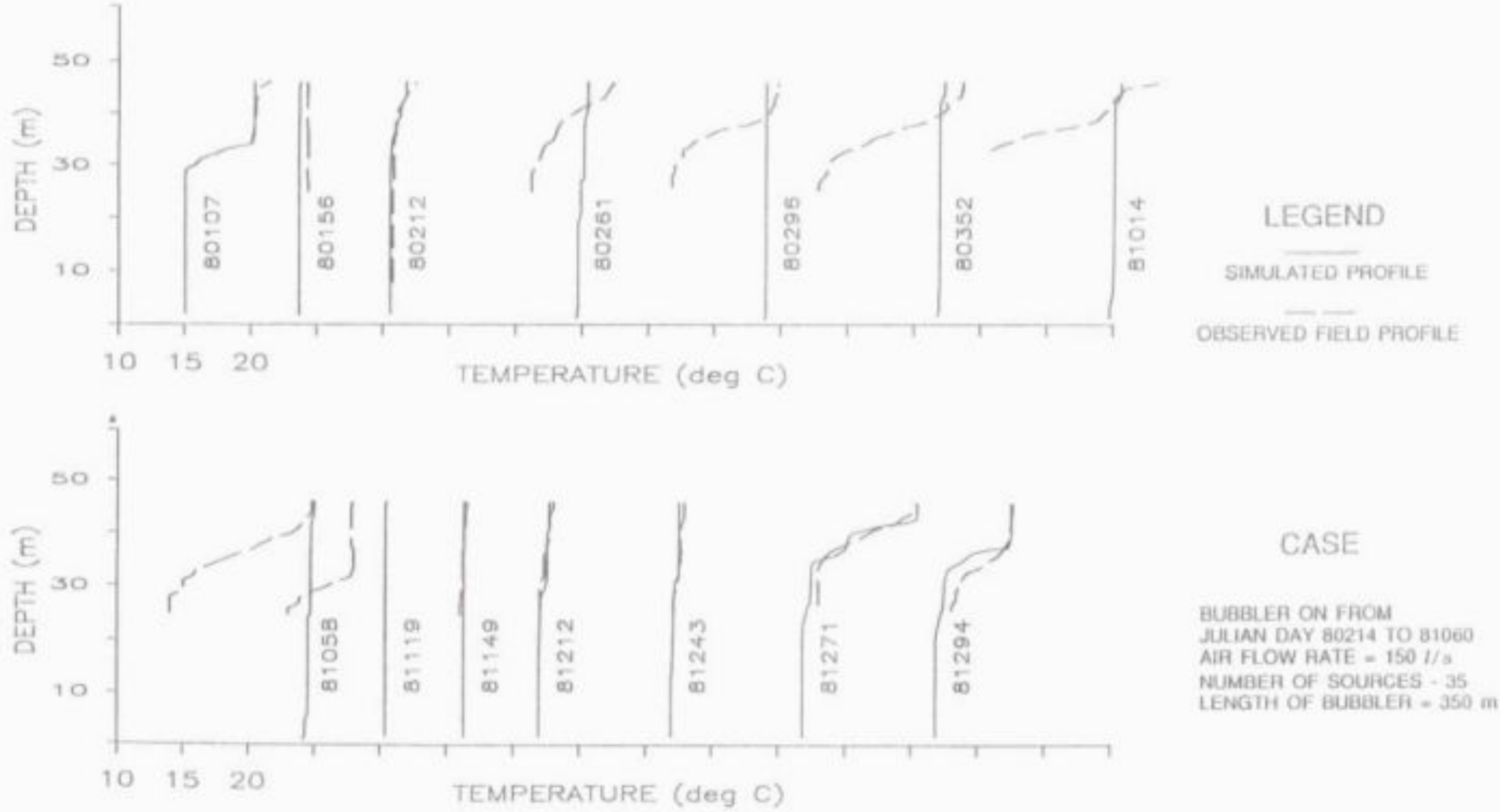
ROODEPLAAT DAM: DYRESM TEMPERATURE PROFILES
Scenario 1 Bubble Plume Destratification

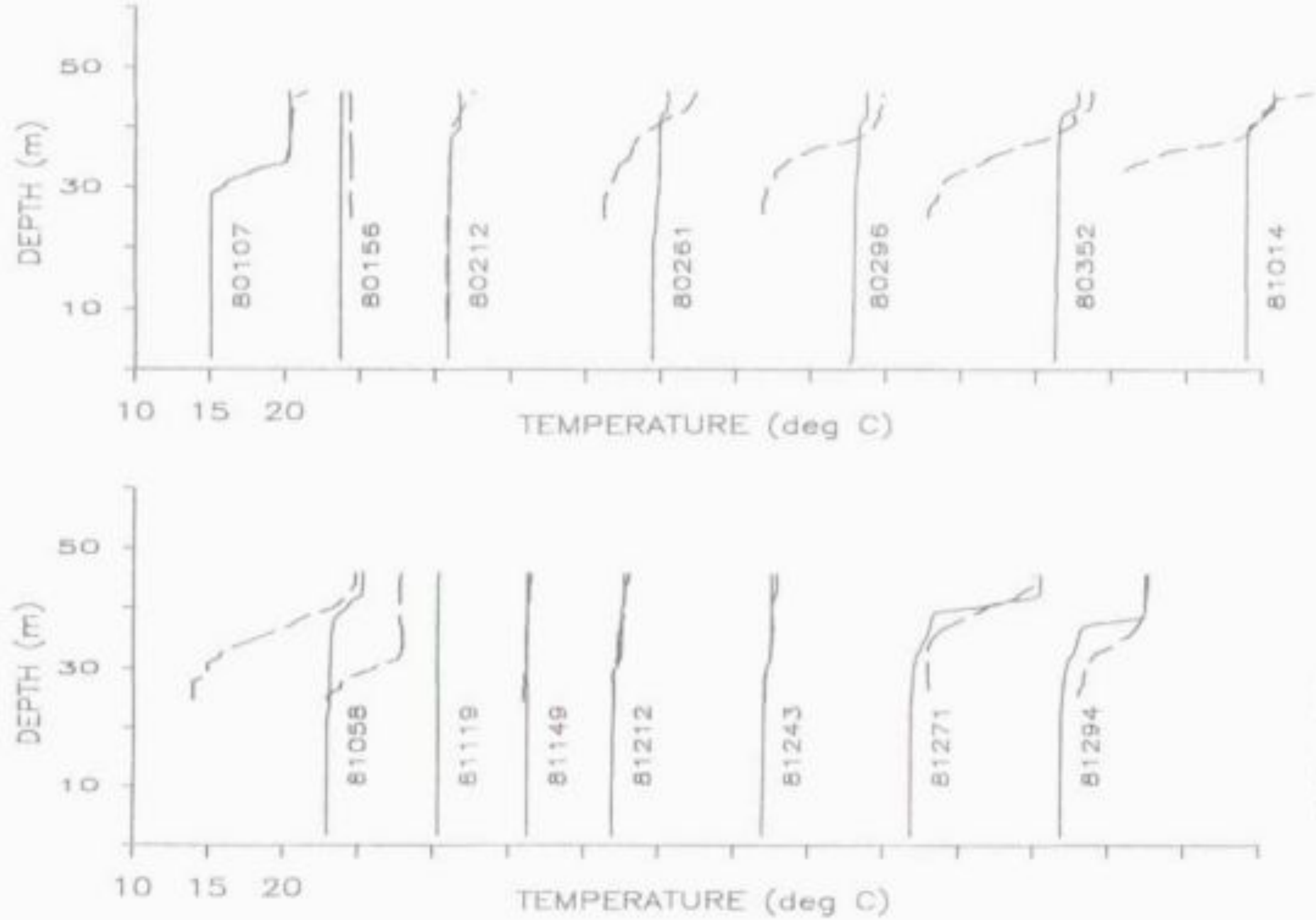
FIGURE 2.13



KINNAIRD SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	ROODEPLAAT DAM: DYRESM TEMPERATURE PROFILES Scenario 2 Bubble Plume Destratification	FIGURE 2.14



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	RODEPLAAT DAM: DYRESM TEMPERATURE PROFILES Scenario 3 Bubble Plume Destratification	FIGURE 2.15



LEGEND

SIMULATED PROFILE

OBSERVED FIELD PROFILE

CASE

BUBBLER ON ONE WEEK,
OFF ONE WEEK FROM JULIAN
DAY 80201 TO 81031
AIR FLOW RATE = 150 l/s
NUMBER OF SOURCES - 35
LENGTH OF BUBBLER = 350 m

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ROODEPLAAT DAM: DYRESM TEMPERATURE PROFILES
Scenario 3 Intermittent Bubble Plume Destratification

FIGURE 2.16

2.4 LOOKING AHEAD

2.4.1 DYRESM-2D : Quasi Two-dimensional Hydrodynamic Reservoir Simulation Model

The development of the quasi two-dimensional version of DYRESM is documented in Hocking and Patterson (1991). The model is based on the one-dimensional DYRESM model and is not strictly two-dimensional in that the input of reservoir cross sections, the presence of incoming side stream inflows and the variation of wind on the various segments of a long, narrow reservoir are not taken into account. Differential wind induced effects, differential heating in shallow side arms and patches of high turbidity, boundary mixing and upwelling are also not simulated, however, the modelling of these effects are possible and are to be included in future (see Figure 2.17). The model does, however, simulate the horizontal transport associated with inflow and the intrusion of streams and withdrawal and allows for the tracking of horizontal transport due to the ability to include a tracer.

The model is also able to track the residence time of every parcel of water within the reservoir and thus a distribution of water age within the reservoir can be viewed and is available as an aid to the evaluation of water quality, eg. the siting of withdrawal offtakes, recreational areas, etc. It is sufficient at this point to note that the capability of the model to track water through a lake or reservoir from any given site for an arbitrary time is a powerful tool for the management of water quality in reservoirs.

DYRESM-2D retains the Lagrangian model structure of DYRESM-1D, which is extended to include horizontal parcels within the model layers. These parcels are only changed when layers are combined or split, or when parcels become too large or too small, reducing the computation required as compared with other two-dimensional models which use a fixed grid approach (see Figure 2.17).

The data input requirements of the model are in fact identical to those of DYRESM-1D, allowing existing data sets to be used in the model. As in the case of the one-dimensional model, no calibration of the model is required, since all the algorithms are process based.

The model is at present not available for general release and is being used only on projects in which the Centre for Water Research, University of Western Australia, Perth, has significant involvement, in order that further verification and enhancement may be made possible before the model becomes widely used.

The two-dimensional screen output of the model also allows for a better understanding of the processes, including stratification, mixing, inflow, outflow and bubble plume simulation, that are at work in the model and how they interact. This is enabled by the fact that the progress of inflows, mixing and bubble plume destratification can be more readily visualised in this version with the use of two-dimensional graphics and colour. The ability to insert a tracer into the water body, inflow stream or bubbler also increases the potential for the understanding and visualisation of the reservoir hydrodynamics, as does the indication of the residence time of each parcel. An example of the screen output of DYRESM-2D as provided by the Centre for Water Research is given in Appendix A2.2.

2.4.2 DYRESM-WQ : Water Quality Model

The water quality version of the DYRESM model is at present based on the one-dimensional DYRESM-1D model. The chemical and biological components modelled in DYRESM-WQ are considered to be analogous to the physical components (eg. temperature and salinity) in the mixing processes that are simulated by DYRESM-WQ. When layers merge the new concentration is a volumetric average of the component layers. If water is removed from a layer by an outflow, the concentration of the water quality components in the layer remains unchanged and only the layer volume is adjusted. Mixing of chemical and biological components is therefore done in conjunction with modelling of temperature, salinity and density, and uses the same sub-daily time step based on surface layer dynamics or a set, constant time step.

Unlike the physical components of the model, specific biochemical calibration coefficients are required for simulations of water quality in a given lake or reservoir. The necessity of calibration reflects the limited current state of understanding of the array of biochemical processes that determine water quality and the complexity of modelling multi-species systems. This statement is echoed in Chapter 3 in discussions of the MINLAKE model's process formulations.

The Centre for Water Research has had promising results with the use of DYRESM-WQ and have successfully modelled, amongst others, dissolved oxygen concentration, chlorophyll *a* concentration (green, blue-green algae and diatoms simultaneously) and a variety of nutrients concentrations.

2.5 CONCLUSIONS

2.5.1 It has been shown that the one-dimensional DYRESM-1D reservoir simulation model is capable of acceptably accurate hydrodynamic simulation using data sets for two different reservoirs, developed from typical South African databases, without recourse to calibration.

2.5.2 Since DYRESM is a physical process based model it does not require fundamental calibration and therefore, each adjustment made to the input data and parameters to obtain a better fit between the simulated and observed profiles must be justifiable and must represent a possible scenario or encompass feasible data measurement, extrapolation or translation anomalies.

2.5.3 The necessity of regular, accurate and representative measurement of the various aspects of inflow, outflow, meteorological and observed field profile data has been highlighted.

2.5.4 The sensitivity of the model to wind data indicates the necessity of instituting and maintaining a suitable wind measuring network and database for all dams that may require an analysis of this nature.

2.5.5 The bubble plume destratification modelling results show that the use of the bubbler routine within DYRESM allows the relatively easy testing of existing bubbler systems and the designing of feasible systems for the destratification and hydrodynamic management of typical South African reservoirs.

2.5.6 The latest version of DYRESM which is available for the PC environment, is now user friendly and includes menus, input screens and colour graphics abilities. The use of free format input files is also significant in making the preparation of input data an easier task.

2.6 RECOMMENDATIONS

2.6.1 Since the wind speed is of major significance in both DYRESM and other models, careful attention should be given to the placement of wind measuring stations where possible. Periods of wind measurement should be undertaken at a height of 10 metres in order to validate the conversion of wind measured at other heights. Similarly, over water wind speeds should be measured where possible and compared with that measured over land, so that these locational effects may be quantified. It is also recommended that further research be undertaken into the over land to over water and height conversion of wind speeds.

2.6.2 The field measurement of profile data should be undertaken at several representative points within water bodies which may require hydrodynamic analysis. The measurement of profiles should be done from the water surface to the dam bottom, at regular intervals, under all circumstances and Secchi disk depth measurements should always be performed.

2.6.3 The present version of the DYRESM-1D model should be implemented on a data set for a reservoir with a significant salinity component in order to test this aspect of the model.

2.6.4 Further investigation into the relationship between total dissolved salts (TDS in mg/l) and NaCl concentration (ppm) is required in order that the density function within the model can be amended for South African conditions, ie. to use TDS in place of NaCl concentration.

2.6.5 Further investigation of the bubble plume destratification facility using data sets from other dams, eg. Inanda Dam, would enable a more clear understanding of the potential of bubble plume destratification as a management tool in South African reservoirs.

2.6.6 The DYPLOT program which is capable of producing, viewing and plotting both profiles and isoline values for temperature and salinity should be converted and enhanced to be able to read directly from the lastest DYRESM version's output files. This will enable greater control over the type and nature of graphical output available from the model results.

2.6.7 The DYRESM-2D and DYRESM-WQ models should be obtained and applied/tested using South African conditions and data. The application of the quasi two-dimensional model to dams such as Inanda Dam, will give greater insight into the physical processes at work within a reservoir in both a vertical and longitudinal direction, and will enable the use of tracers and residence time analyses. In the case of the water quality model, apart from the benefit of the availability of an additional tool for the prediction of the biological and chemical aspects of water quality, which has been shown by the Centre for Water Research to give good results, the use DYRESM-WQ will enable an investigation of the effects of the use of bubble plume destratification on the biological and chemical components of reservoir water quality in South Africa.

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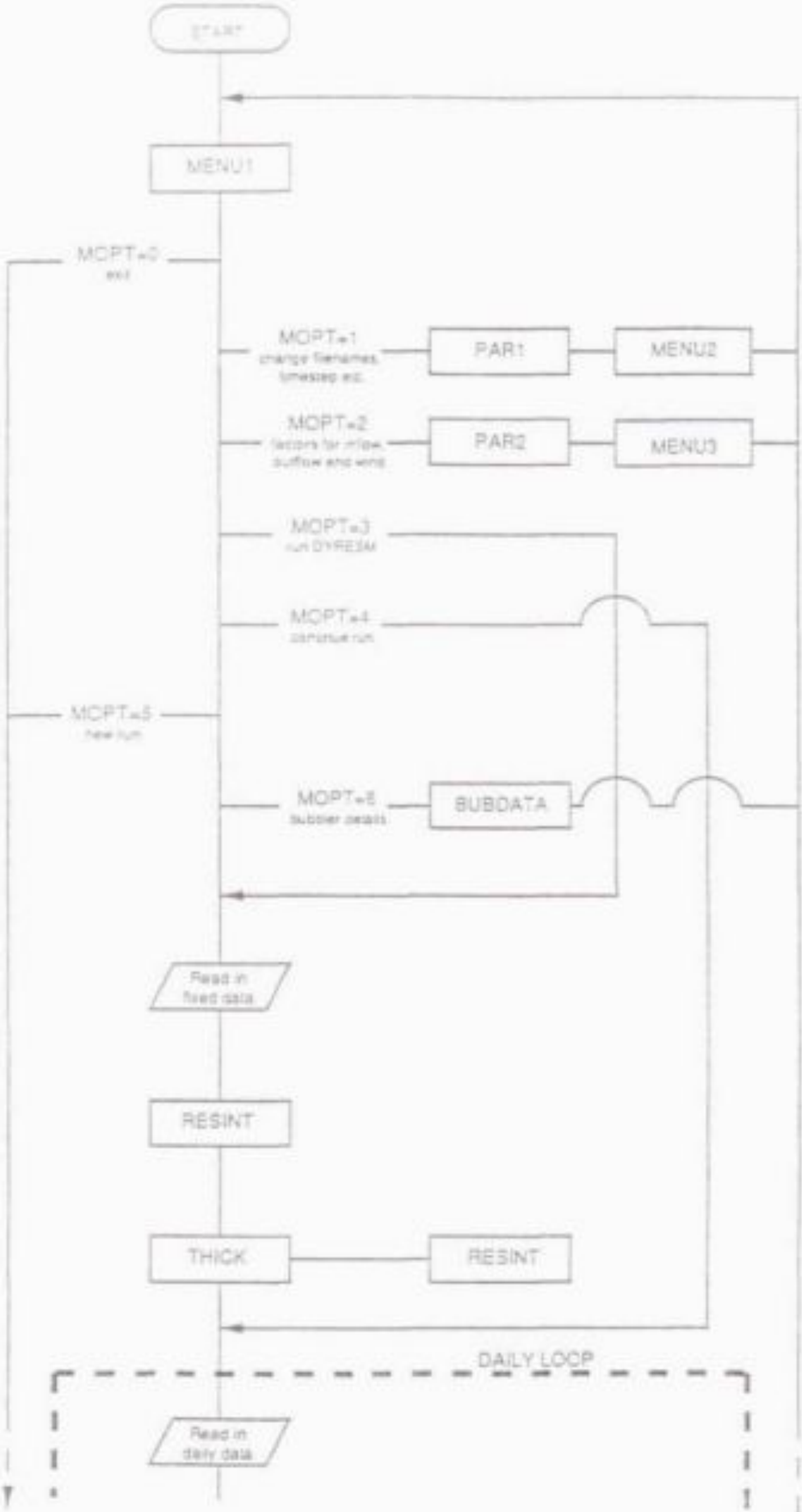
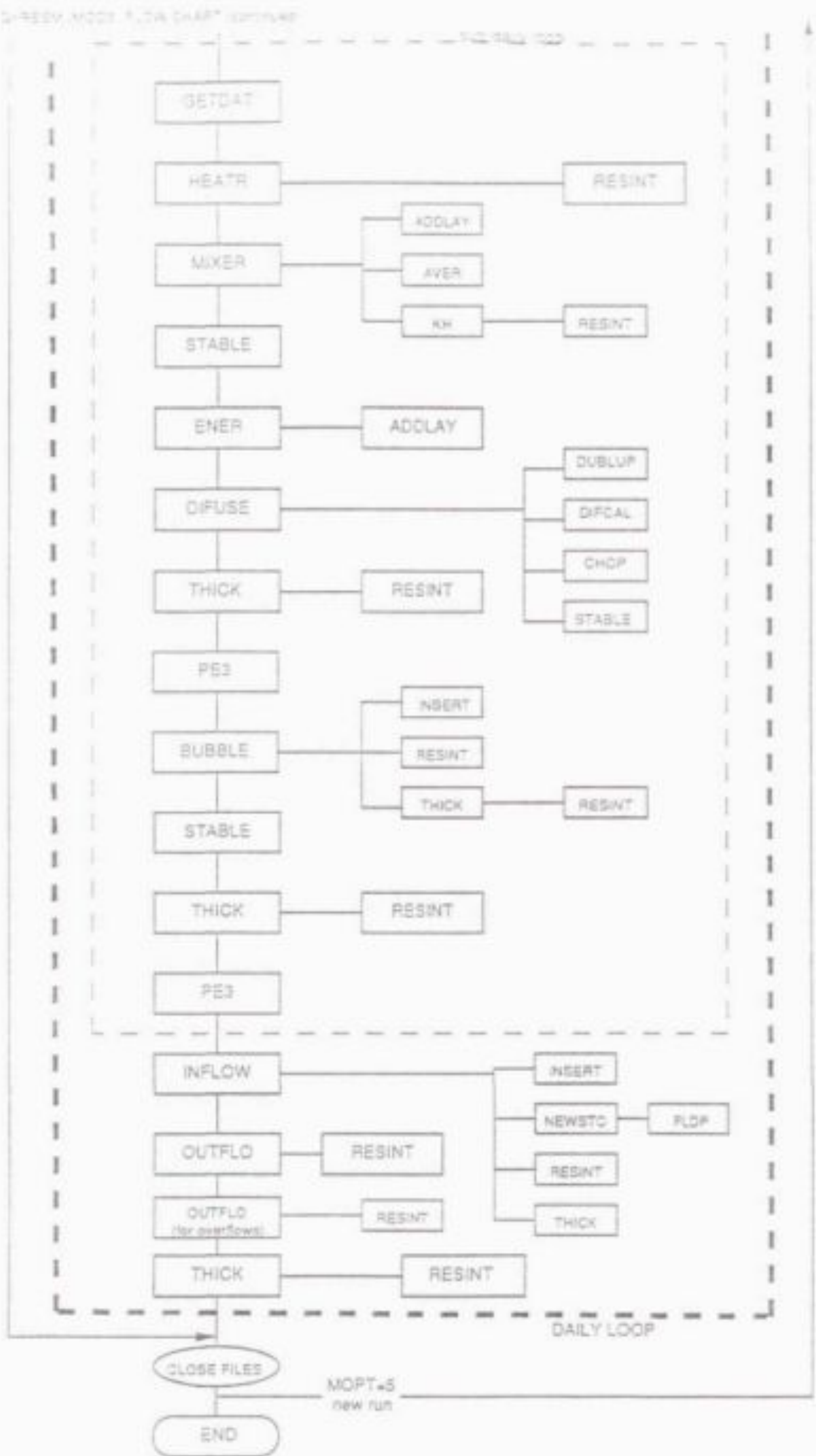
APPENDIX A2.1

DYRESM PROGRAM FLOW CHART AND SUBROUTINE AND FUNCTION DESCRIPTIONS

DYRESM (MOD5) FLOW CHART




GETDAT
HEATR
RESINT
ADDLAY
MIXER
AVER
KH
RESINT
STABLE
ENER
ADDLAY
DUBLUP
DIFUSE
DIFCAL
CHOP
THICK
RESINT
STABLE
PE3
INSERT
BUBBLE
RESINT
THICK
RESINT
STABLE
THICK
RESINT
PE3
INFLOW
INSERT
NEWSTC
FLDP
OUTFLO
RESINT
RESINT
OUTFLO
(for overflows)
RESINT
THICK
THICK
RESINT
DAILY LOOP
CLOSE FILES
MOPT=5
new run
END

SUMMARY OF DYRESM SUBROUTINES

ADDLAY	Adds the mass of the prescribed layer to that of the adjoining layer, and calculates the mass-weighted average temperature, salinity and density of the two layers.
AVER	Deepens the surface mixed layer by assigning the mean properties (computed by ADDLAY) to the surface layer and the next deepest layer, increments the surface layer pointers J1 and K1, and computes the residual turbulent kinetic energy.
BUBBLE	Calculates the amount of entrainment by a bubble plume destratification system, removes the entrained water from the appropriate layers and inserts the mixed water at its level of neutral buoyancy.
BUBDATA	Interactively requests input data concerning the operation of the bubble plume destratification system.
CHOP	Recreates the individual 1-dimensional arrays of the concentrations of diffusable species from the single 2-dimensional array.
DIFCAL	Calculates the diffusion between two layers in a single time step using the sum of the molecular and eddy diffusivities. In this version, the diffusion is handled explicitly between each set of two layers. A decay term is calculated and only one sweep of the concentration array is made.
DIFUSE	Calculates the eddy diffusivity for each layer based on the energy dissipation and adds this to the molecular diffusivity of each diffusing species.
DUBLUP	Creates a single 2-dimensional array of the concentrations of diffusable species from the individual 1-dimensional arrays.
ENER	Calculates energy dissipation due to wind and inflow energy inputs.

FLDP	Solves the cubic equation for flow depth in a triangular river valley.
GETDAT	Checks for mismatch between specified simulation period and read data.
HEATR	Performs the thermal transfers due to radiant energy (both short- and long-wave), sensible and latent heat transfers. Calculates the sub-daily timestep if running with daily data.
INFLOW	Calculates the flow characteristics (including entrainment) associated with each of the river inflows. Separates the inflow process into downflow, when the river water is flowing down the drowned river valley, and insertion, when the flow separates from the valley floor at the point of neutral stability. Provision is also made for surface flows (inflow less dense than reservoir water) and underflows (inflow is still denser than the reservoir bottom water after it has flowed to that depth). Maintains separate "stacks" for downflow and insertion, with the inflowing water only being physically added to the reservoir profile when the elapsed time is sufficiently large for a particular day's inflow to have travelled across the reservoir. Inflow volume is apportioned among those layers within the intrusion thickness.
INSERT	Finds the level of neutral buoyancy for a given inflow and returns the layer number, the half-thickness, basin length at the intrusion midpoint, basin width at the intrusion midpoint and the mean intrusion velocity.
KH	Simulates the effect of Kelvin Helmholtz billowing at the base of mixed layer. If calculated billow height is less than the minimum layer thickness or if billow time scale is longer than shear production time scale it is bypassed. Otherwise, the sharp density interface is replaced with a smoothed transition over the billow length scale.

MENU1 Main menu for DYRESM control.

MENU2 Menu for changing run time parameters.

MENU3 Menu for changing input data.

MIXER Performs the mixing at the lake surface due to meteorological forcing based on a turbulent kinetic energy (TKE) budget. Computes addition to the TKE budget by summing contributions due to penetrative convection (surface cooling), wind stirring and shear at the thermocline. The potential energy to be overcome in mixing the layer below the thermocline with the surface mixed layer is computed and if this is less than the available TKE the layers are amalgamated. The process continues until insufficient energy remains for potential energy to be overcome or until the reservoir is completely mixed, whichever occurs sooner.

NEWSTO Calculates the new temporary storage table associated with inflow "stacks" for use in subroutine RESINT.

OUTFLO Calculates the flow characteristics associated with each reservoir offtake point (including crest overflows). A withdrawal envelope is calculated, based on a withdrawal layer thickness and the vertical fall velocity for fluid above the withdrawal layer. The fluid contained in this envelope is then removed and the remaining layer volumes are adjusted.

PAR1 Changes the model files and days to run based on the selections made in MENU2.

PAR2 Inputs multiplicative factors for the inflow volumes, wind strength or withdrawal volumes depending on selections made in MENU3.

PE3 Computes the potential energy stored above the level of the bubble aeration system.

STABLE Checks through all of the layers of the model for any local gravitational instabilities between layers (i.e. a more dense layer above a less dense layer). If any are found, the layers are combined and the mean temperature, salinity and density is computed.

RESINT From the given physical data, evaluates arrays of depths and areas corresponding to an array of volumes (ICODE = 2) or arrays of volumes and areas from depths (ICODE = 1).

THICK This subroutine checks the reservoir layer structure for compliance with the specified volume and depth limits. If a layer size falls below the minimum, it is amalgamated with the smaller of its neighbouring layers and their temperatures, salinities and densities are averaged. If a layer size exceeds the maximum, it is split and the same layer properties assigned to each of the new layers.

SUMMARY OF DYRESM FUNCTIONS

COMBIN	Combines two layers and return the mean concentration or temperature.
DENSTY	Calculates the sigma-T (Density-1000) of water given temperature (deg C) and salinity (ppm).
DV1	Calculates the proportion of fluid withdrawn from any layer, given its top and bottom depths. Uses a curve which fits the region of fluid withdrawn in a given time. If large withdrawal (fall velocity dominates) use curve 1. If small withdrawal (selective withdrawal dominates) use curve 2.
EXVOL	Computes the volume in the inflow stacks which lies between two depths.
GPRIME	Calculates the reduced gravity given two sigma-T values.
SATVAP	Calculates the saturated vapour pressure at a particular temperature.

APPENDIX A2.2

DYRESM EXAMPLES SHOWING OUTPUT FROM DYRESM-2D AND BUBBLE PLUME DESTRATIFICATION USING DYRESM-1D SIMULATION DATA

CHAPTER 3

APPLICATION OF A ONE-DIMENSIONAL WATER QUALITY MODEL : MINLAKE

by

A Venter, A Görgens, A Bath and G Marais

Contents Page:

APPENDICES

PART 1
GENERAL DESCRIPTION OF THE MINLAKE MODEL

3.1 INTRODUCTION

The MINLAKE model is a dynamic one-dimensional water quality model for lakes and reservoirs. It was developed by the University of Minnesota (St Anthony Falls Hydraulic Laboratory). The model is intended to be used to simulate some of the physical, chemical and biological variables that describe the existing hydrodynamic and water quality behaviour of a lake/reservoir, and to provide a method to test the feasibility of different reservoir management alternatives that will affect the eutrophic state of the reservoir (MINLAKE, 1988). The variables being simulated include water temperature, dissolved oxygen, phosphate, nitrogen, chlorophyll-a and suspended solids as a function of depth and time. The reservoir is treated spatially as a series of horizontal layers; each layer is considered to be homogeneously mixed, with the relevant components and states to be uniform within the layer. The model requires limnological field data for calibration and verification, and the time step is one day.

3.2 MODEL DESCRIPTION

The model deals interactively with its hydrodynamic and water quality components. The hydrodynamic behaviour has a dominating influence on the water quality response, whereas the water quality has a relatively weaker interactive effect on the hydrodynamics. This feature implies that the inputs affecting the hydrodynamic behaviour are of primary importance. Of these inputs the wind and solar radiation are the major hydrodynamic driving forces. Because the driving forces originating from the water quality response are relatively weaker, it allows the hydrodynamic behaviour to be simulated to an acceptable level even though the water quality simulation may still be inadequate. Hence, in evaluating the MINLAKE model it is necessary first to obtain satisfactory correlation between the observed and simulated hydrodynamic variables before attempting to deal with the water quality aspects.

A quantitative, detailed exposition of the formulation of the physical/chemical /biological processes is not feasible for this part of the report, accordingly only the principal ones and the manner of their application in MINLAKE will be considered here. (See Schematic diagram, Figure 3.1). Modifications originating from our application of the model will be discussed with the simulation results in Sections 3.12 and 3.13.

3.2.1 Hydrodynamic sub-model

The evaluation of the temperature in each layer and the distribution of temperature with depth forms the principal outcome against which the hydrodynamic response can be evaluated. In simulating a depth profile of temperature, consideration must be given to the amount of radiation energy reaching each layer; the amount of energy reaching each layer is affected by net solar radiation reaching the surface of the lake, diffusion, turbulent mixing due to wind (inter layer transport), inflows and outflows, and physical changes brought about by water quality variables (eg. algal concentration).

In greater detail, consider the model formulation of the hydrodynamic driving forces (MINLAKE, 1988):

Net radiation arriving at the surface of the lake/reservoir: In MINLAKE the net solar radiation energy retained at the surface of the reservoir is calculated each day from the balance between incoming heat from solar and long wave radiation, and the outflow of heat through convection, evaporation and back radiation. A fraction of net solar radiation reaching the surface of the reservoir is reflected, while the rest penetrates into the water.

Diffusion of both heat and water quality parameters between layers: In MINLAKE diffusion is computed separately in the epilimnion and hypolimnion. In the epilimnion the diffusion coefficient is formulated as a function of wind speed, and in the hypolimnion it is a function of the Brünt-Våsala frequency (Jassby and Powell, 1975). The vertical velocity of the diffusion rate for the suspended inorganic sediment component is computed from a formulation by Gibbs (MINLAKE, 1988). The settling velocity of algae and detritus must be specified.

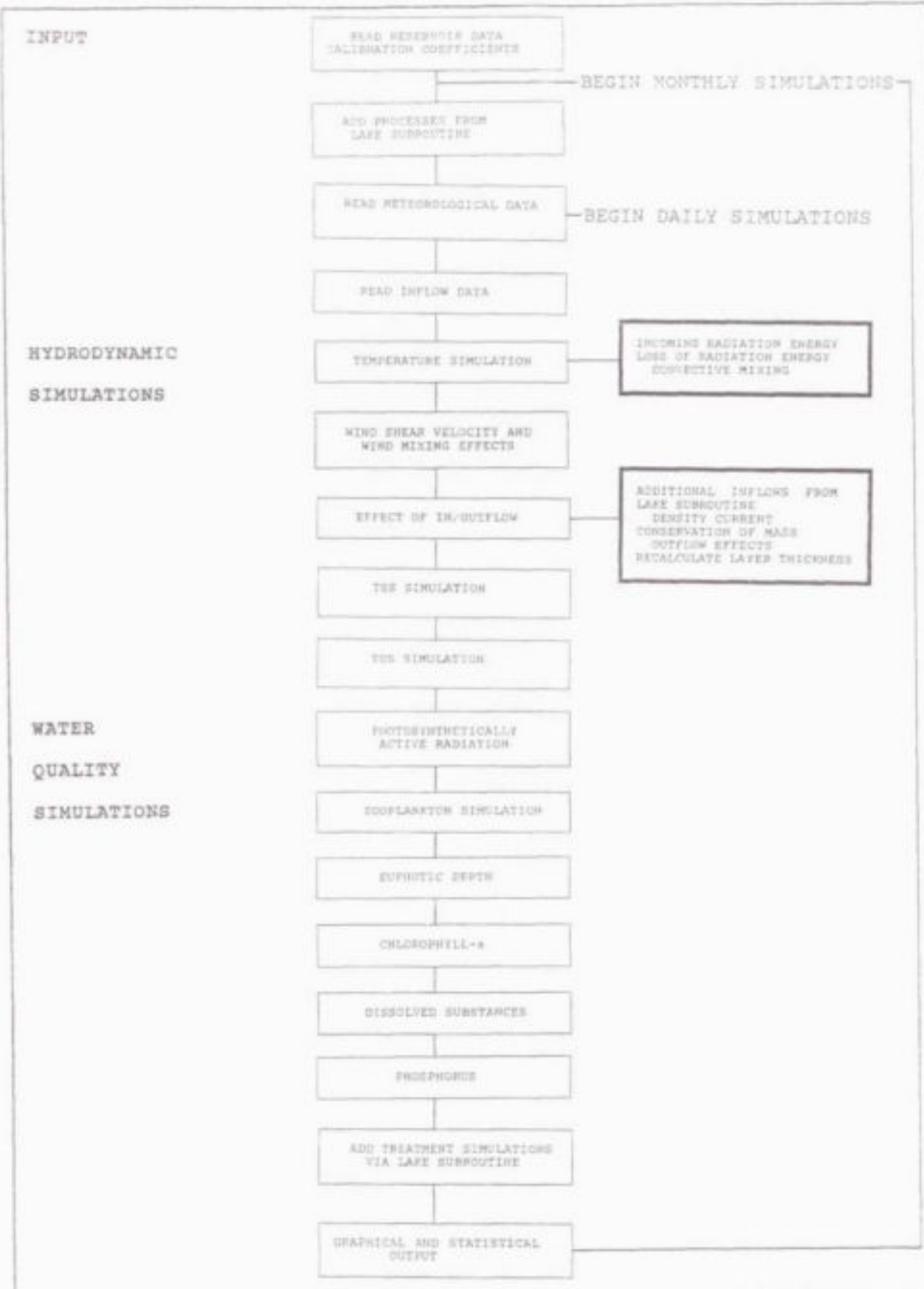


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FIGURE 3.1

Schematic representation of MINLAKE

Turbulent mixing of both heat and water quality parameters: The turbulence generated in a reservoir by wind or natural convection mixes the upper layers into a homogeneous surface layer. In MINLAKE the depth of wind mixing is determined daily after the heat budget had been calculated.

Effect of inflows and outflows: The vertical distribution of heat and water quality parameters will be affected by the temperature and density of inflowing water, as well as by the turbulence generated by in- and out-flowing water. In MINLAKE the inflowing water may flow into any layer, depending on the density of the inflowing layer. If the density of the inflow is equal or less than that of the surface mixed layer, the inflowing water will flow into the surface mixed layer and mix with it. If the density of the inflow is greater than that of the surface mixed layer, it plunges through layers of lower density until it reaches a layer of equal or greater density whereupon it mixes with that layer. Entrainment between layers due to turbulence created by in/outflows is calculated for each layer.

3.2.2 Water quality sub-model

The concentration of the different chemical/biological components in a layer is determined by the biological and physical processes that act on these components. For example, the concentration of dissolved phosphate in a layer will be affected by adsorption onto and desorption from inorganic suspended sediment, and therefore also by the concentration/settling velocity of inorganic sediment. Dissolved phosphate concentration is affected further by absorption and storage of dissolved phosphate by algae, principally, but also by other micro-organisms, excretion by zooplankton and fish, as well as bacterial decay of organic sediment. The concentration of various components in a layer and the processes that affect these are treated as follows in MINLAKE:

Inorganic suspended sediment: Inorganic suspended sediment may act as either a sink or a source of nutrients in a reservoir, therefore the simulation of inorganic suspended sediment must be acceptable before water quality parameters such as phosphorus concentration can be simulated. In MINLAKE an inorganic suspended sediment profile is calculated by taking inorganic sediment concentration, vertical mixing intensity, rate of deposition and time into account. Resuspension of bottom sediments is not taken into account.

Algal growth: In MINLAKE the concentration of algae is influenced by the combined effects of growth, diffusion, settling, respiration, mortality, and grazing by zooplankton. With regard to growth, absorption of nutrients (N and P) and growth are treated as two separate processes. The algae has the propensity to store absorbed phosphorus in excess of what is needed. Subsequent growth can take place from the stored P as phosphorus source, ie. growth is not governed directly by the concentration of dissolved P in the surrounding water. Although algae do not have the same capacity for storing nitrogen, nitrogen limited growth is calculated in the same way as phosphorus limited growth, using ammonia as substrate. In MINLAKE growth limitation by light, as well as the effect of temperature on growth, are also taken in account. Up to three different algal classes can be simulated, and three different methods of simulation are available, depending on the desired complexity level. More complex levels require more field data to calibrate the model.

Interactively, the concentration of inorganic suspended sediment and of algae affect the penetration of radiation, and hence energy transfer, to the different layers; and therefore affect the hydrodynamic response.

Nutrients: Phosphorus and nitrogen are the only nutrients simulated in MINLAKE. For nitrogen, nitrate-nitrite is modelled separately from ammonia. For phosphorus, total phosphorus is modelled separately from dissolved phosphate. Adsorption of dissolved phosphate by suspended inorganic sediment is not taken into account, nor is removal of phosphorus by settlement to the bottom. Phosphorus release from the bottom sediment must be specified.

Dissolved oxygen: Simulation of dissolved oxygen concentration is included in MINLAKE to aid the simulation of zooplankton movement and to provide information for lake management strategies.

Some of the processes described above are affected by radiation and most of them by temperature. The intensity of radiation and temperature in a layer is interactively dependent on data obtained from the hydrodynamic part of the model. The processes acting in a layer are also influenced by factors acting at the boundary of each layer, because there is transportation of variables (eg. algae and dissolved phosphate), into and out of the layer, by turbulent mixing and diffusion. In the MINLAKE model, processes acting on compounds in a layer are often approximated by simplified formulations with the use of calibration coefficients.

3.3 INPUT DATA REQUIREMENTS

Four types of data are required by MINLAKE, ie. meteorological, inflow/outflow, in-dam profile data, and physical reservoir constants. Furthermore, process coefficients for particular processes must also be provided. These coefficients usually act as calibration parameters.

3.3.1 Meteorological data

This group contains variables such as solar radiation (Langley) and wind speed (mph), which have been identified as the two main hydrodynamic driving forces in MINLAKE. Further meteorological data are:

- Air temperature (°F)
- Dew point temperature (°F)
- Precipitation (inches)
- Wind direction (degrees)
- Percentage sun

The units required are the units used by the National Weather Service in the USA. Meteorological data are needed on a daily basis. If site-specific meteorological data are not available, a site-specific meteorological database would need to be generated by interpolation from other databases.

3.3.2 Inflow/outflow daily time series

Regarding inflow, average **daily** flow rate (cfs) and temperature of inflowing water (°C) are essential variables for the hydrodynamic part of MINLAKE. Provision is made for data on the following water quality variables in the inflowing rivers:

- Dissolved oxygen (mg/l)
- Total dissolved solids (mg/l)
- Suspended inorganic sediment (mg/l)
- Dissolved phosphate (mg/l)
- Nitrate-nitrite (mg/l)
- Ammonium (mg/l)
- Chlorophyll-a (mg/l)

Only those variables that have been identified to affect the water quality of the reservoir significantly need to be included.

Regarding outflow, the flow rates of water being discharged, and of water flowing over the top of the dam wall, are entered as negative flow rates. Water quality variables are not specified in the outflow.

The original software makes provision for only one inflow/outflow. The model was subsequently modified to make provision for up to five inflows/outflows.

3.3.3 Reservoir data

In order to calibrate and verify the model, depth profiles of reservoir water quality variables of importance to the specific reservoir are required. Provision is made in the model for the following:

* Reservoir water temperature (°C)
* Dissolved oxygen (mg/l)
* Dissolved phosphate (mg/l)
* Total phosphorus (mg/l)
* Detritus as BOD (mg/l)
* Suspended inorganic solids (mg/l)
* Nitrate-nitrite nitrogen (mg/l)
* Ammonium nitrogen (mg/l)
* Three classes of chlorophyll-a (mg/l)

3.3.4 Physical reservoir constants

In MINLAKE, the following constants must be specified by the user for each reservoir:

* Width of each inflowing river
* Maximum width of the reservoir perpendicular to the inflowing river
* Height of reservoir bottom above sea level
* Height of discharge outlets above sea level
* Width of discharge outlet
* Initial height of the reservoir water level (stage) above sea level
* Downstream slope of each inflowing river
* Manning friction factor for each of the rivers

3.3.5 Calibration coefficients

In MINLAKE, many of the processes are simplified or even approximated, by the use of calibration coefficients. These must be specified by the user (*cf.* Table 3.5).

3.4 STRUCTURE OF MINLAKE

3.4.1 Data input

The input data required are represented in three separate computer files, ie. a meteorological file containing the meteorological data; an inflow file containing river water quality data, and an input file containing observed profiles of reservoir water quality variables, calibration coefficients, as well as various reservoir specific constants.

3.4.2 Data output

Data output from the MINLAKE model is in the form of graphics and statistics, as well as in file format. Graphics, consisting of profiles as well as time-series, and statistics are displayed during operation of the model, and can be printed by request.

3.4.3 The model structure

The model is divided into two separate, but linked, computer programs. The first programme incorporates the main MINLAKE program, while the second program incorporates a lake specific subroutine.

Main MINLAKE program: The main program consists of 40 subroutines and two function routines (Figure 3.1). The subroutines calculate daily changes in states/concentration of various compounds, and the influence of inflows and outflows. The three input data files (see Section 3.3) are accessed from the main program via these subroutines. Graphical and tabular output, as well as all statistical calculations are also done in the main program. (The user manual suggests that there should be no need to make modifications to the main program; the program is constructed in such a way that, should modifications be required, it can be done via the lake specific subroutine).

The lake specific subroutine: The main program makes periodic calls to the subroutine which allows the user to change processes, add processes, or add inflows and outflows. Reservoir specific features such as depth-area relationships and the fetch of the lake are dealt with in the lake specific subroutine.

3.5 MINLAKE MANUAL

A user's manual is supplied with the MINLAKE package. The manual is relatively user-friendly. It gives an overview of the governing equations and the methods of solution used in MINLAKE, as well as more detailed descriptions in the appendices. The model structure, data input requirements, calibration procedure, statistical analysis of results and the use of the model to simulate some treatment scenarios are explained. A step by step example of running the model is given, including a description of the compiling procedure with the required compiler. Examples of both graphical and file output are given. Listings of the input and output data file, as well as a description of the various subroutines, are given in Appendices A and B.

3.5.1 Remarks

- Formulations as presented in the manual are not always correct. The references from where these formulations were obtained, had to be consulted. The references are listed in the manual, but all the references are not available in South Africa.

- Tracking of errors in the main program is complicated by the fact that all the common block variables are not listed in the manual. Also, variables are often renamed in the program, and this is not indicated in the manual.

- Some formulations, eg. astronomical day length, are hardwired into the main program for a specific latitude.

3.6 MINLAKE SOFTWARE

3.6.1 The model

The MINLAKE program can be used on personal computers with a DOS version of 3.0 or higher. The program is written in Fortran and must be compiled before it can be run. Compiling is facilitated by the structure of the program. Compiling can be a very time consuming procedure, but, according to the suppliers, there should be no need to recompile the main program, as no changes ought to be made to the main program. However, as will be shown later, apparent errors in the code and modifications deemed necessary, necessitated many recompilations of the main program. The lake specific subroutine must be recompiled whenever changes are made to this subroutine, but this is not time consuming as the subroutine is relatively short. After compilation of the lake specific subroutine, the subroutine must be linked to the main program; compiling and linking must be done separately. The program requires the Microsoft Fortran 3.31, 4.01 or 4.10 compiler and the PLOT88 graphics library. The compiler program is not supplied with the MINLAKE package, but it is freely available in South Africa.

3.6.2 Data input

The three data input files are standard ASCII data files, and the data format is in free form, ie. data files can be constructed without concern for the spacing between data. The only requirement is that columns of data must be separated by at least one blank space. The free form format is particularly suited to using spreadsheet programs, such as Lotus or Quattro, to construct data input files.

The MINLAKE package also contains data file listing programs for each of the three data files. Errors in the data files will cause an error exit when the MINLAKE program is run. Considerable time can be spent in debugging data files, not only because the data files usually are quite large, but also because the data file containing an error often cannot be determined from the error exit code. The debugging of data files is facilitated by the use of the data listing programs provided. These programs list the contents of a data file to the screen, allowing the user to view the data. Errors in the data file will cause the data listing program to stop at the line where the error occurs.

Remarks: It is recommended that, whenever an error exit occurs, the first step in tracking the error that caused the exit, should be the listing of the data files with the data listing program. An error exit is usually caused by an error in the data files.

To provide a bench mark example, test data files for each of the three data files, and for the lake specific subroutine are supplied for Lake Riley in Minnesota. This allows the user to gain familiarity with the MINLAKE program before attempting to run the program with their own input.

3.6.3 Software implementation

Implementing the model presented no problem. As a test, both the main program and the lake specific subroutine, as received from the supplier, were recompiled and linked. Compilation time for the main program on a 386 personal computer is approximately six minutes. Compilation of the lake specific subroutine is done in a few seconds, while linking of the two files also takes a few seconds only.

3.6.4 Graphics support software

To overcome a number of shortcomings in the MINLAKE graphical routine, the DYPLOT package was developed by Ninham Shand Inc. as part of this project. The package enables plotting of time-series with depth of any one of eight different MINLAKE output variables. The resultant graph can be displayed on screen or printed (Figure 3.5b)

3.7 APPLICATION OF THE BENCH MARK TEST DATA SET - LAKE RILEY

A test run was done using the bench mark test data set for Lake Riley in Minnesota, provided by the supplier, to:

* ensure that the model performs according to the supplier's specifications
* gain familiarity with the graphic output and the operating instructions

Test data for a six month period were supplied. The model was run with the test data sets according to the instructions in the manual. The model operated satisfactorily, and visually the graphical responses generated appeared identical to those provided in the manual. It was therefore accepted that the model implementation was correct.

3.8 GENERAL TASKS

In investigating the applicability of the MINLAKE model to South African reservoirs, the approach was as follows:

- Investigate if there are reservoirs in South Africa with databases that satisfy the requirements of the model, and to select at least one reservoir with an adequate, or near adequate database for intensive study.

- Transform the data and units of measurement of all relevant data relating to the selected reservoir into the format required by the model.

- Calibrate the model optimally by:
  - a) following the calibration sequence recommended in the model instruction.
  - b) selecting optimal values of each of the calibration coefficients (± 24 in number) from a literature study, using as a starting point the range of values for each coefficient suggested in the manual.

- Enquire into the causes for deviations between simulated and observed results by:
  - a) critically evaluating the process formulations and constants.
  - b) checking for the presence of programming errors.

- Modify the model and correct any errors identified, and resimulate the reservoir response.

- Evaluate the applicability of the model and propose further action.

3.9 RESERVOIR SELECTION

Two reservoirs were selected for the evaluation of MINLAKE, ie. Roodeplaat Dam and Hartbeespoort Dam.

Roodeplaat Dam was selected for evaluation of MINLAKE for the following reasons:

- When the data requirements of the MINLAKE model were compared to the data that was measured at Roodeplaat Dam, it was found that the measurements at Roodeplaat Dam matched most of the MINLAKE data requirements. Monthly depth profiles of temperature and dissolved oxygen, as well as surface measurements of several other water quality parameters in the dam, were available. Flow rate, and a few water quality parameters were measured on a daily basis in the inflowing rivers. Meteorological data also were measured on a daily basis for extensive periods.

- Roodeplaat Dam receives both secondary treated domestic wastewater effluent, and run-off from agricultural land. It is a popular recreational site and a source of irrigation water, and consequently there is concern about the water quality in the dam. In 1976 Roodeplaat Dam was ranked as the third most eutrophic water body in a study of 98 South African impoundments (Toerien, 1976).

Hartbeespoort Dam was selected for the following reasons:

- Extensive research has been done on Hartbeespoort Dam by the CSIR and various universities and the data that were measured at Hartbeespoort Dam matched most of the data requirements of the MINLAKE model. Weekly depth profiles of temperature, dissolved oxygen, electrical conductivity, dissolved phosphate, chlorophyll-a and light distribution were taken. Flow rate and a few water quality parameters were measured on a daily basis in the inflowing rivers. Meteorological data were also measured on a daily basis for extensive periods.

* Hartbeespoort Dam receives both urban effluent, and runoff from agricultural land. It is a source of irrigation, as well as raw water, and is a popular recreation site. The dam can be classified as hypertrophic, with outbreaks of aesthetically undesirable hyperscums, and toxic algae, eg. *Microsystis* (FRD, 1985).

Remark: Regarding Hartbeespoort Dam, it was soon discovered that the inflow volumes were too low for the first few years of available data, and that a factor of approximately 1,45 was required before a reasonable mass balance could be achieved. Problems with the inflow records of the gauges on the two inflowing rivers, as well as with the outflow records, have been encountered in the past (Bosman, personal communication, 1991). Further investigation into this matter is required, which was not possible within the scope of this study. Attention was therefore focused on Roodeplaat Dam in evaluating the MINLAKE model. The database development for Hartbeespoort Dam is summarised in Appendix 3.3.

PART 2

APPLICATION OF THE MINLAKE MODEL TO ROODEPLAAT DAM

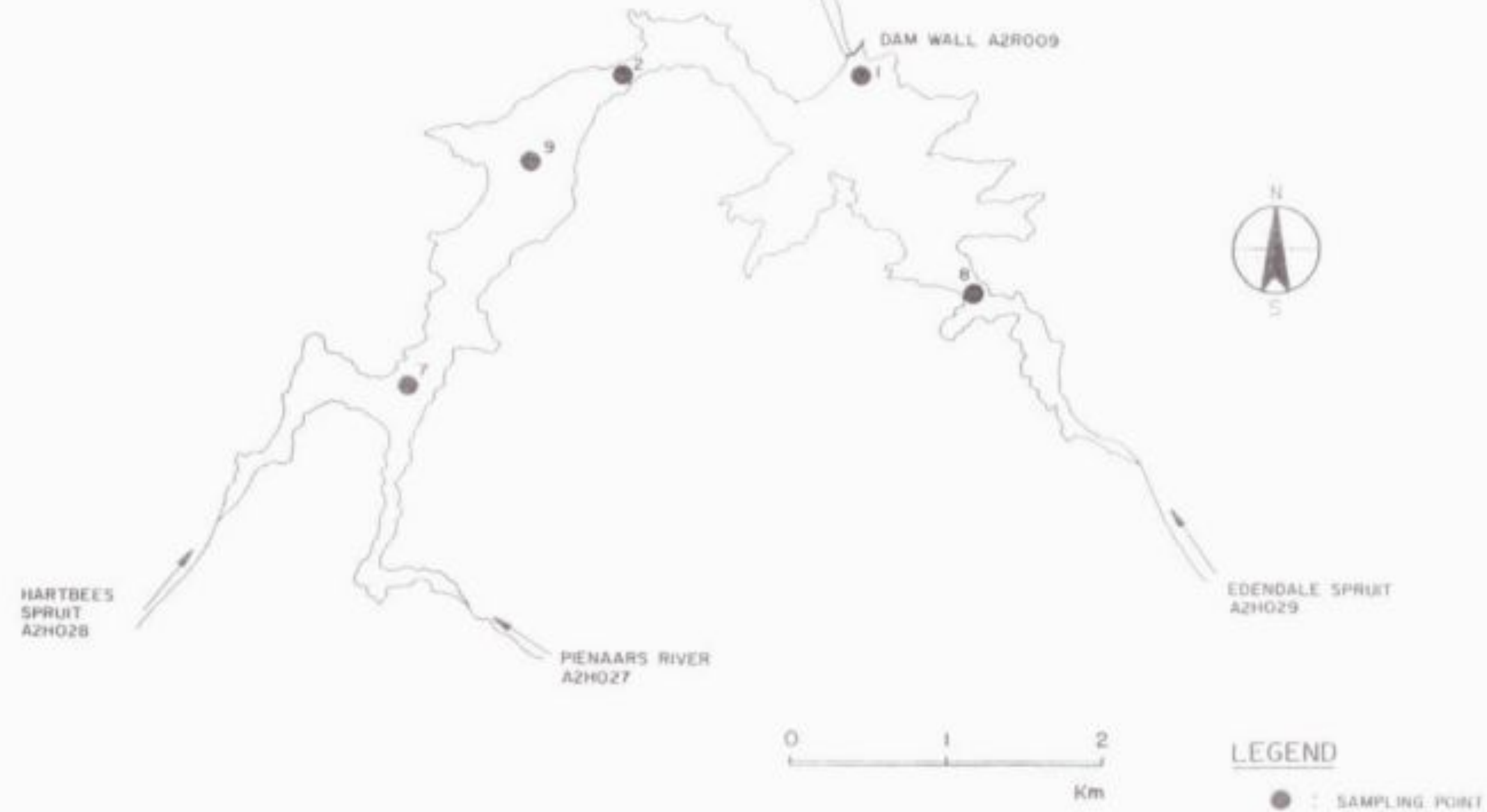
3.10 RESERVOIR DESCRIPTION

Roodeplaat Dam is situated 20 km north of Pretoria (23°58'S; 27°43'E). The reservoir lies in a summer rainfall region with an average annual rainfall of about 700 mm. Three rivers, the Pienaars River, Edendalespruit and Hartbeesspruit, discharge into the reservoir. The Pienaars River flows through Mamelodi Township and then past the Baviaanspoort sewage works which treats effluent from the Township. This river is the major nutrient source of Roodeplaat Dam, contributing up to 75% of the annual dissolved nitrogen load and up to 87% of the annual phosphorus load. Edendalespruit receives run-off from agricultural and grassland, while Hartbeesspruit originates in the urban areas of Pretoria, whereafter it flows through the industrial area of Silverton. The river inflow is strongly seasonal with flooding of the system during the rainy season in summer (Butty and Walmsley, 1979).

The point of inflow for each river, as well as the shape of the dam and the different sampling points, is shown in Figure 3.2. Further characteristics of Roodeplaat Dam are presented in Table 3.1. Area, volume, and maximum and mean depth are indicated at full supply level.

TABLE 3.1 : CHARACTERISTICS OF ROODEPLAAT DAM

Area	396 ha
Volume	$41,9 \times 10^6$ m^3
Maximum depth	43 m
Mean depth	10,6 m
Height above sea level	1214 m
Annual inflow	$59,01 \times 10^6$ m^3
Annual outflow	$55,68 \times 10^6$ m^3



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Map of Roodeplaat Dam showing sampling points

FIGURE 3.2

3.11 DATABASE DEVELOPMENT FOR ROODEPLAAT DAM

3.11.1 Meteorological and inflow data

Retrieval of meteorological and inflow data: A summary of various institutions where meteorological and inflow data were obtained, the format of the obtained data, and the units of measurement, as opposed to the units required by MINLAKE, is given in Table 3.2.

TABLE 3.2 : SUMMARY OF UNITS AND FORMAT OF OBTAINED DATA AND INSTITUTIONS WHERE DATA WERE OBTAINED

Variable	Measured Unit	Required Unit	Institution*	Format of obtained data
River flow rate	m^3s^{-1}	cfs	DWAF	Floppy disks
River water temperature	°C	°C	DWAF/HRI	Copy of original handwritten record
PO_4, NO_3, NH_4, TDS	mg l^{-1}	mg l^{-1}	DWAF	Floppy disks
Air temperature	°C	°F	DWAF/HRI	Photostat copy of recorder charts
Dew point (calculated from humidity)	°C	°F	DWAF/HRI	Photostat copy of recorder charts
Precipitation	mm	inches	DWAF/HRI	Photostat copy of handwritten record
Wind speed	km h^{-1}	mph	DWAF/HRI	Mostly photostat copies of undigitised wind run chart
Wind direction	degrees	degrees	DWA/HRI	Mostly photostat copies of undigitised wind direction chart
Sun hours	hours	% sun	DWAF/HRI	Photostat copy of handwritten record
Solar radiation	Watt-hr m^{-2} Joule m^{-2}	Langley (cal cm^{-2})	DWAF/HRI WB	Photostat copy of original records

*Institutions:

DWAF : Department of Water Affairs and Forestry Head Office, Pretoria.

DWAF (HRI) : Hydrological Research Institute, Department of Water Affairs and Forestry, Roodeplaat Dam.

WB : The Weather Bureau, Department of the Environment, Pretoria.

Processing of meteorological and inflow data: From Table 3.2 it is evident that the data that were needed were lodged with various state departments, and that the data were not in a readily usable format. Only river flow rate and chemical water quality parameters were available in computerised format. Where photostat copies of original records were obtained, (ie. river water temperature, sun hours and solar radiation), these had to be computerised. Because of the format of, for instance, solar radiation, this was often a laborious process. Where photostat copies of original recorder charts were obtained (ie. wind speed and direction, air temperature and humidity), these had to be digitised.

Two meteorological variables required by the model, dew point temperature and percentage sun hours, were not available, and therefore had to be calculated. Daily dew point temperature was calculated from daily relative humidity data, using the Clausius-Clapeyron formulation (Barrow, 1973). Percentage sun is defined as the number of hours of observed sunshine per day, divided by the maximum number of hours of sunshine possible (astronomical day length). Observed sunshine data were obtained from the Department of Water Affairs and Forestry (HRI). Tables of the astronomical day length for Pretoria, as well as a general formula for calculating astronomical day length at any latitude, were obtained from the Observatory in Cape Town.

Infilling of missing meteorological and inflow data: Though the required data were available on a daily basis for extensive periods during 1980 to 1984, there were still some periods in between where no data were available. The worst period was April to November 1984. No radiation data were available for this period, as well as no river water quality data for Hartbeesspruit and Edendalespruit. The study period therefore had to be limited to January 1980 to December 1983. A summary of the availability of required inflow data, as well as meteorological data, is given in Appendix 3.1

Even though there were still some data missing from the period 1980 to 1983, infilling of data was possible. Table 3.3 gives a summary of the inflow and meteorological variables that needed infilling, the variables that were used to aid in the infilling, and the relationship that existed between the variables.

TABLE 3.3 : INFILLING OF METEOROLOGICAL AND WATER QUALITY VARIABLES

Parameter with missing data	Parameter used for infilling	Condition	R^2	X-coeff	Infilling technique
Water temp (Edendale)	Average air temp	-	0.80	0.96	Linear regression
Water temp (Hartbees)	Average air temp	-	0.80	0.92	Linear regression
Water temp (Pienaars)	Average air temp	-	0.86	0.96	Linear regression
ln** PO_4 (Pienaars)	ln flow	May-Nov flow<$0.22 m^3 s^{-1}$	0.00	0.006	Interpolation
		May-Nov flow>$0.22 m^3 s^{-1}$	0.40	-0.68	Program*
		Dec-April flow<$0.25 m^3 s^{-1}$	0.04	0.66	Interpolation
		Dec-April flow>$0.25 m^3 s^{-1}$	0.40	-0.79	Program
ln PO_4 (Hartbees)	ln flow	-	0.22	0.29	Program
ln PO_4 (Edendale)	ln flow	-	0.31	0.39	Program
ln TDS (Pienaars)	ln flow	-	0.52	-0.24	Program
ln TDS (Hartbees)	ln flow	-	0.30	-0.23	Program
ln TDS (Edendale)	ln flow	-	0.72	-0.13	Program
Wind speed	Wind speed (Forum)***	Aug-Dec	0.44	0.22	Linear regression
Wind dir.	Wind dir. (Forum)	-			
%Sun hours	Radiation	-	0.84	0.005	Linear regression
Radiation	% Sun hours	-	0.84	166	Linear regression

* Program refers to the three-stage technique discussed below.

** 'ln' refers to the natural logarithm.

*** Forum refers to the Forum Building in Pretoria, the site where the wind data used for infilling, were measured.

Exhaustive efforts were made to find relationships between variables with missing values and other variables with more complete values. Daily flow was often used for infilling, as the flow records were complete (only three days missing from the entire record). When daily flow was used for infilling other data, it was done with the aid of a three-stage time-dependent seasonal technique.

- **First stage:** Infilling was done with a time-dependent seasonal non-linear regression of grab sample against daily flow, for days with flow above a certain truncation level, but with the infilled values weighed by proximity to a grab sample value at either end of the missing period

- **Second stage:** Data for days with flows below the truncation level was filled in by linear interpolation.

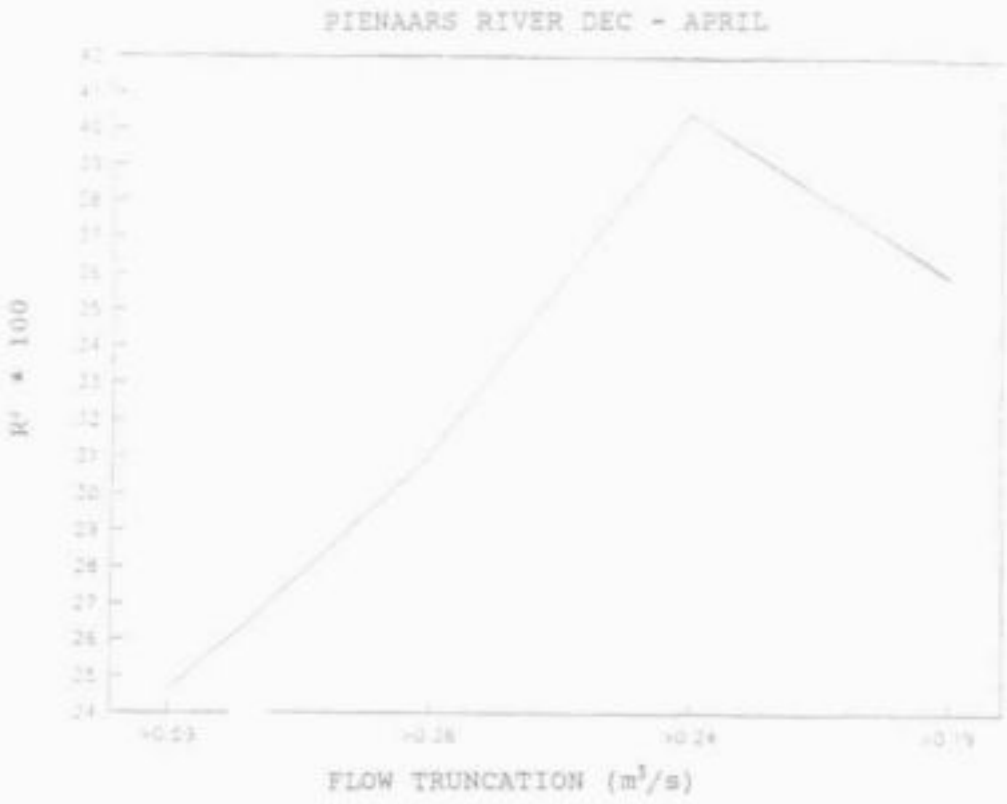
- **Third stage:** The grab sample values are imbedded in the created series and discontinuities and seasonal transitions are smoothed.

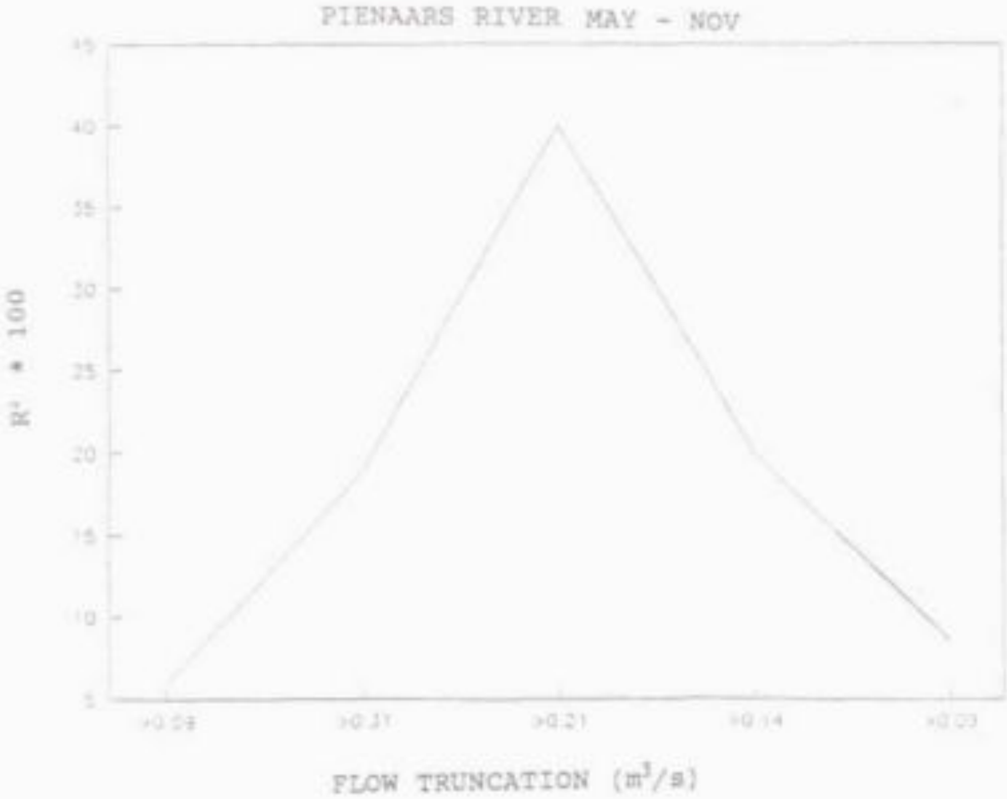
Water temperature: The water temperature was determined from the 'average' air temperature as follows: The 'average' air temperature for a specific day was defined as the mean of the true average air temperature for that day and the true average air temperature for the preceding day. A satisfactory correlation of 0.96 was found between water temperature and this 'average' air temperature.

Dissolved phosphate concentration: Missing dissolved phosphate concentrations were filled in with the aid of river flow rate data. The best regression between phosphate concentration and river flow rate was obtained using the natural logarithm of the two variables. It was found that the regression for Pienaars River differed from the other two rivers. This difference is probably due to a point source of dissolved phosphate to the Pienaars River, namely effluent from a sewage works upstream from measuring point. A definite seasonal phosphorus/flow trend could be discerned in the regression analysis, for flows greater than 0.22 $m^3\ s^{-1}$ for the period May to November, and for flows greater than 0.25 $m^3\ s^{-1}$ for the period December to April (Table 3.3). The truncation level of the flow influenced the value of R^2 significantly, as may be seen in Figure 3.3 - a graphical representation of R^2 against truncation level. The final infilling was done with the aid of the three-stage technique mentioned previously, for the period May to November (flow > 0.22 $m^3\ s^{-1}$) and for the period December to April (flow > 0.25 $m^3 s^{-1}$). Below these flows linear interpolation were used. No annual trend could be established.

The other two rivers did not show any seasonal phosphorus/flow dependence. In spite of exhaustive efforts, no discernible cause for the spread of data could be identified. The linear regression coefficient was low, ≈ 0.2 and ≈ 0.3 (Table 3.3). However, in view of the much lower dissolved phosphate concentration in these two rivers, the regression relationship between flow and dissolved phosphate was accepted.

Total dissolved salts: Although a very good linear regression between TDS and conductivity was found for each river, the regression relationship could not be used for infilling TDS data from conductivity data, because both TDS and conductivity were monitored at the same time, or both not at all. The missing values therefore had to be filled in with the aid of river flow rate, using the aforementioned three-stage approach. The regression relationship between TDS and river flow rate was also described best by the natural logarithm of the two variables. The regression coefficients for Pienaars River and Edendalespruit were reasonable (R^2 = 0.52 and 0.72 respectively) but the R^2-value for Hartbeesspruit was low, ≈ 0.3.





NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Graphical representation of R^2 against truncation level	FIGURE 3.3

Inorganic suspended sediment (TSS): No data on inorganic sediment concentration were available. TSS is modelled as an implicit part of the processes that govern water quality and temperature distribution in a reservoir, therefore it was vital that some estimate of TSS be made in order to simulate the behaviour of the reservoir.

The approach to find surrogate TSS data went through two phases: In the first phase, time-series data on the concentration of total suspended matter (TSM) in the reservoir were available. TSM is defined as comprising dead and alive phyto- and zooplankton, as well as inorganic suspended sediment and detritus (DWAF, 1988). TSM concentration was measured three times per week at points 1, 2, 7 and 8 in the reservoir. (See Figure 3.2). Point 7 is near the confluence of Pienaars River and Hartbeesspruit and therefore it was concluded that TSM concentration at this point very likely approximated the weighted average TSM concentration of Pienaars River and Hartbeesspruit. The TSM data at point 8 should adequately reflect the TSM concentration of Edendalespruit. Point 1 is well away from the effect of inflows and consequently TSM data at this point were used as field data to compare the simulated and observed TSS/TSM results. Missing time-series TSM data were filled in by linear interpolation. Section 3.13.1 below gives an account of the results achieved with this data and the eventual rejection of this data.

The second phase of the search for surrogate TSS data centred on the synthesising of daily TSS concentrations by use of the daily inflow record, as well as unit streampower theory. The unit streampower equation, based on daily flows, as developed by Rooseboom, was calibrated against the surveyed sediment volume in Roodeplaat Dam for the period 1959 to 1980.

Wind speed: Monitoring of wind speed data was done at Roodeplaat Dam. The data were not complete (see Appendix 3.1). To infill the missing data, it was found that, for the windy period, August to December, a slight correlation ($R^2 = 0.4$) existed between the daily wind speed measured at Forum Building in Pretoria and wind speed measured at Roodeplaat Dam. For this period, infilling of missing data was done using the regression relationship between the wind speeds at the two locations. During the low wind period, January to July, the correlation between the wind speeds was near zero and accordingly infilling of Roodeplaat Dam wind speed was done by linear interpolation between the known wind speed at the beginning and end of the missing period.

Analysis of the wind speed (and wind direction) data required digitising of the data from Roodeplaat Dam from the original wind recorder charts (an extremely time consuming process).

Wind direction: A study of the dominant monthly wind directions at Roodeplaat Dam and Forum Building in Pretoria showed a similarity only during the windy period from about August to January (Table 3.4). Missing wind direction data for the period August to January for Roodeplaat Dam therefore were filled in from the daily wind direction at Forum Building. For the low wind period (February to July) the dominant monthly wind direction at Roodeplaat Dam was used to fill in the daily missing values.

TABLE 3.4 : MONTHLY DOMINANT WIND DIRECTION* AT FORUM BUILDING IN PRETORIA AND AT ROODEPLAAT DAM

	J	F	M	A	M	J	J	A	S	O	N	D
1980												
Forum	3	7	7	25	7	7/25	3/7	3	3	3	3	3
Roode	3	16/3	12	12	16	16	16	3	3	3	3	3
1981												
Forum	3	7	7	7	7	25	3	7	25	7	3	3
Roode	16	16	16	21	16	21	21	21	3	7	3	3
1982												
Forum	3	7	3	25	25	25	3	25	3	3	3	3
Roode	16	16	16	16	16	16	16	16	16	7	3	3
1983												
Forum	3	7	7	3	21	25	25	25	3	3	3	3
Roode	16	12	16	16	16	16	16	16	16	3	3	16

* In degrees/10, with zero = north and angle of rotation clockwise

Sun hours and solar radiation: The linear regression between sun hours and solar radiation is based on an Ångstrom-type formula, ie.

$$\frac{Q}{Q_A} = a + b\left(\frac{S}{S_o}\right)$$

Q = Solar radiation as measured

Q_A = Ångot value of radiation (radiation before passing through atmosphere)

S = Hours of sunshine as measured

S_o = Astronomical (theoretical) day length

a,b = Constants

The constants **a** and **b** are preferably calculated for each month. According to the literature, there may be a deviation from linearity when $(S/S_o) < 0.5$ (Louw, 1965) or when $(S/S_o) < 0.2$ (Reid, 1981). However, no significant difference could be found between the monthly values of **a** and **b**, and neither was the linearity improved by only considering values where $(S/S_o) > 0.5$ or 0.2. The infilling of both radiation and sun hours therefore were done by a straight regression correlation with no special conditions.

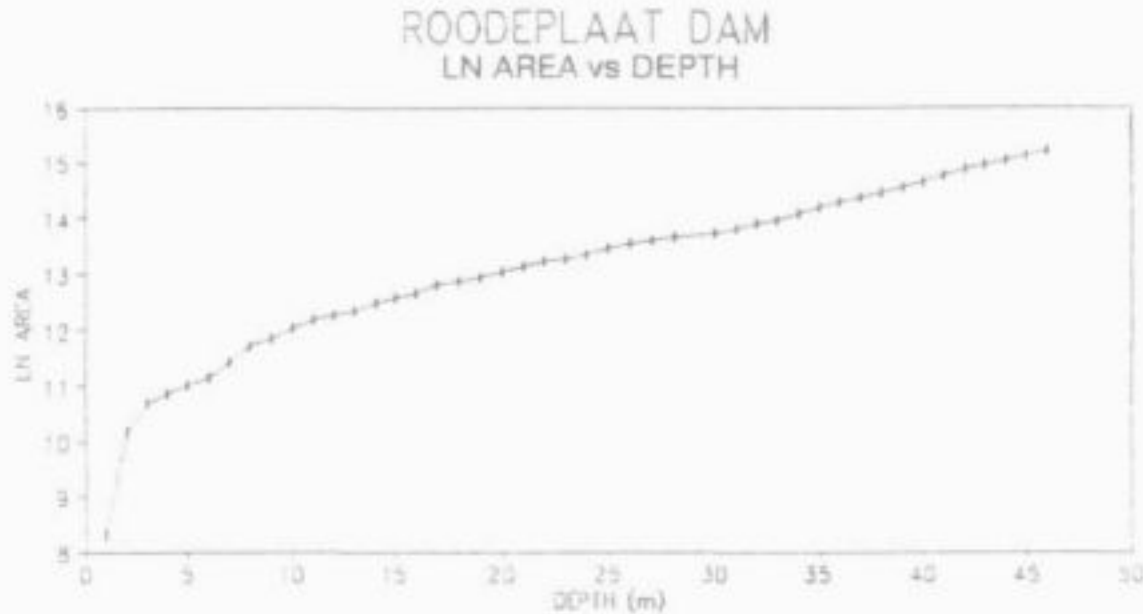
3.11.2 Reservoir characteristics, water quality variables and calibration coefficients

Lake specific subroutine: The lake specific subroutine contains two lake-specific functions that must be developed and coded into the subroutine. These are:

a) The relationship between water surface area and depth: The relationship was developed from hydrographic information received from Department of Water Affairs and Forestry and 1:10 000 orthophoto maps (Figure 3.4).

b) Wind fetch as a function of wind direction: The function was developed from 1:10 000 orthophoto maps of the reservoir, and varies with the wind direction.

Reservoir water quality: Depth profiles of the following variables were considered necessary for Roodeplaat Dam: water temperature, dissolved oxygen (DO), dissolved phosphate, inorganic suspended sediment and chlorophyll-a. Depth profiles of water temperature and DO were measured monthly and sometimes weekly, but usually only down to the thermocline, and not always on the same date. Concentrations of dissolved phosphate, nitrate-nitrite, ammonia, TDS and chlorophyll-a were also measured monthly, and sometimes weekly, and not always on the same date as water temperature and DO. Usually an integrated sample from surface to 5 metres was taken. Regular samples were also takan below the thermocline, but the depth of sampling was not consistent. Depth profile data were obtained from the Hydrological Research Institute (Department of Water Affairs and Forestry).



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Depth / area relationship for Roodeplaat Dam	FIGURE 3.4

Calibration coefficients and reservoir constants: A total of 24 calibration coefficients on the process behaviour, and 12 constants on the physical characteristics of the Roodeplaat Dam, are required by the program (Table 3.5). Values for the constants describing the physical characteristics of Roodeplaat Dam were obtained from the Department of Water Affairs and Forestry. In sofar as the calibration coefficients are concerned, only a few of these could be estimated from the literature on studies that had been done previously on Roodeplaat Dam. Although a range of values for each calibration coefficient is given in the manual, these are often of restricted use; for instance, the 12 coefficients relating to algal growth are algal and climate specific, and there is little indication in the manual as to the values for specific algal species in a given climate. As a starting point, where the value of a calibration coefficient could not be determined for Roodeplaat Dam, the default value suggested for Lake Riley was used. The calibration coefficients, and the values that were used in the first simulation, are listed in Table 3.5.

TABLE 3.5 : CALIBRATION COEFFICIENTS REQUIRED BY MINLAKE **

Calibration coefficient	Required unit of measurement	Numeric value of coefficient
Maximum hypolimnetic diffusion coefficient	$m^2\ day^{-1}$	0.2*
Wind function coefficient		25.6*
Wind sheltering coefficient		≈ 1.0*
Detrital decay rate	day^{-1}	0.07*
Sediment oxygen depletion rate	$g\ m^{-2}\ day^{-1}$	1.00*
Sediment phosphorus release rate	$g\ m^{-2}\ day^{-1}$	0.05*
Detrital settling rate	$m\ day^{-1}$	0.01*
Maximum phosphorus uptake rate	$mg\ P\ mg^{-1}\ Chla\ day^{-1}$	7*
Maximum nutrient saturated growth rate	day^{-1}	0.03*
		Continued ...

Temperature at which growth is reduced 90%	°C	32
Optimal temperature for growth	°C	27
Algal respiration rate	day^{-1}	0.15*
Algal mortality rate	day^{-1}	0.05*
Half saturation coefficient for phosphorus uptake	$mg\ l^{-1}$	0.03*
Half saturation coefficient for light limited growth	$\mu E\ m^{-2}\ s^{-1}$	500*
Minimum intracellular phosphorus concentration required for growth	$mg\ P\ mg^{-1}$ Chla	3.3*
Maximum phosphorus storage capacity of algal cell	$mg\ P\ mg^{-1}$ Chla	33.0*
Settling rate of algae	$m\ day^{-1}$	0.15*
Mass ratio of dissolved oxygen produced/consumed by algae	mg Chla $mg^{-1}\ O_2$	0.0083*
Mass ratio of chlorophyll to detritus	mg Chla mg^{-1} BOD	0.0083*
Mass ratio of phosphorus produced from detrital decay	$mg\ P\ mg^{-1}$ Chla	0.0091*
Light extinction coefficient of lake water	m^{-1}	0.99
Light extinction coefficient due to chlorophyll-a	$m^2\ g^{-1}$ Chla	12

* Default value suggested for Lake Riley.

** Zooplankton and nitrogen calibration coefficients not included.

3.12 HYDRODYNAMIC SIMULATION RESULTS

3.12.1 Introduction

As the hydrodynamic response has a significant influence on the water quality response, whereas the reverse effect is much smaller, initial attention was focused on the hydrodynamic response.

The MINLAKE model, as supplied, made provision for only a single inflow or outflow and could be run for one year only. As Roodeplaat Dam receives inflow from three rivers, and both overflow and draw-off could take place, the program was changed to incorporate a total of five in/outflows. For outflows, the program made provision for the level of outflow and the discharge rate, to be specified. The run period was extended to three years. Furthermore, the MINLAKE graphical output was geared for time-series graphs at a specified depth only. This was inadequate for the large output of data generated by MINLAKE. The transparency of results and the flexibility of output manipulation were improved by adding a graphics program to plot depth profiles at regular intervals of any of the simulated variables.

With the above modifications, to calibrate the model, the program was run over a period of two years, with input data files and calibration coefficients as set up for Roodeplaat Dam. Three years of data were available; two years were allocated for calibration and the third year for verification.

3.13.2 Temperature simulation

The temperature profiles are the basic response against which the hydrodynamic response can be evaluated. Water temperature is one of the most important variables for the modelling of water quality in lakes and reservoirs. The vertical temperature gradient affects the stability of the water column; thermal stability plays a part in the amount of turbulent mixing, and in vertical exchanges of energy and nutrients, such as dissolved oxygen and phosphorus. It was essential therefore that the simulated water temperature correlated reasonably with the observed water temperature before attempting to optimise the simulated values of the other variables.

Using the two year time-series input data and the calibration coefficients as listed in Table 3.5, the model was run for Roodeplaat Dam. In Figures 3.5(a and b) the MINLAKE simulations of water temperature at different depths are shown. Though the simulated temperature values at the surface and at five metres followed the same trend as the measured values, the simulated temperatures were too high. Deeper down, at twenty metres below the surface, the simulated and observed water temperatures deviated significantly, both in trend and in value.

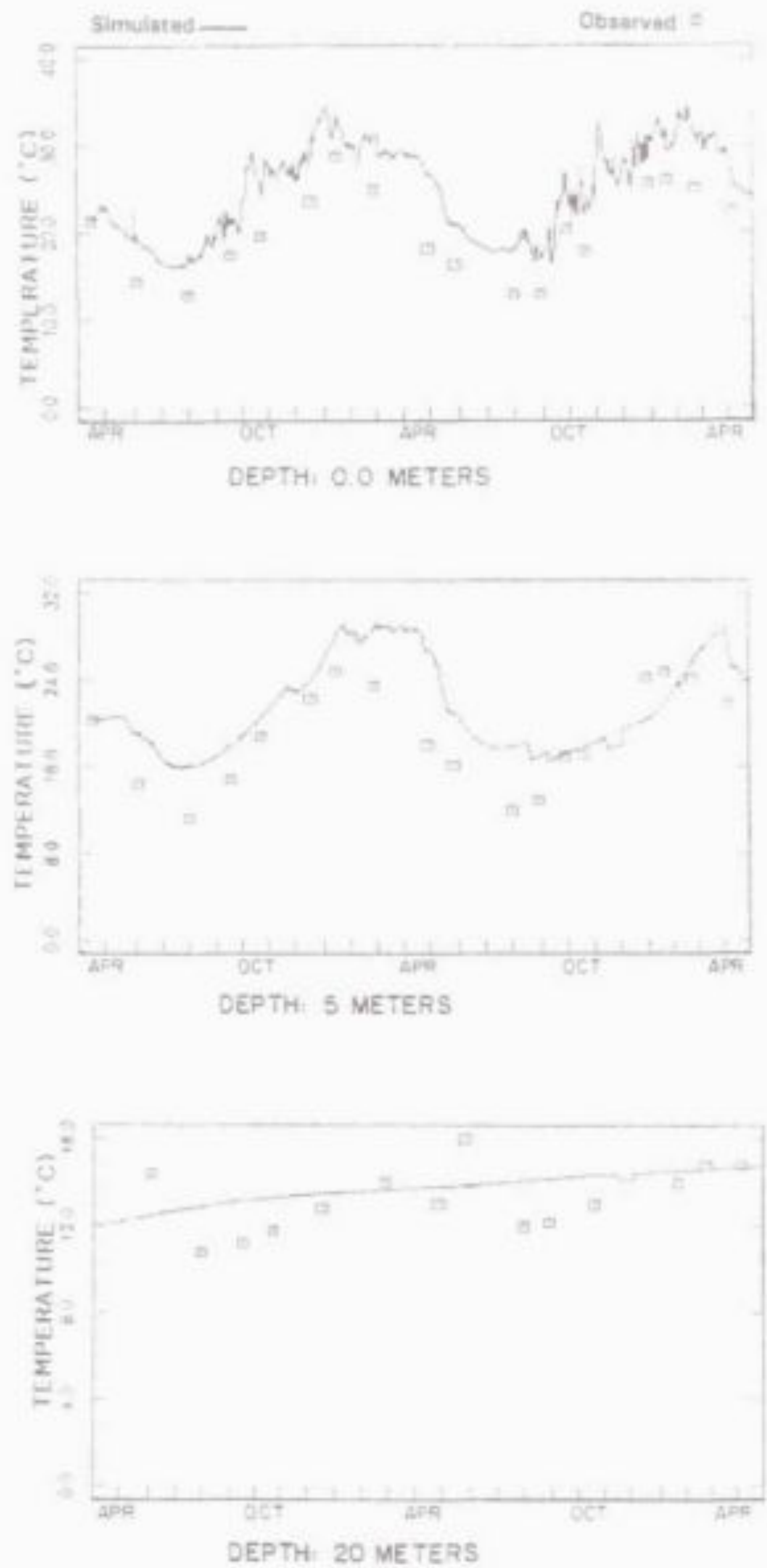
To find the causes for these deviations the various factors that may affect the temperature profiles were studied. The vertical temperature profile appears to be very sensitive to solar radiation, wind and the temperature of the inflowing water. Accordingly, these variables were subjected to detailed scrutiny.

Effect of solar radiation: To investigate the affect of solar radiation, the solar radiation time-series data, as measured at Roodeplaat Dam, were investigated. The reliability of the solar radiation data were checked by comparing the data for Roodeplaat Dam to those at other stations in the vicinity and were found to be consistent. To check the sensitivity of the temperature response to the level of radiation a run was done with solar radiation decreased by 50%. The results are shown in Figure 3.6. Simulation of the water temperature at the surface improved, but the deviation from the observed temperature increased with depth. It was concluded that the measured solar radiation data were not the main cause of the deviations.

There remained the possibility that the formulation of the absorption of the radiation into the water body was defective in MINLAKE. A study was made of the theoretical assumptions on which the water temperature simulations are based in MINLAKE: A depth profile of temperature is computed from a balance between incoming energy from solar as well as long-wave radiation and the outflow of energy through convection, evaporation and back radiation. The net increase in energy causes an increase in water temperature.

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

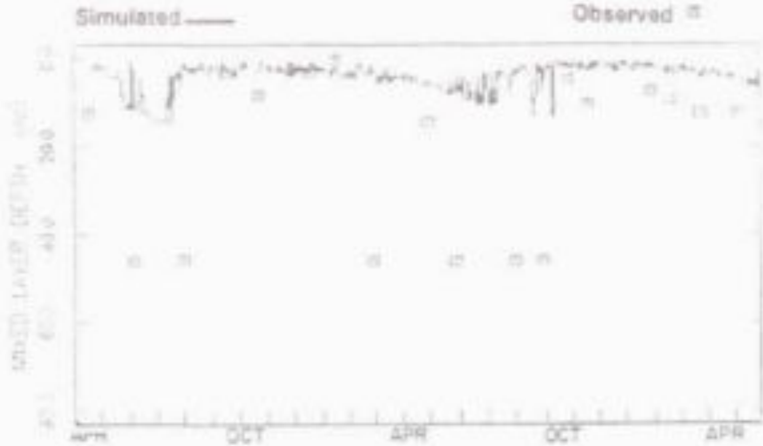
CONDITIONS : WINDSPEED MEASURED AT 1.8m, TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed temperature as obtained with original model	FIGURE 3.5 a

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED MEASURED AT 1.3m. TSS = TSM



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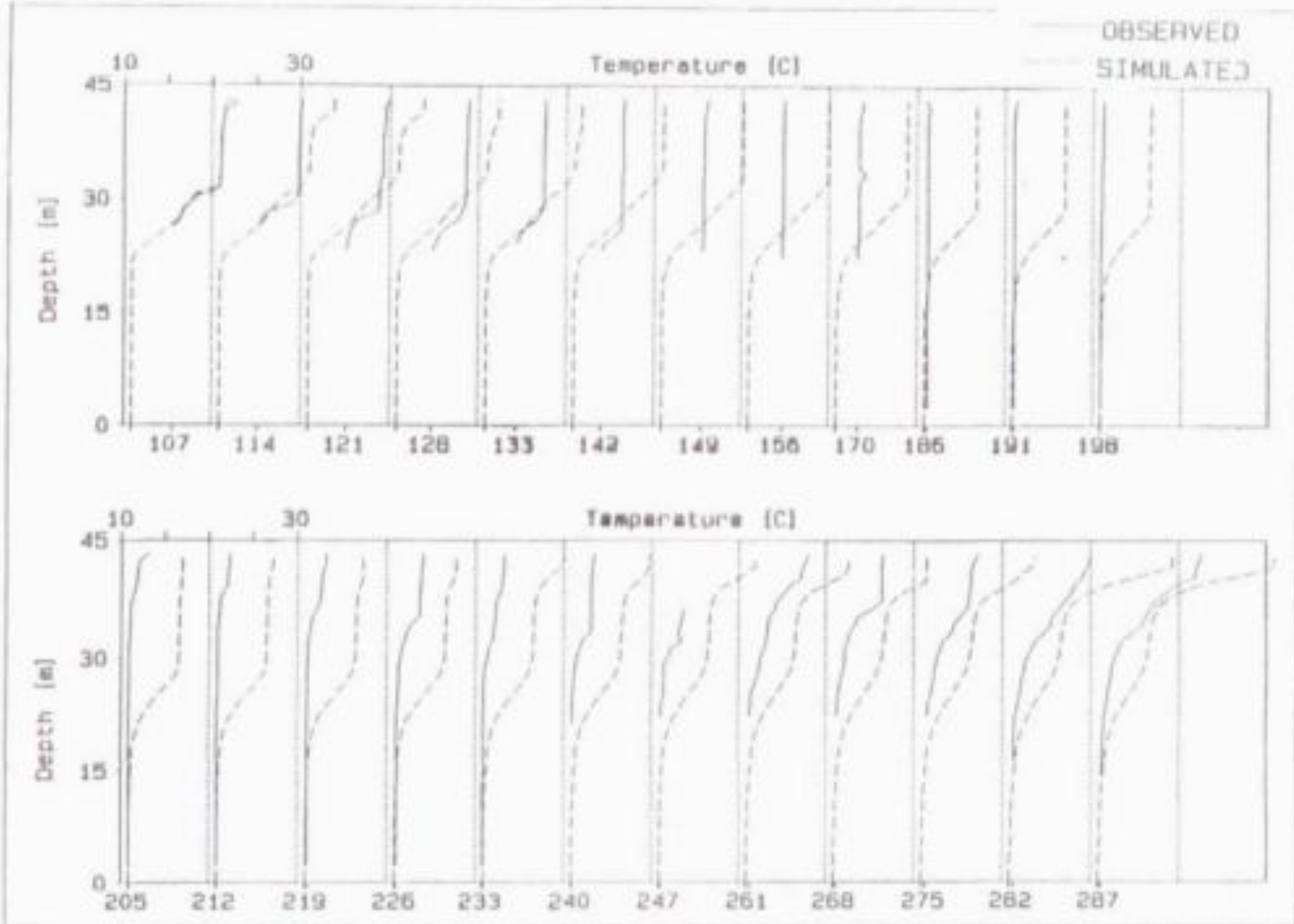
Plot of simulated vs. observed mixed layer depth obtained with original model

FIGURE 3.5b

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

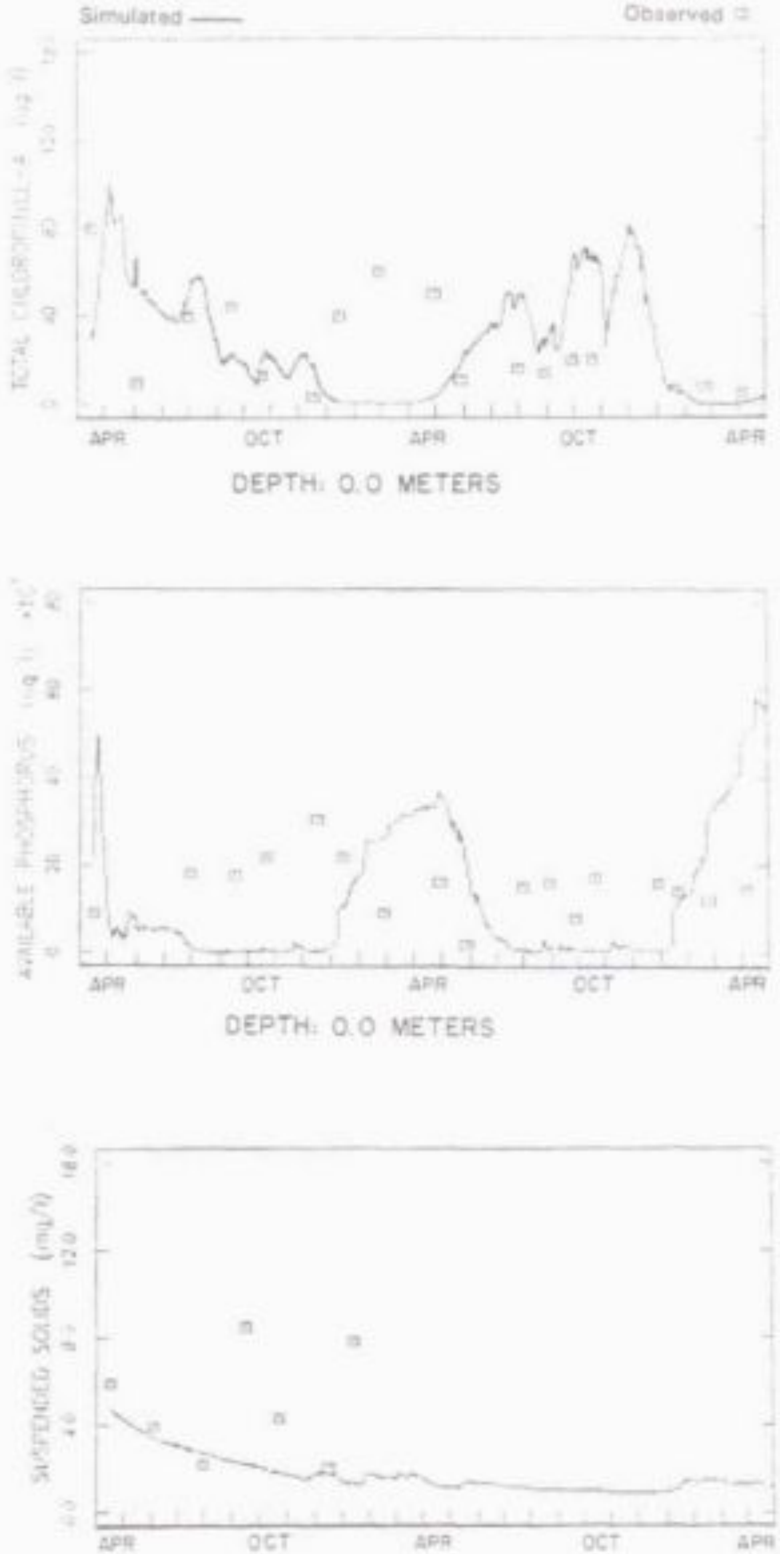
CONDITIONS : WINDSPEED MEASURED AT 1.8m. TSS = TSM



KINNAIRD SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs observed temperature with depth obtained with original model	FIGURE 3.5c

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

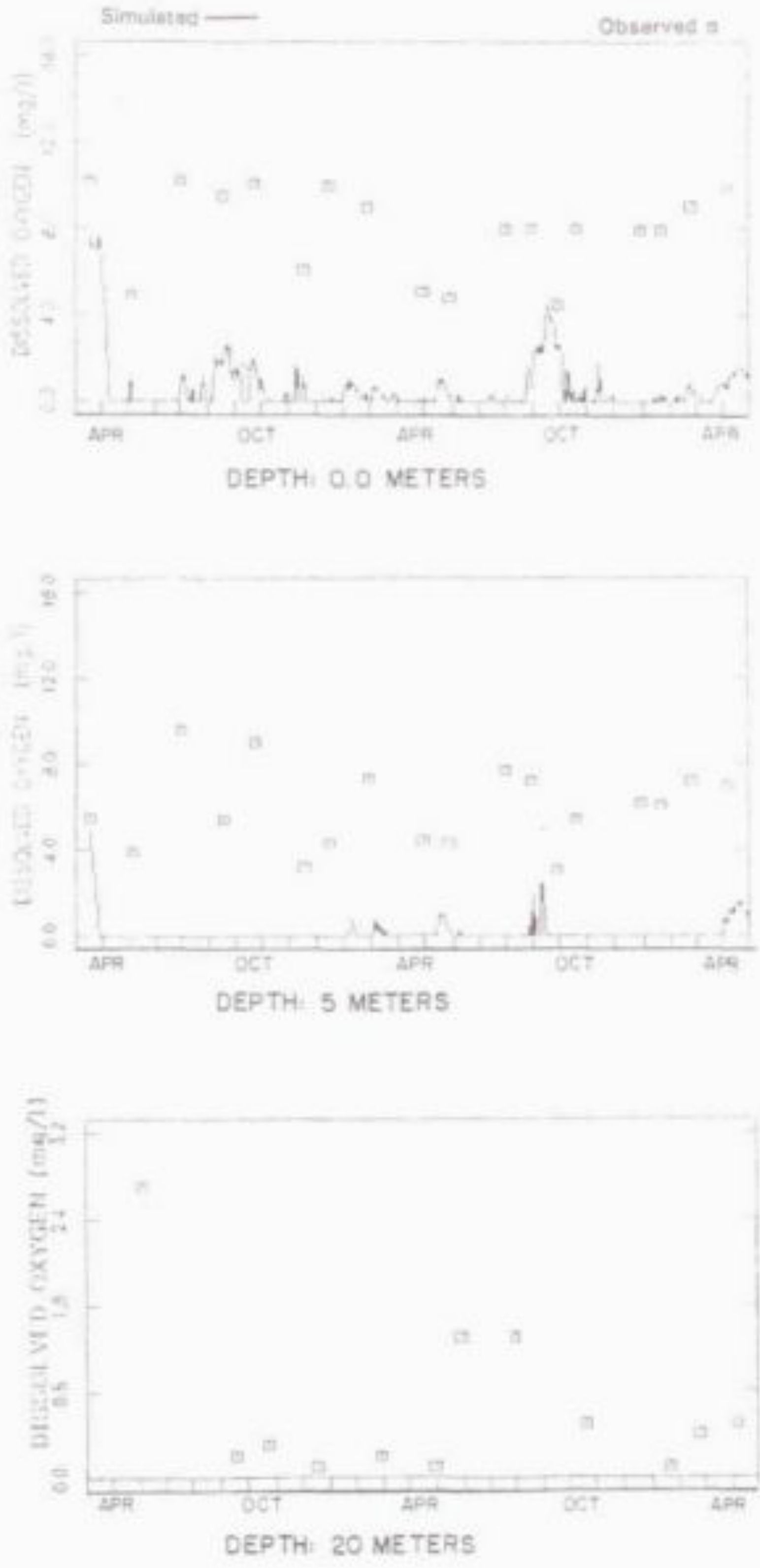
CONDITIONS : WINDSPEED MEASURED AT 1.8m. TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with original model	FIGURE 3.5d

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

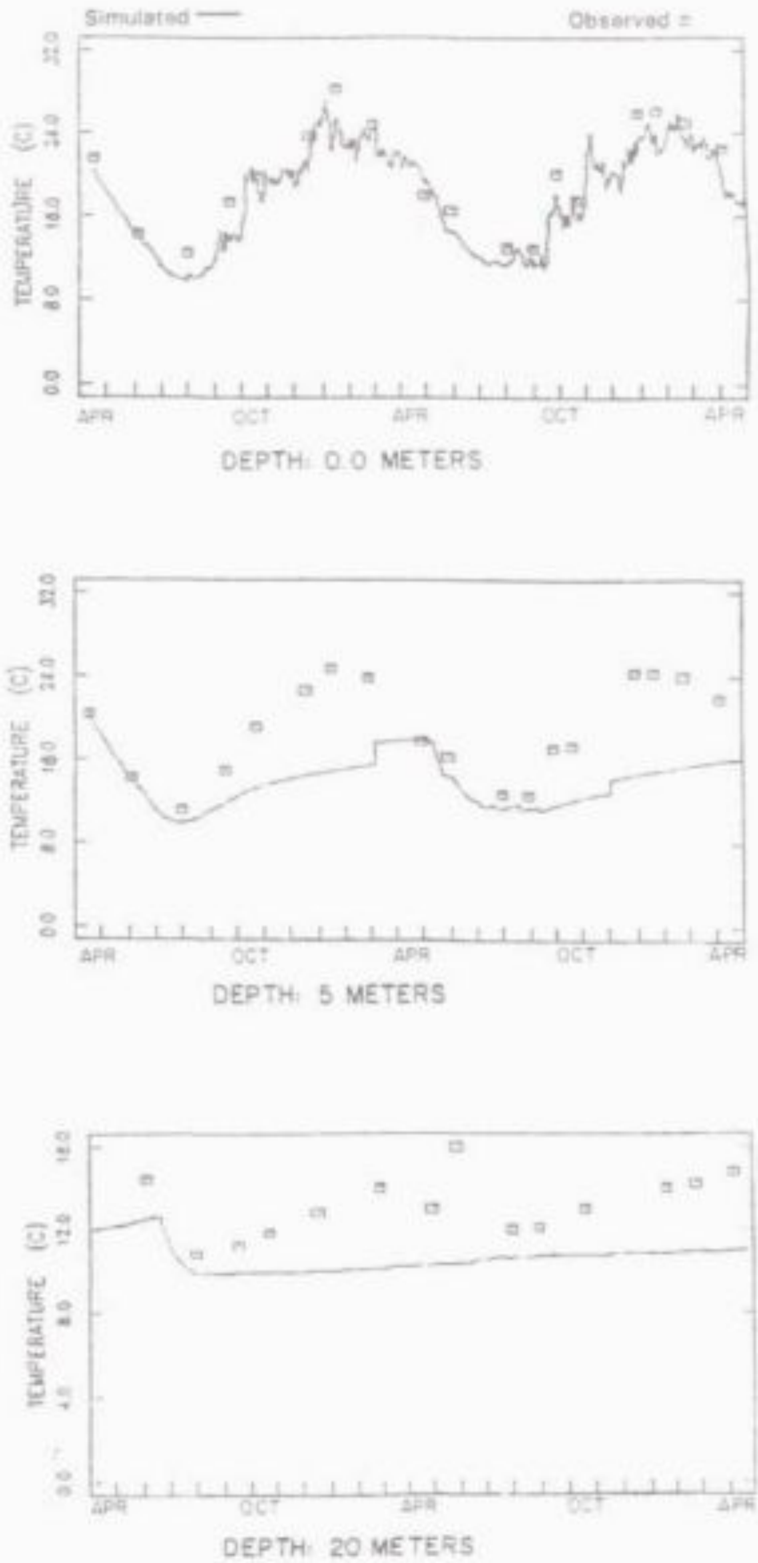
CONDITIONS : WINDSPEED MEASURED AT 1.8m. TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with original model	FIGURE 3.5e

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : SOLAR RADIATION REDUCED 50%, TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION		FIGURE
			Plot of simulated vs. observed temperature obtained with reduced solar radiation.	3.6

The basic energy balance equation, applied on a daily basis, is (MINLAKE, 1988):

$$n = H_{sn} + H_a - H_c - H_e - H_b \qquad (1)$$

H_n = net heat available to the reservoir (kcal m^{-2} day^{-1})
H_{sn} = net solar radiation (kcal m^{-2} day^{-1})
H_a = long-wave atmospheric radiation (kcal m^{-2} day^{-1})
H_c = convective heat transfer
H_e = evaporative heat transfer
H_b = back radiation (kcal m^{-2} day^{-1})

Consider each of the parameters in the right hand side of Equation 1:

> H_{sn} **(net solar radiation):** Some of the incoming solar radiation is reflected at the surface of the water, therefore

$$H_{sn} = (1-r)H_s \qquad (2)$$

H_s = incoming solar radiation (kcal m^{-2} day^{-1})
r = reflected fraction
= $0.087 - (6.76\mathrm{x}10E\text{-}5)H_s + 0.11\{1-\exp(-0.01SS)\}$
SS = suspended sediment concentration in first layer (mg l^{-1})

A literature study supported the above expressions (Dake, 1969; Dake, 1972; Ryan, 1974; Henderson-Sellers, 1984). However, there was concern as to the fraction of solar radiation absorbed by the surface layer: A fraction, ß, of the net solar radiation is absorbed by the surface layer, the remainder penetrates to greater depth according to Beer's Law, (an exponential decay function). The absorbed fraction ß is 'hard-wired' into MINLAKE as a value of 0.4, but it may be more realistic to relate ß to the water turbidity by expressing ß in terms of the extinction coefficient (Henderson-Sellers, 1984):

$$\beta = 0.265 \ln n + 0.614 \qquad (3)$$

n = extinction coefficient

The above expression for ß was incorporated into MINLAKE, but it resulted in no significant change in the simulation results.

A further area of concern was the effect of inorganic suspended sediment, TSS, on the extinction coefficient, n, and on the reflected fraction, r. The TSS in the reservoir enters into the calculation of the extinction coefficient in Beer's Law, Equation 4, and in the calculation of the reflected fraction, Equation 2. In MINLAKE, the extinction coefficient in Beer's Law is expressed by:

$$n = K_w + 0.043SS + K_2 Chla \qquad (4)$$

n	=	extinction coefficient
K_w	=	extinction coefficient of the water (m^{-1})
	=	0.55 to 1.99 for Roodeplaat Dam
SS	=	TSS concentration in the layer ($mg\ l^{-1}$)
K_2	=	extinction coefficient due to chlorophyll-a (m^2g^{-1} chla)
$Chla$	=	chlorophyll-a concentration in the layer ($mg\ l^{-1}$)

No measurements of TSS (*SS* in Equation 4) were available for Roodeplaat Dam. As an approximation the average Total Suspended Matter (TSM) concentration at point 1 in Roodeplaat Dam (Figure 3.2) was used as substitute. The average TSM concentration ranged around 5 mg/l for the period 1980 to 1984. From Equation 4, with this TSM concentration, the extinction contribution due to TSS/TSM would be 0.22. This value is insignificant when compared to the extinction contribution due to chlorophyll: With a typical chlorophyll-a concentration of 0.4 mg l^{-1} and an extinction coefficient of approximately 12 $m^2\ g^{-1}$ Chla (a typical value quoted in the literature, *cf.* FRD, 1985) the extinction contribution due to chlorophyll would be approximately 5 in Equation 4.

With regard to the reflected fraction in Equation 2, a typical value for incoming solar radiation is 450 Langleys per day. If the reflected fraction is calculated without any TSM-concentration, the resultant net solar radiation, according to Equation 2, is 424 Langleys. If a typical TSM-concentration of 10 mg l^{-1} is taken into account, the net solar radiation would be 393 Langleys, a difference of about 30 Langleys (less than 10%).

From the above it was concluded that TSS/TSM concentration is not of major importance in the temperature simulation. This conclusion was supported when runs were done with no TSS/TSM, and with arbitrarily high TSS/TSM; no significant change in the temperature simulation could be discerned.

H_a and H_b: The theory used in MINLAKE to calculate long-wave radiation and back radiation also appeared to be correctly formulated. It was therefore concluded that the deviations between simulated and observed temperatures were due to the two remaining components of Equation 1, that is, convective and evaporative heat transfer, H_c and H_e respectively.

H_c and H_e: According to MINLAKE the evaporative heat transfer is given by:

$$H_e = Lf(W)(e_s - e_a) \quad (5)$$

$$f(w) = cW$$

L	=	latent heat of vaporisation (g-cal g^{-1})
$f(W)$	=	wind function
c	=	wind coefficient, suggested to be 25.62
W	=	average wind speed (m s^{-1})
e_s	=	saturated vapour pressure at the water surface (mbar)
e_a	=	vapour pressure of air (mbar)

The convective heat loss is given by

$$H_c = 0.618\, f(W)(T_s - T_a) \qquad (6)$$

T_a = air temperature (°C)

T_s = water surface temperature (°C)

$f(W)$ = wind function as before

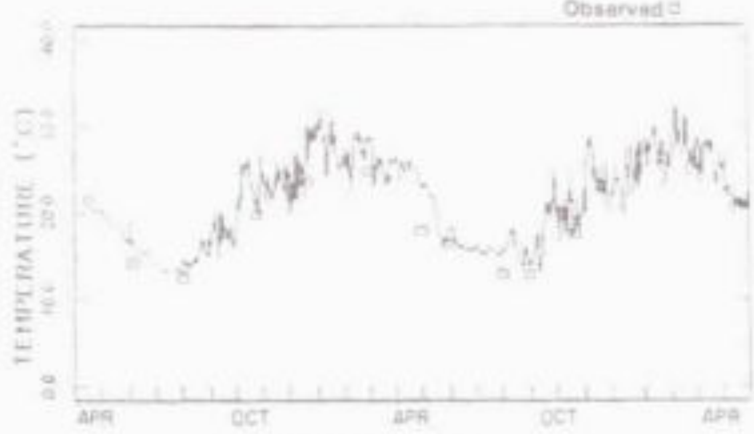
The literature accepts Equations 5 and 6 as standard formulations, also the constant, 0.618, in Equation 6 (Henderson-Sellers, 1984). With regard to the wind function, $f(W) = cW$ in Equation 6, two possible causes for error can be identified. Either the value of c is in error or W is incorrectly measured or interpreted. Accordingly these two parameters were investigated.

Wind coefficient c: The coefficient, c, is identified as a calibration coefficient in the input data file, which implies that this value should be specified by the user. After an extensive literature survey it was concluded that the wind coefficient should be determined for each location, but that a value of 25.62 as used in MINLAKE is a fairly average value (Harbeck, 1970; Henderson-Sellers, 1984). To check the sensitivity of the simulations to the wind coefficient c, its value was arbitrarily increased from 25.62 to 42.5. The correlation between observed and simulated temperatures improved significantly at the surface (Figure 3.7a), but was poorer at five and twenty metre depths (*cf.* Figure 3.7b and 3.5b). Also, there was no improvement in the simulation of the mixed layer depth (*cf.* Figure 3.7b and 3.5b). This seems to indicate that greater correlation between observed and simulated temperatures could not be achieved by changing the wind coefficient c.

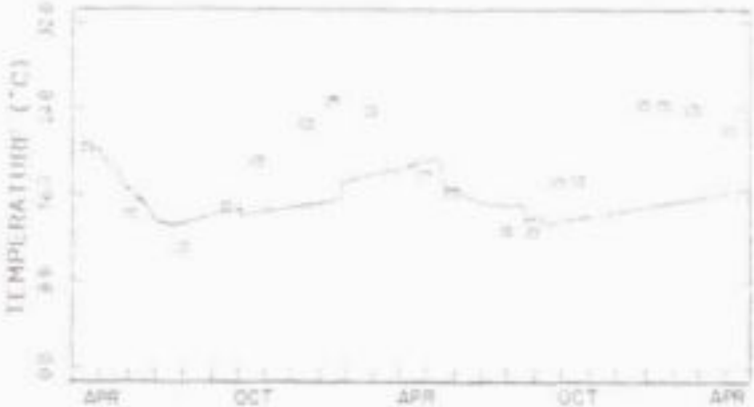
Wind sheltering: A further factor that may affect the wind is the effect of wind sheltering due to the surrounding topography and the fact that the wind speed is measured at one location only. In the MINLAKE model the effect of wind sheltering is provided for by the use of a calibration coefficient, which can be specified by the user, and which can range from zero to 1. The model was run with a coefficient of 0.1, and 0.99, but the temperature

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

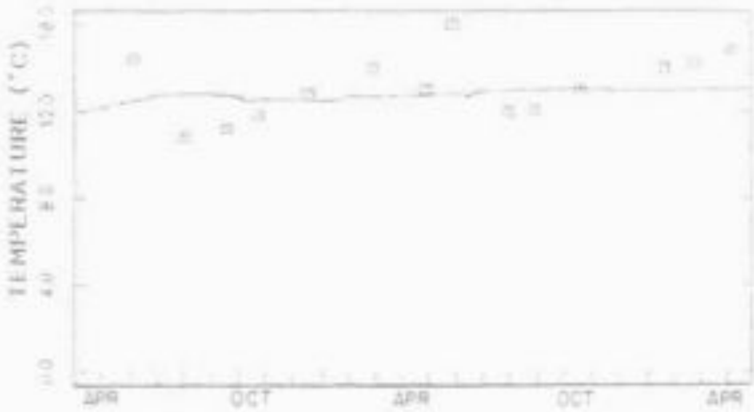
CONDITIONS : WIND COEFFICIENT INCREASED TO 42.5,TSS = TSM



DEPTH: 0.0 METERS



DEPTH: 5 METERS

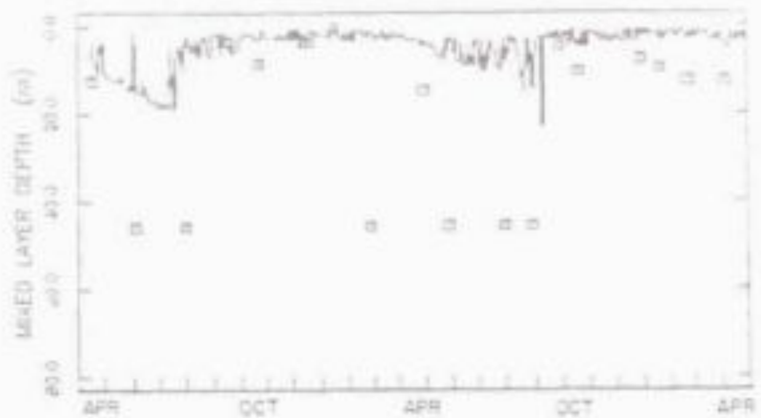


DEPTH: 20 METERS

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed temperature obtained with increased wind coefficient	FIGURE 3.7a

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS: WIND COEFFICIENT INCREASED TO 42.5. TSS = TSM



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Plot of simulated vs observed mixed layer depth as obtained with increased wind coefficient

FIGURE 3.7b

profile was affected insignificantly. Clearly the formulation in which this coefficient occurs, gives rise to only a minor effect.

Effect of wind speed W: MINLAKE requires that the input wind speed data be measured at 10 m above ground level. However, at Roodeplaat Dam the wind speed is measured at 1.8 m above ground level. Theoretically, the relationship between wind speed and height above ground level is expressed by either the Power Law or the Logarithmic Law (*cf.* Addendum 2).

The Power Law can be applied only if the terrain is horizontally homogeneous (CIRIA, 1970). From a study of the topography around Roodeplaat Dam it was determined that the reservoir is surrounded by hills on the northwestern, northeastern and southwestern sides. These hills are at least six metres above the full supply level of the reservoir, with the hills towards the north even higher. The reservoir is in a trough that runs from a northwesterly to a southeasterly direction. The terrain therefore cannot be considered horizontally homogeneous, and consequently the Logarithmic Law is to be preferred to adapt the wind speed to the required height.

According to the Logarithmic Law the relationship between wind speed and height above ground level is expressed by:

$$\frac{V}{V_o} = \frac{\ln(\frac{H}{z})}{\ln(\frac{H_o}{z})} \qquad (6)$$

V = wind speed at height H

V_o = wind speed measured at height H_o

z = roughness factor (*cf.* Addendum 2, Table 2.2)

In Addendum 2, Table 2.2, a roughness factor of 0.3 m is indicated for a terrain with low shrubs and/or sparsely built up suburbs. This seems to correspond to the hilly terrain around Roodeplaat Dam. Consequently, the wind speed measured at 1.8 m above ground was adapted to wind speed at 10 m above ground level, using the Logarithmic Law with a roughness factor of 0.3 m. Furthermore, in MINLAKE, the conversion from conditions above land to those above water is incorporated in the source code - the wind speed at 10 m above ground level, is adapted to wind speed at 10 m above the water surface, according to Equation 5 in Addendum 2. Originally, the land roughness factor in this equation was hard-wired in the source code to a value of 0.01 m. We changed this value to 0.3 m.

The results obtained with the wind speed corrected as described above, are shown in Figure 3.8(a) and (b). There is a marked improvement in the simulation of the mixed layer depth. Also, the simulated temperatures at the surface and at 5 m depth correlated very well with the observed temperatures. However, the simulated temperature at 20 m depth did not improve significantly. From an enquiry into the possible causes for this it was concluded that the divergence could have arisen from an incorrect value of the maximum hypolimnetic eddy (turbulent) diffusion coefficient, which was set at the default value of 0.2 m^2d^{-1}.

The eddy diffusion coefficient: The eddy diffusion coefficient increases with depth, reaching a maximum in the hypolimnion. In MINLAKE, the eddy diffusion coefficient is computed separately in the epilimnion and the hypolimnion.

In the epilimnion, the diffusion coefficient is given as a function of wind speed only:

$$K = 28\ W^{1.3} \qquad (7)$$

K = eddy diffusion coefficient (m^2d^{-1})
W = wind speed at 10 m above water ($m\ s^{-1}$)

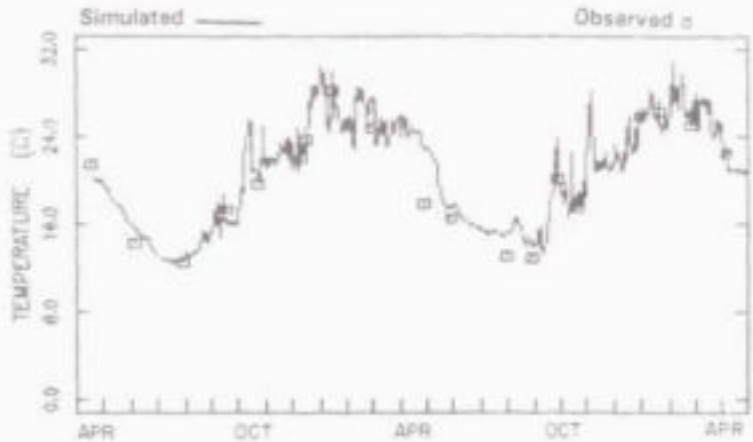
In the hypolimnion, the eddy coefficient is given by (Jassby and Powell, 1975):

$$K = K_{max} \text{ or } K_{max}CN^{-1} \qquad (8)$$

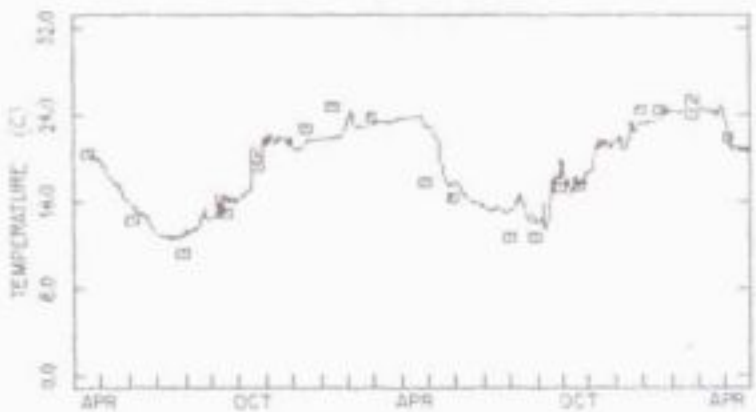
(whichever yields the minimum value)

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

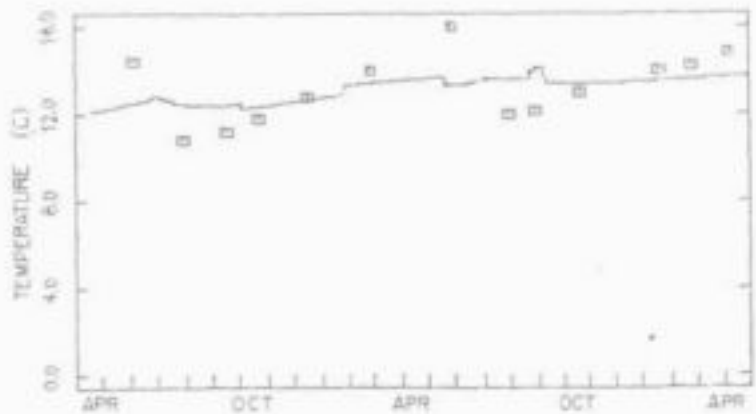
CONDITIONS : WINDSPEED MEASURED AT 10m. TSS = TSM



DEPTH: 0.0 METERS



DEPTH: 5 METERS

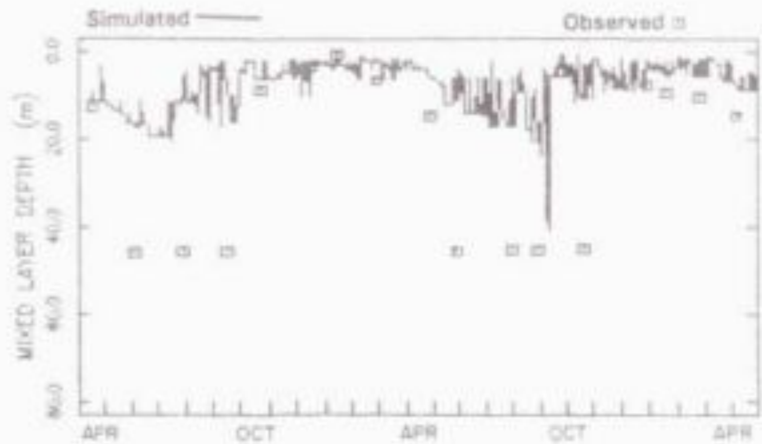


DEPTH: 20 METERS

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed temperature obtained with wind speed measured at the height required by the model	FIGURE 3.8a

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m . TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed mixed layer depth obtained with wind speed measured at the height required by the model	FIGURE 3.8b

K	=	eddy diffusion coefficient (m^2d^{-1})
K_{max}	=	maximum hypolimnetic diffusion coefficient (m^2d^{-1})
C	=	minimum value of N at which the maximum hypolimnetic diffusion rate occurs
N	=	Brünt-Våsala frequency

Mortimer (1942) reports that the maximum hypolimnetic diffusion coefficient increases with increasing reservoir surface area. In MINLAKE, this maximum coefficient has to be set by the user. This can be done either by calculation, or, where the necessary data for this calculation are not available, the **mean** value of the eddy coefficient in the hypolimnion can serve as a rough estimate of the maximum value (Mortimer, 1942).

Calculation of the maximum eddy diffusion coefficient: The eddy diffusion coefficient is calculated from the bathometry of the reservoir, the water temperature and the incoming solar radiation, on the assumption that there is no heat exchange with the bottom sediments (Jassby and Powell 1975, Henderson-Sellers, 1984):

$$K_H = -\frac{1}{\frac{\partial\theta}{\partial z}}\left(\frac{S}{A_z} - \frac{R}{C_p}\right) - \alpha \qquad (9)$$

where

$$S = \frac{d}{dt}\int_z^{z_b} A\theta du \qquad (10)$$

K_H	=	eddy diffusion coefficient ($cm^2\ s^{-1}$)
θ	=	water temperature (°C)
z	=	depth of layer (cm)
z_b	=	depth of bottom layer (cm)
A	=	area of the reservoir at depth z (cm^2)
R	=	net incoming solar radiation (cal $cm^{-2}s^{-1}$)

C_p = specific heat of water (cal $g^{-1}{}^{\circ}C^{-1}$)

α = molecular diffusion coefficient

= $0.12 \times 10^{-2} cm^2 s^{-1}$

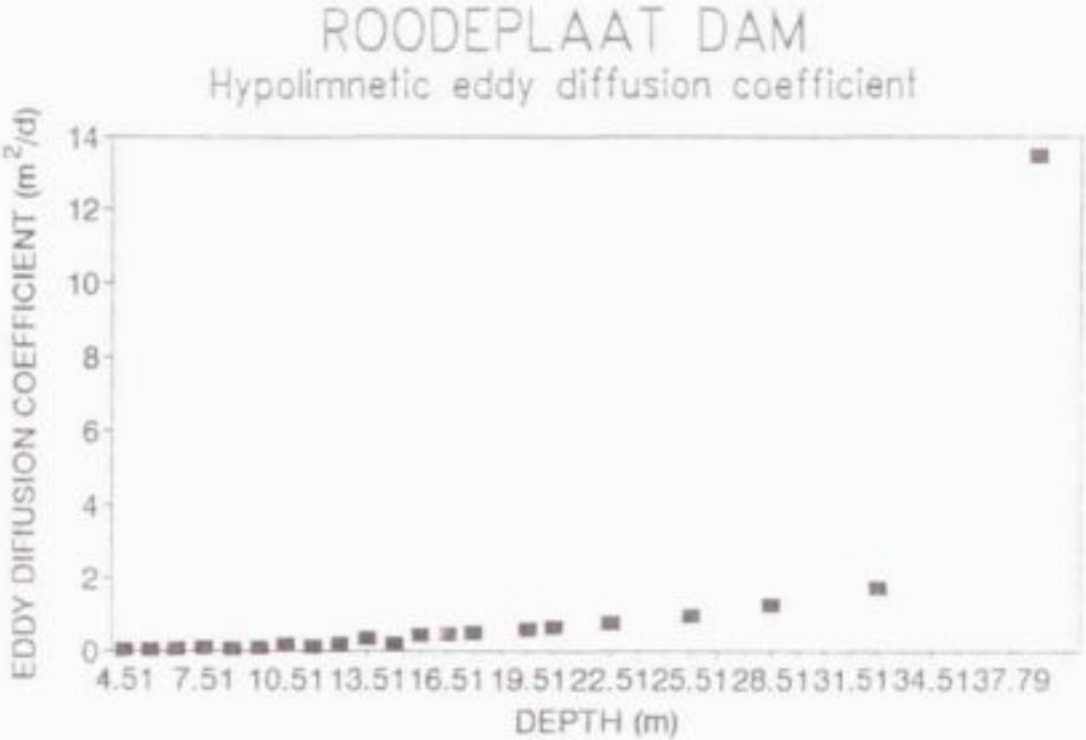
u = horizontal component of vertical advection

This derivation is valid only for the hypolimnion, that is, during the period when the reservoir is stratified and when convective transport of heat is negligible (Henderson-Sellers, 1984). Also, horizontal transport of heat is very small compared to the vertical transport. With one-dimensional models, eg. MINLAKE, where horizontal homogeneity is assumed, the change in du/dt can be taken as zero and therefore the integral between z and z_b in Equation 10 is not affected by u.

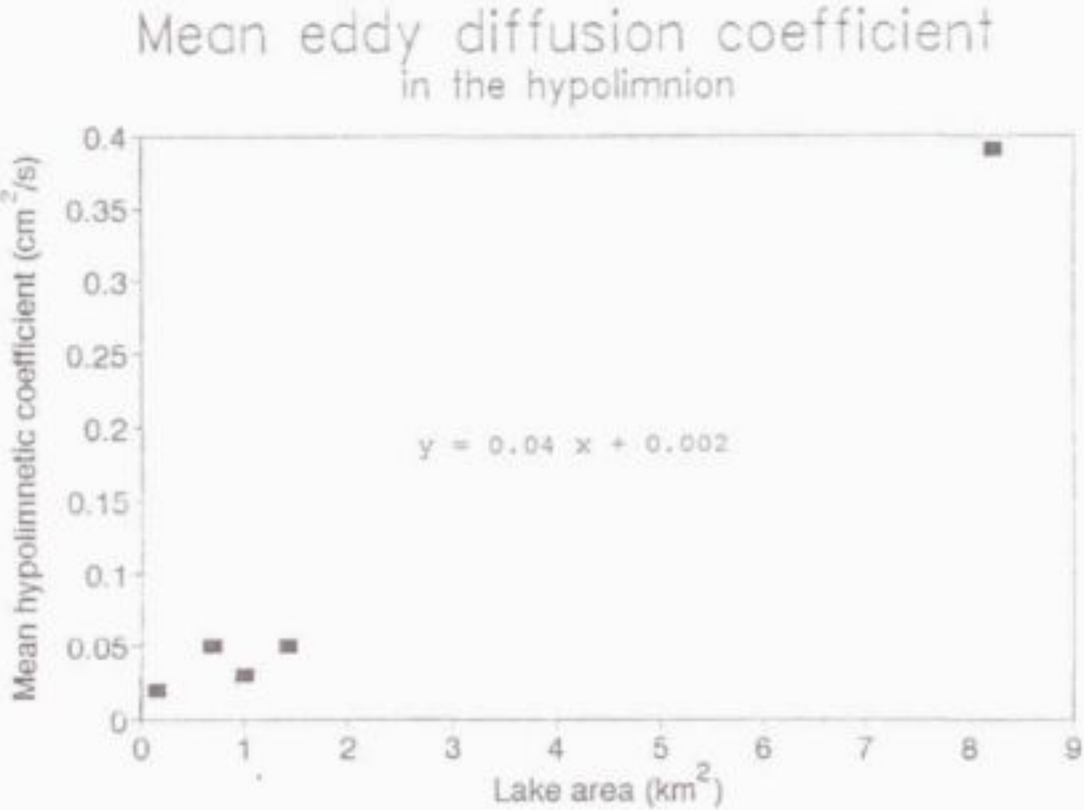
To determine the maximum value of the eddy diffusion coefficient, the coefficient is calculated in the different layers of the hypolimnion, and the maximum value is determined at the depth where turbulent diffusion reaches a minimum, ie. where dΘ/dz reaches a minimum.

In Figure 3.9 the values of the eddy diffusion coefficient in the hypolimnion of Roodeplaat Dam, as calculated from Equation 9 and 10, are plotted against depth. The **maximum** value of the hypolimnetic eddy coefficient was assumed to be indicated by a sharp change in the slope, to give a value of 1.73 m^2d^{-1}.

Estimation of the mean eddy diffusion coefficient: Where the maximum value of the eddy diffusion coefficient in the hypolimnion cannot be calculated, the **mean** value in the hypolimnion may serve as a rough estimation of the **maximum** eddy diffusion coefficient. The **mean** value for a particular reservoir can be obtained by interpolation in a plot of the **mean** values of the eddy diffusion coefficient vs. the lake area, of a number of lakes. (Table 3.6, plotted in Figure 3.10)



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of hypolimnetic eddy diffusion coefficient with depth as calculated for Roodeplaat Dam	FIGURE 3.9



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of mean eddy diffussion coefficient vs lake area for a number of lakes	FIGURE 3.10

TABLE 3.6 : DIFFERENT MEAN HYPOLIMNETIC EDDY DIFFUSION COEFFICIENTS WITH DIFFERENT LAKE AREAS (MORTIMER, 1942)

Lake	Area (km^2)	Mean hypolimnetic eddy diffusion coefficient ($cm^2 s^{-1}$)
Lomond	71.0	0.53
Windermere	8.2	0.39
Kizakiko	1.4	0.05
Lunz	0.68	0.05
Esthwaite Water	1.0	0.03
Schleinsee	0.15	0.02

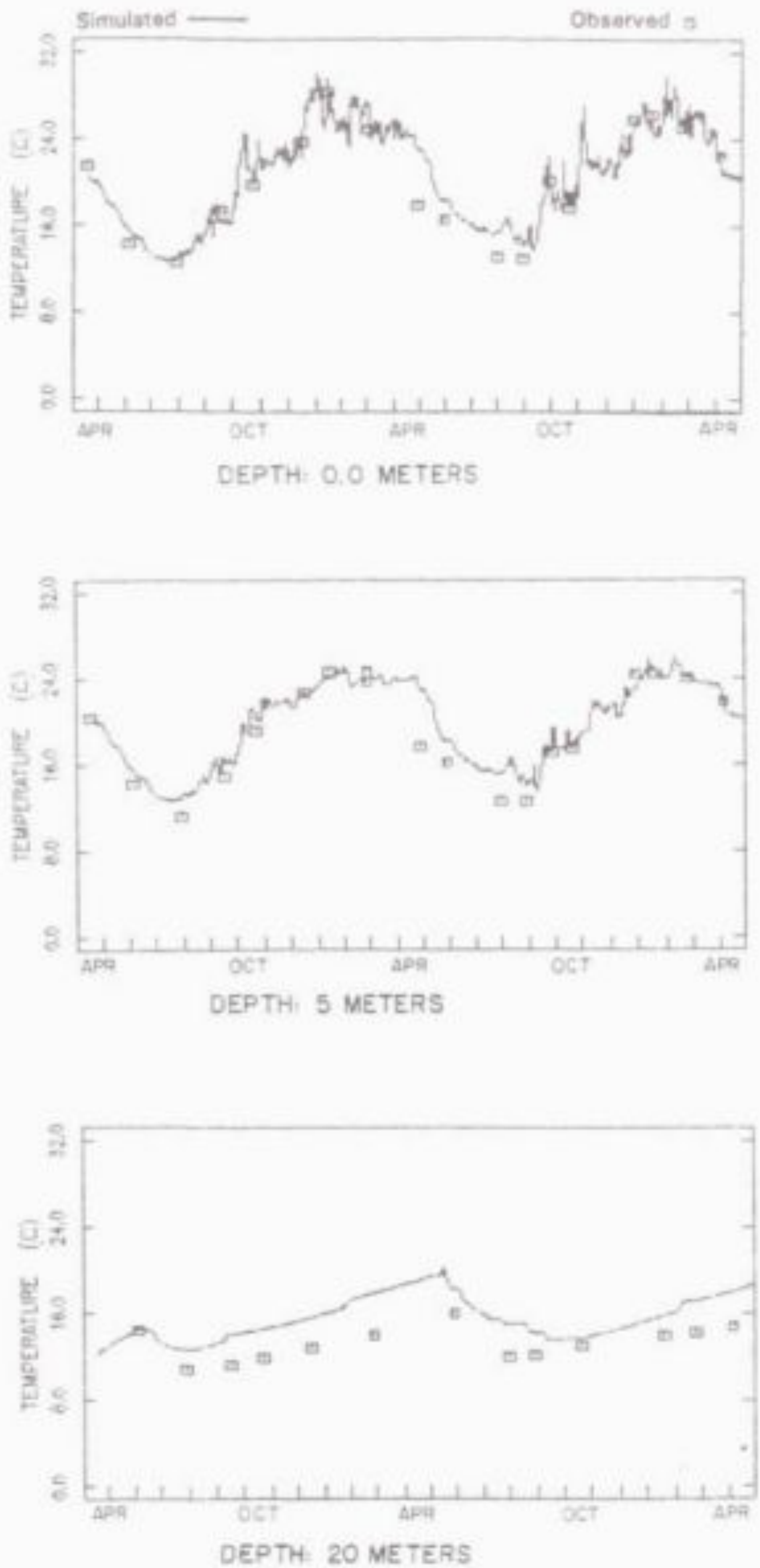
Roodeplaat Dam has an area of 4.0 km^2. From the plot in Fig 3.10, the mean hypolimnetic eddy diffusion coefficient for Roodeplaat Dam is 0.19 cm^2s^{-1}, or 1.62 m^2d^{-1}.

Using the calculated value of 1.73 m^2d^{-1} for the maximum hypolimnetic eddy diffusion coefficient for Roodeplaat Dam, instead of the default value of 0.2 supplied for Lake Riley, the simulation of temperature at different depths, as well as the simulation of mixed layer depth, is shown in Figure 3.11(a) and (b). These plots show a marked improvement in the simulation of the mixed layer depth (*cf.* Figure 3.8b and 3.11b). Also, the correlation between observed and simulated temperatures at the surface remains good (*cf.* Figure 3.8a and 3.11a). There is a slight improvement at 5 m depth, while at 20 m depth there is marked improvement in the trend, even though the simulated values are too high.

The goodness-of-fit displayed by Figures 3.11a and 3.11b was accepted by us as an adequate verification of the ability of MINLAKE to model the hydrodynamic behaviour of Roodeplaat dam for the period in question.

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

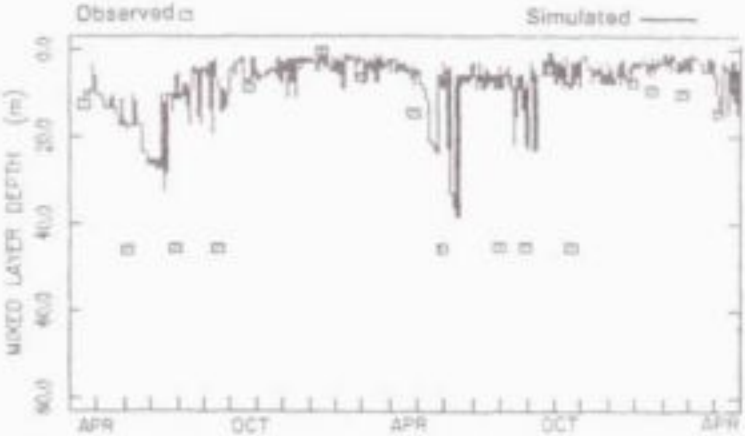
CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed temperature obtained with eddy diffusion coefficient calculated for Roodeplaat Dam	FIGURE 3.11a

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m²d⁻¹ TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed mixed layer depth obtained with eddy diffusion coefficient calculated for Roodeplaat Dam	FIGURE 3.11b

3.13 WATER QUALITY SIMULATION RESULTS

Using the improved hydrodynamic response discussed above, a water quality simulation was done using the default calibration coefficients as shown in Table 3.5. In Figure 3.12 (a) the simulated and observed algal, soluble phosphorus, and TSS/TSM concentrations are depicted. The simulated water quality variables still deviated considerably from those observed. Clearly this deviation cannot be attributed to inadequate hydrodynamic simulations. One may identify two possible causes for these differences:

1. Algal growth in Roodeplaat Dam could be phosphorus or nitrogen limited at different periods.
2. Our TSS/TSM time-series data approximation are inadequate.

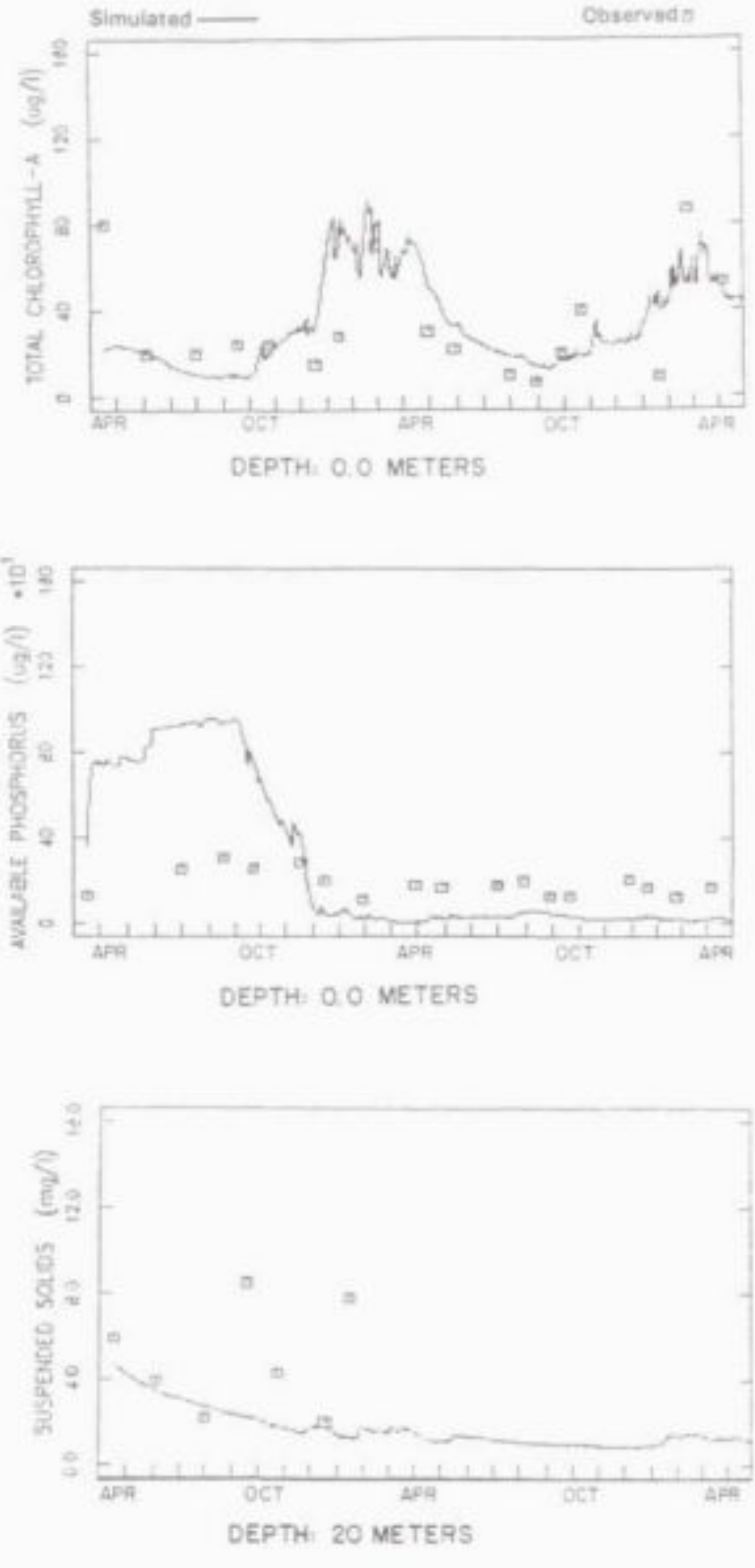
With regard to possible phosphorus/nitrogen limitation of algal growth, only phosphorus limited algal growth has been simulated. Clearly it would be desirable to simulate both phosphorus and nitrogen growth limitation.

3.13.1 The effect of TSS/TSM

Whereas TSS/TSM was shown to be of little importance in simulation of water temperature profiles, this is not the case with regard to water quality. TSS may act as a source/sink of nutrients in a reservoir, and the literature indicates that this has a relatively large effect on algal growth. Therefore the simulation of TSS has to be acceptable before the rest of the water quality parameters such as phosphorus and algal growth could be simulated. As discussed in Section 3.11, TSS concentration in the inflows to Roodeplaat Dam was not measured, nor was it measured in the reservoir. It was therefore necessary to find an associated or surrogate parameter from which it would be possible to approximate the TSS in the inflows and in the reservoir. It was stated in Section 3.11 that the TSM time-series data near the point of confluence of the Pienaars and Hartbeesspruit Rivers in the reservoir were taken to approximate the TSS in these rivers. The TSS for Edendalespruit was

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

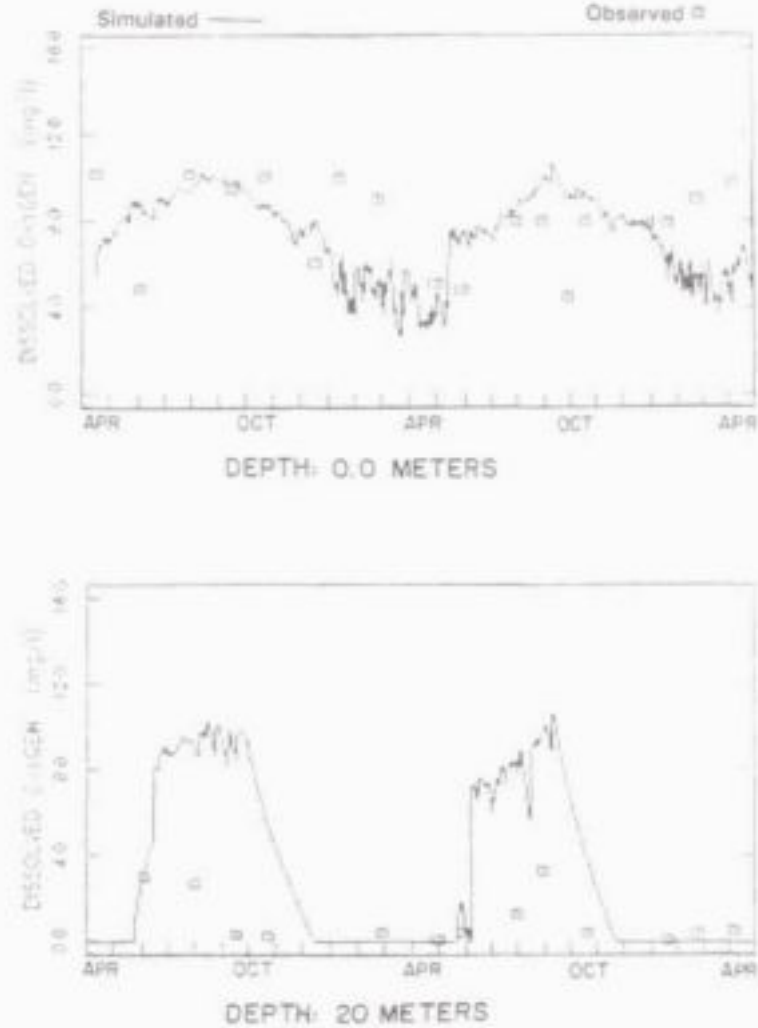
CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with eddy diffusion coefficient calculated for Roodeplaat Dam	FIGURE 3.12a

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ TSS = TSM



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with eddy diffusion coefficient calculated for Roodeplaat Dam	FIGURE 3.12b

approximated by the time-series TSM data at point 8 in the reservoir (see Figure 3.2). TSM data at point 1 (away from the inflow) was assumed to approximate TSS in the reservoir.

A preliminary study was made as to the effect of TSS/TSM on algal growth and soluble phosphorus concentration by doing a simulation with TSS/TSM equal to zero in the inflowing rivers. The results are shown in Figure 3.13. Clearly TSS/TSM has a marked effect, therefore it was necessary to improve the reliability of our TSS data approximations.

When the TSM data, serving as surrogate for TSS data, were compared with the flow data it did not reflect the relationship usually expected between TSS and flow. Upon investigation it was found that (DWAF (HRI), personal communication, 1992):

* Total Suspended Matter at measuring point 1 at Roodeplaat Dam consists of only algal biomass, and not phyto- and zooplankton, inorganic suspended sediment and detritus, as defined in TR 136: Analytical Methods Manual (DWAF (HRI), 1988)

* The assumption that TSM concentration at measuring point 8 approximated the weighted average TSM concentration of Pienaars River and Hartbeesspruit is incorrect.

It was concluded that TSM cannot serve as a reliable measure of TSS, and therefore, as explained in Section 3.11, another surrogate TSS data set was synthesised by means of the unit stream power equation. A run was done with this TSS data; the results are shown in Figure 3.14(a) to (e). As there were no TSS field data, a comparison of the simulated and observed TSS concentrations was not possible, but it is to be expected that the TSS concentration in the reservoir should follow a seasonal trend as it is related to daily inflow from the three rivers. The simulated TSS does seem to follow a seasonal pattern. The effect of TSS on, for example, the simulation of dissolved phosphorus, is indicated in Figure 3.14e, a depth/time graph of dissolved phosphorus simulations, with and without TSS.

When simulations, using the surrogate TSS data thus generated, were compared with the TSS/TSM based data set, there was no significant improvement in correlation between observed and simulated temperatures (*cf.* Figure 3.11a and 3.14a). The simulation of the mixed layer depth improved slightly (*cf.* Fig 3.11b and 3.14b). The simulated concentrations of both available phosphorus and chlorophyll-a still deviated significantly from the observed concentrations in trend and value, but the optimum values of all the calibration coefficients had not yet been ascertained.

3.13.2 Calibration coefficients

In Section 3.11.2 it was stated that 24 calibration coefficients need to be estimated. Only a few of these could be estimated from literature on studies that had been done on Roodeplaat Dam, as listed in Table 3.5. The rest (marked with an * in the table), need to be determined from literature on algal growth and water quality modelling studies. The coefficients relating to algal growth (12 in number) are algal and climate specific. Many parts of South Africa have a subtropical climate, and the dominating algal species often is *Microsystis aureginosa*, which prefers higher water temperatures. However, most of the work to establish values for the calibration coefficients was done in the temperate climates of the northern hemisphere, where *Microsystis* appears to be one of the species of lesser importance. From the literature, values for 11 of the 12 required algal specific calibration coefficients could be obtained; very likely these values are not optimal, particularly those relating to temperature and light, as some of these had to be determined by extrapolation for the temperature range in South Africa. In Appendix 3.2 algal and climate specific values for the calibration coefficients for a number of algal species common in water quality modelling, are listed, as well as the literature sources from which these values were derived.

3.13.3 Coding errors

While the calibration coefficients were being investigated, it was noted that daily calculation of **astronomical day length** was hardwired in the MINLAKE source code. The formulation is not in terms of northern or southern latitude, but derived values for Lake Riley are inserted as constants, consequently the formulation does not apply elsewhere. The astronomical day length is an important parameter in calculating algal growth and an error in its formulation could lead to significant error in the simulation of algal concentration.

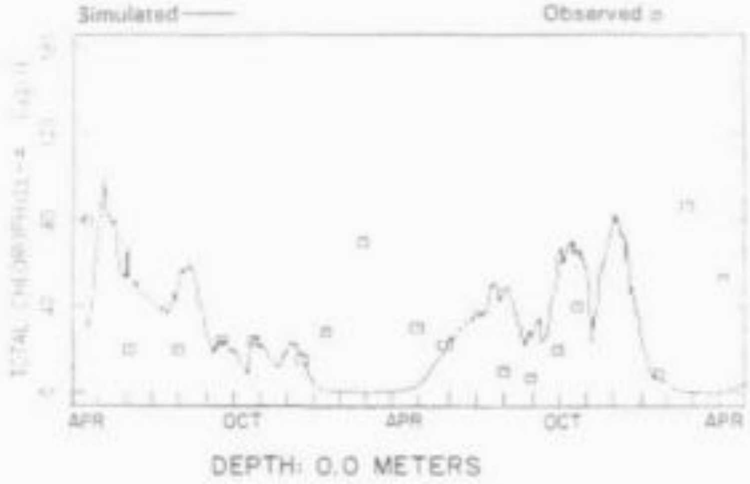
Accordingly, as an interim measure, the constants were adjusted to give the astronomical day length for the southern latitude of Roodeplaat Dam. (This formulation needs to be generalised for any latitude, north or south).

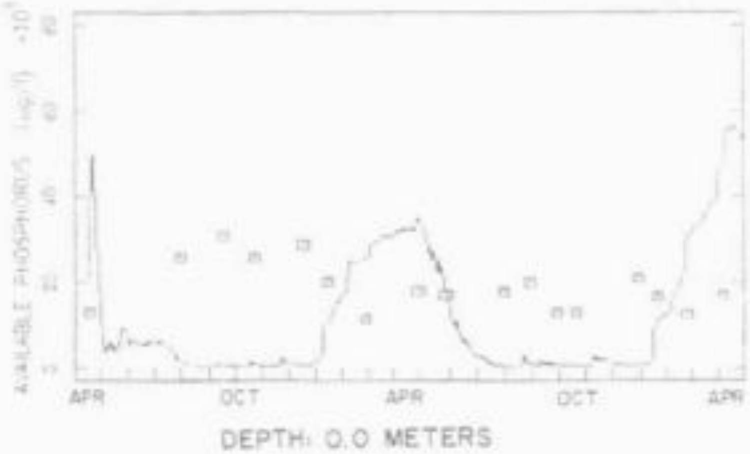
It was also discovered that the symbol for astronomical day length was coded, in error, for the symbol for dew point temperature in the expression to calculate daily vapour pressure of the air. This could affect the temperature simulation.

Also, in the expression relating algal growth rate with temperature, the minimum temperature below which algal growth would not occur, was hardwired as 0 °C. In South Africa, however, the minimum temperature below which algal growth does not occur, appears to be approximately 10 to 12 °C. We reformulated the formulation containing the hardwired value so that the appropriate minimum temperature can now be specified by the user.

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ ZERO TSS

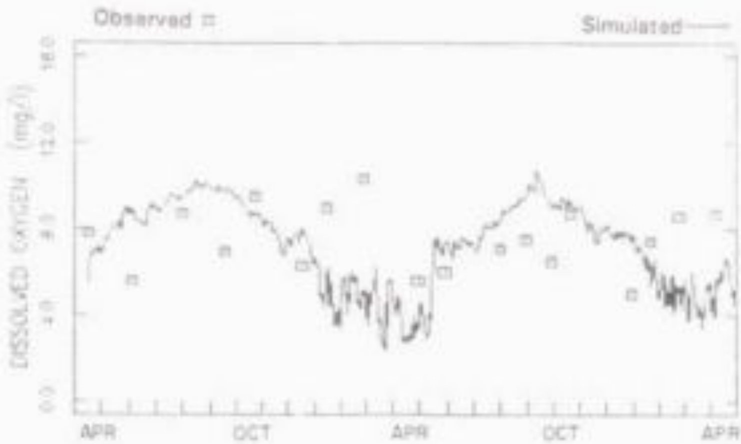




NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with zero TSS concentration in the inflow.	FIGURE 3.13a

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ ZERO TSS



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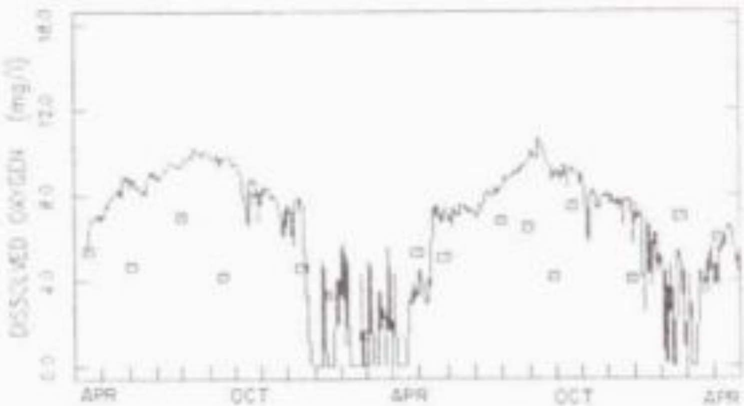
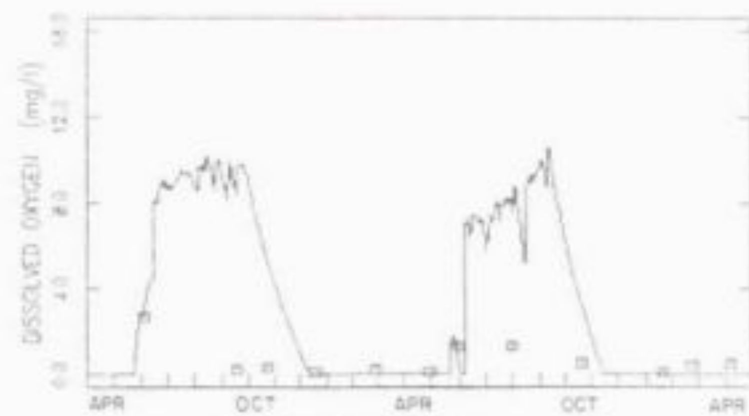


DEPTH: 5 METERS

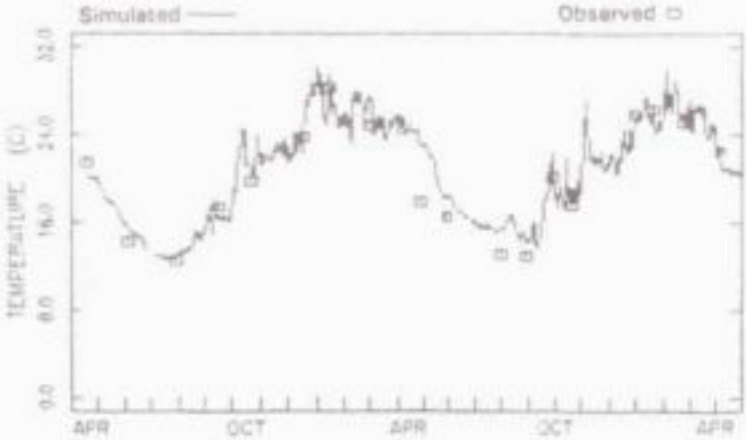


DEPTH: 20 METERS

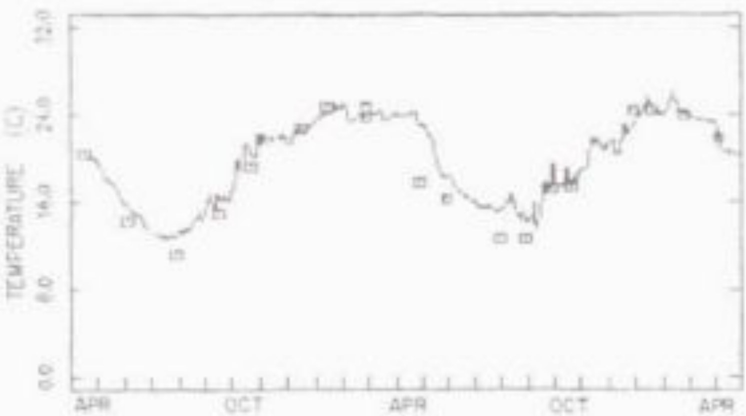
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with zero TSS concentration in the inflow.	FIGURE 3.13b

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

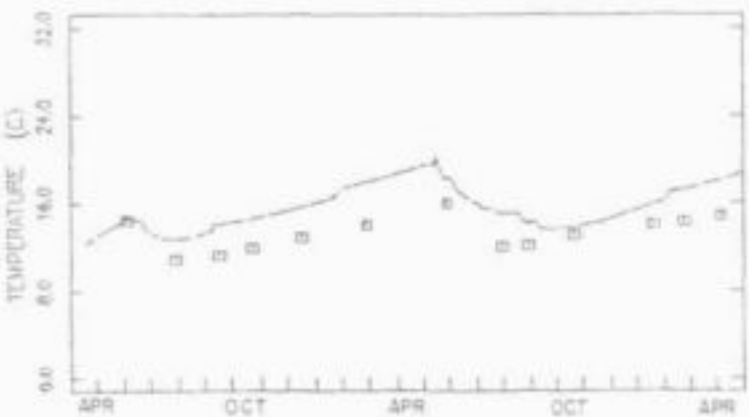
CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ SYNTHESIZED TSS



DEPTH: 0.0 METERS



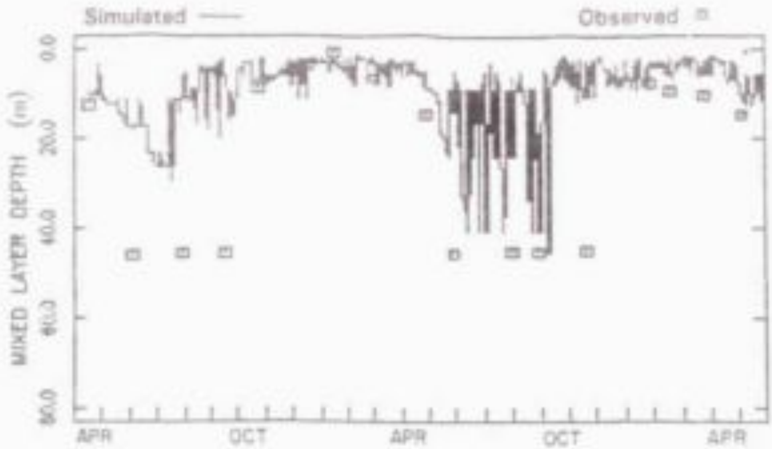
DEPTH: 5 METERS



DEPTH: 20 METERS

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed temperature obtained with synthezised TSS concentration in the inflow.	FIGURE 3.14a

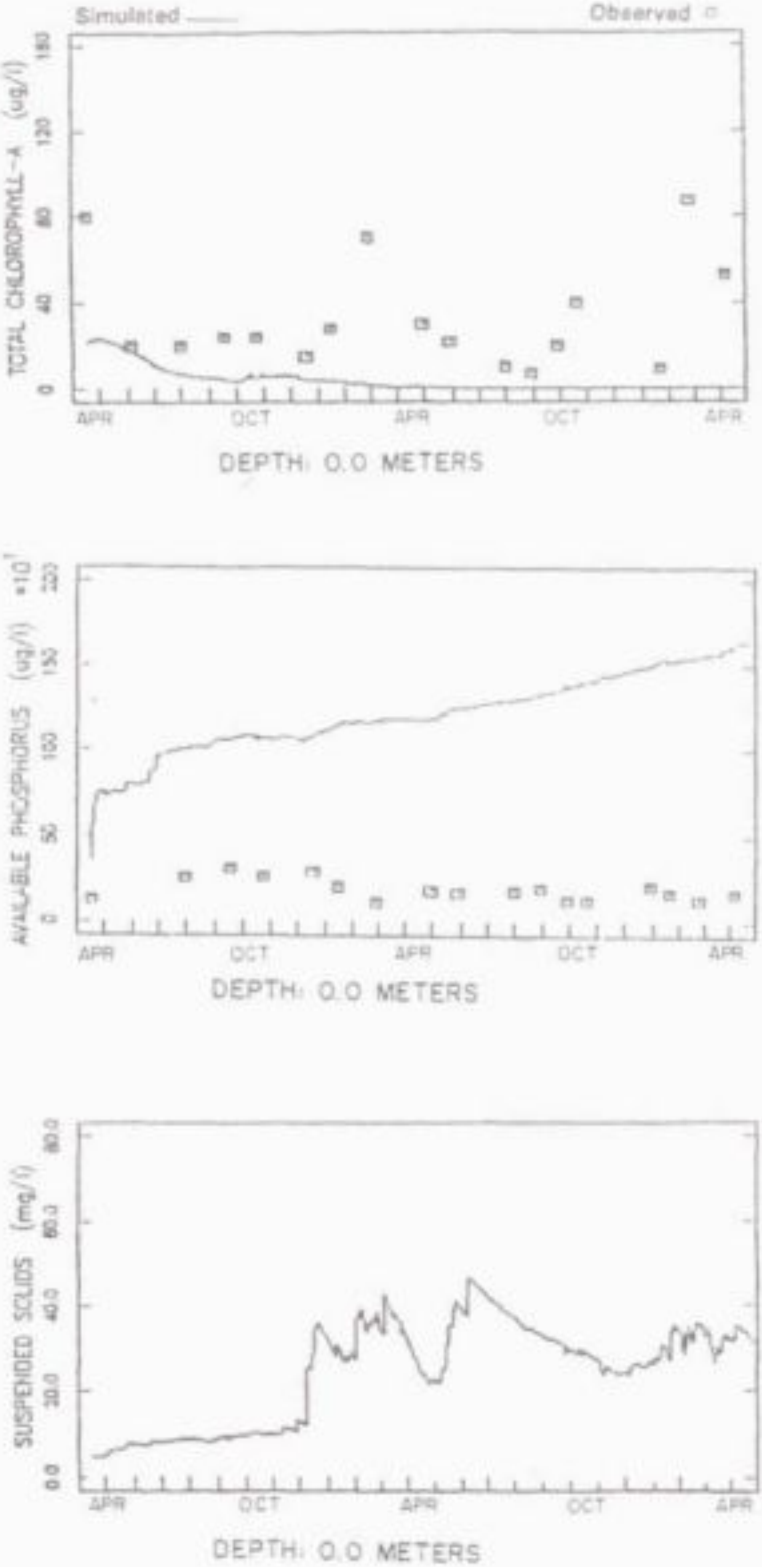
ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed mixed layer depth obtained with synthezised TSS	FIGURE 3.14b

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

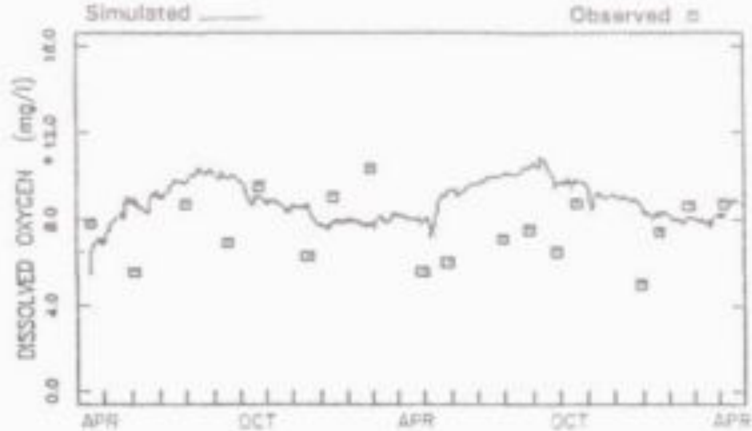
CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ SYNTHESIZED TSS



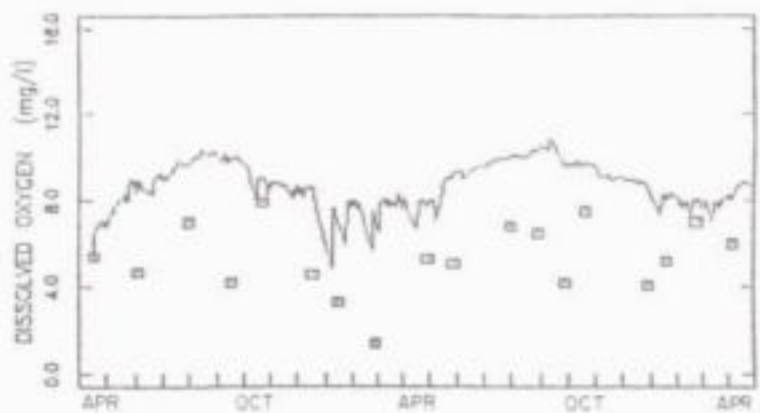
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with synthezised TSS in the inflow.	FIGURE 3.14c

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

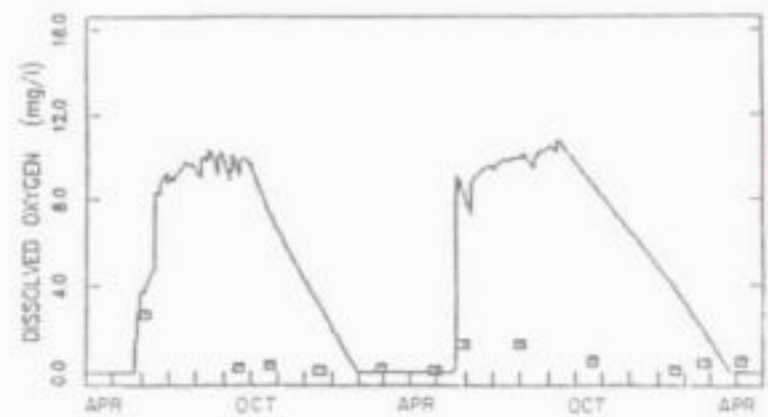
CONDITIONS : WINDSPEED AT 10m, EDDY COEFFICIENT = 1.73$m^2 d^{-1}$ SYNTHESIZED TSS



DEPTH: 0.0 METERS



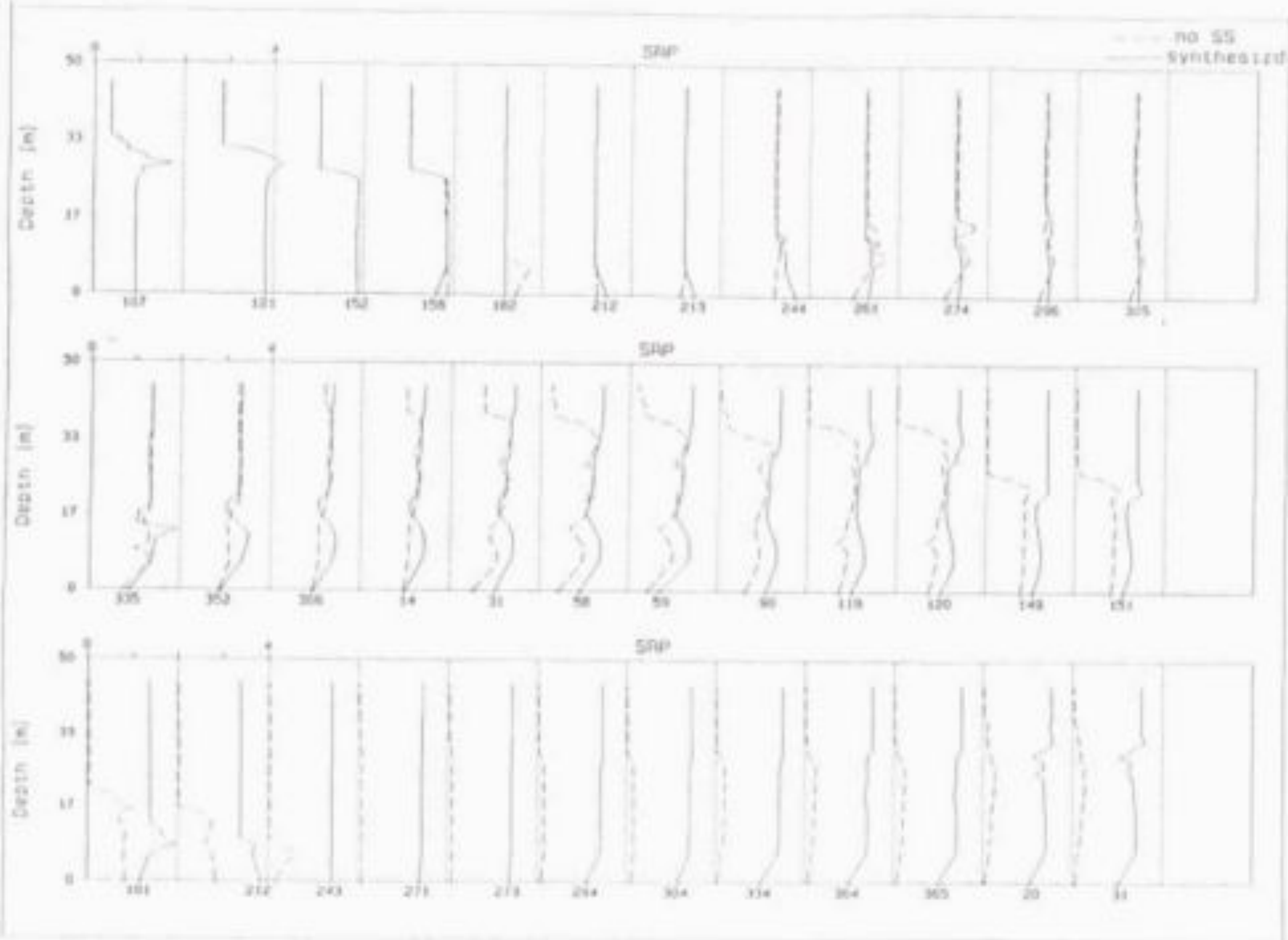
DEPTH: 5 METERS



DEPTH: 20 METERS

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with synthezised TSS in the inflow.	FIGURE 3.14d

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982



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WATER RESEARCH COMMISSION

Depth / time graph of simulated phosphorus concentrations with and without suspended sediment concentration

FIGURE 3.14e

3.14 LATEST SIMULATION RESULTS

The latest simulation results for the selected variables are shown in Figures 3.15a to 3.15f. These results were obtained with:

- coding errors that have been identified, corrected in the source code.
- input wind speed adapted to that at 10 m (as required by the model).
- TSS data synthesised as discussed in Section 3.11.
- calibration coefficients as indicated in Appendix 3.2.
- the rest of the input data as used previously.

3.14.1 Hydrodynamic simulation results

The simulated and observed temperatures (Figures 3.15a and 3.15b) show excellent correspondence at the surface, and at 5 m and 20 m. The temperature simulation can be regarded as very satisfactory.

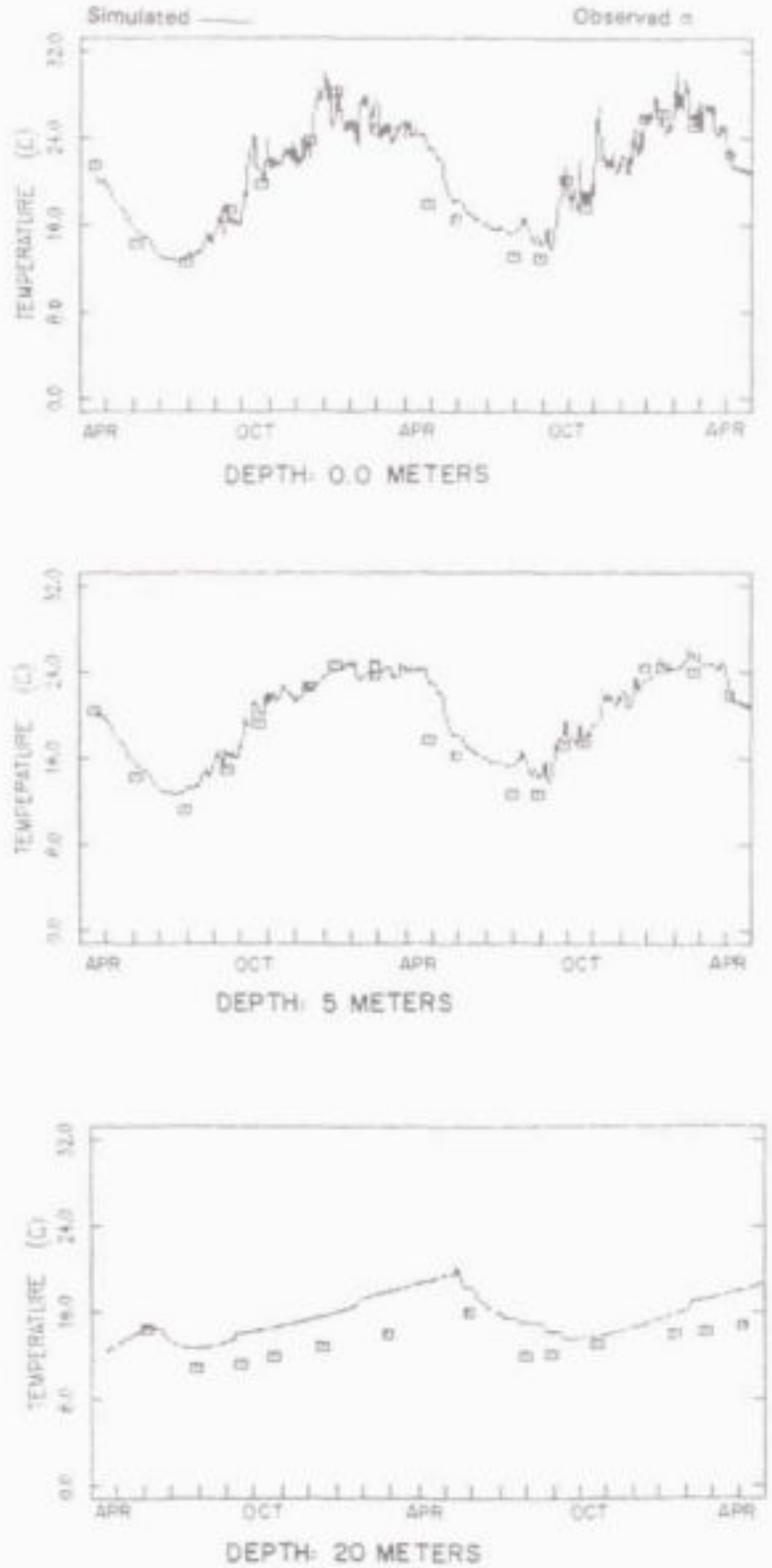
Some discrepancy still exists between the simulated and observed mixed layer depth. First indications are that this may be linked to the TSS concentration. It is difficult to assess the TSS simulation as there is no observed TSS data. However, in Figures 3.15b and 3.15d it can be seen that, during the period where mixed layer depth is inadequately simulated, the simulated TSS concentration is lower than during the rest of the simulation period. This aspect will need further study, the synthesised TSS concentration may have to be re-evaluated.

3.14.2 Water quality simulation results

For the purposes of calibration, the developers of MINLAKE suggest that the simulation of hypolimnetic phosphorus needs to be acceptable before dissolved phosphate/algal growth in the photic zone can be resolved. However, for Roodeplaat Dam, dissolved phosphate

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3. CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m^2 d^{-1} SYNTHESIZED TSS



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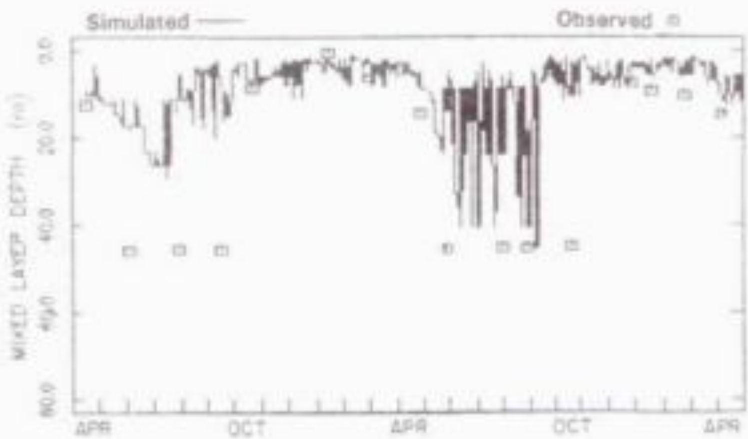
WATER RESEARCH COMMISSION

Plot of simulated vs. observed temperature obtained with corrected model

FIGURE 3.15a

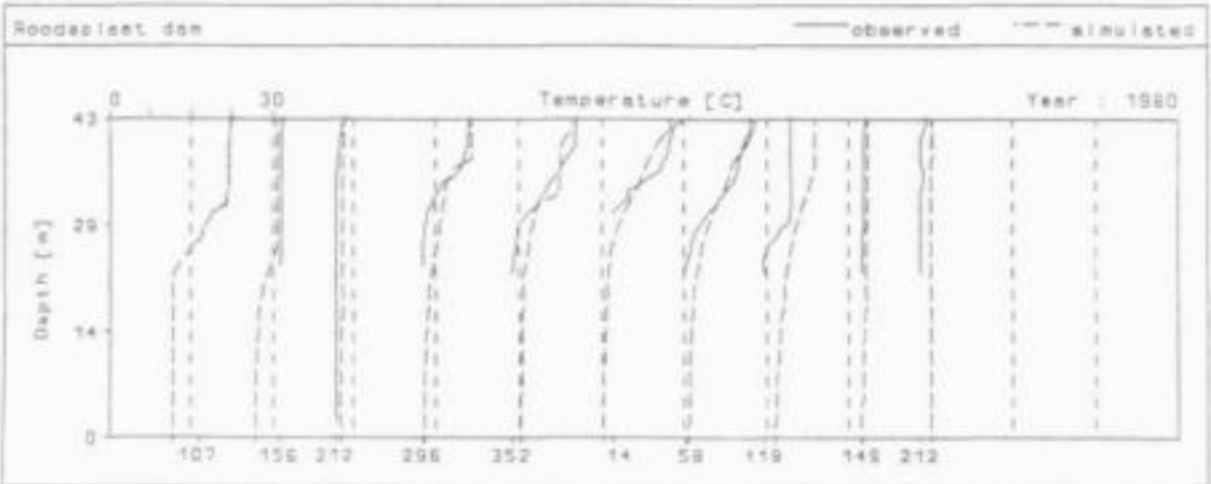
ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3.CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ SYNTHESIZED TSS



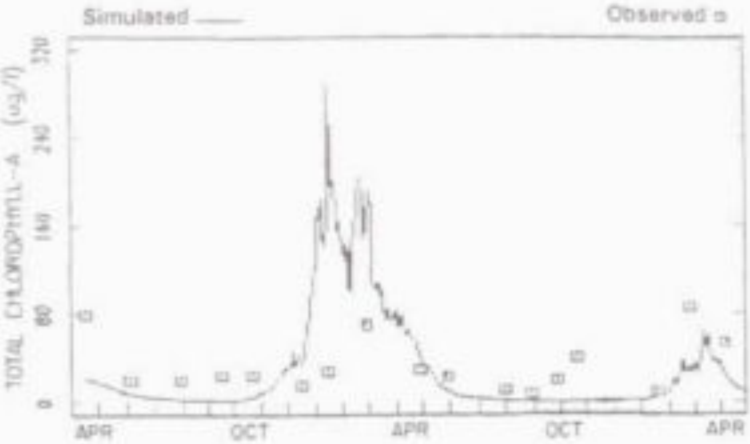
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed mixed layer depth obtained with corrected model.	FIGURE 3.15b

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

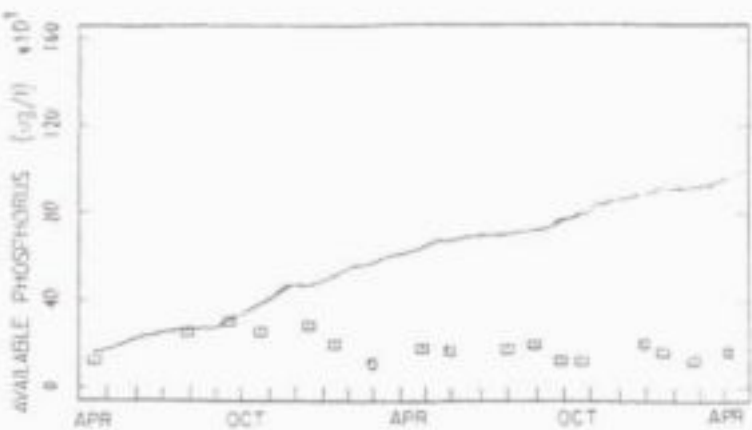


ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

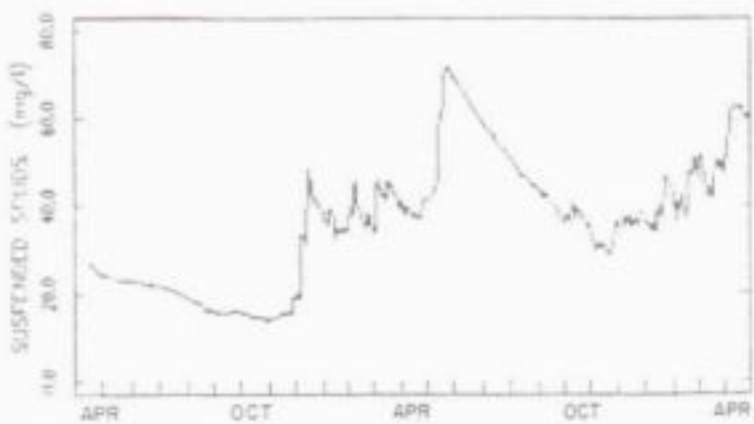
CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3. CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73$m^2 d^{-1}$ SYNTHESIZED TSS



DEPTH: 0.0 METERS



DEPTH: 0.0 METERS

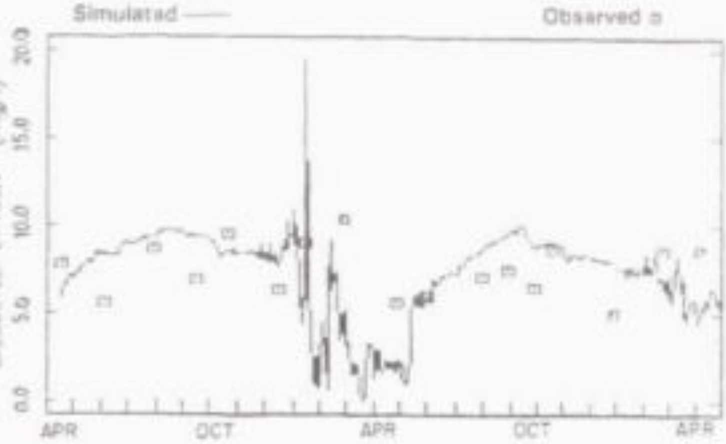


DEPTH: 0.0 METERS

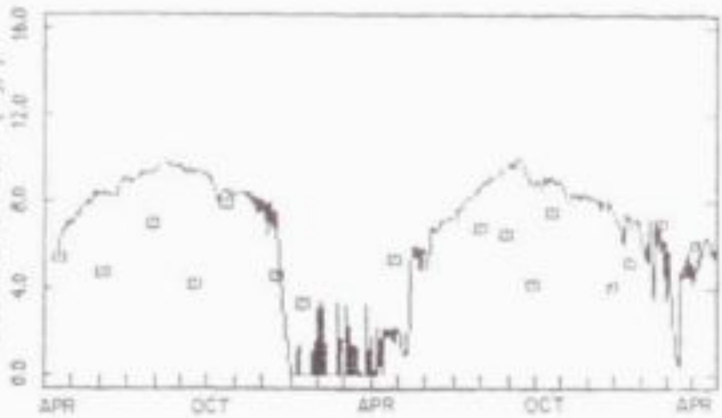
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with corrected model.	FIGURE 3.15d

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

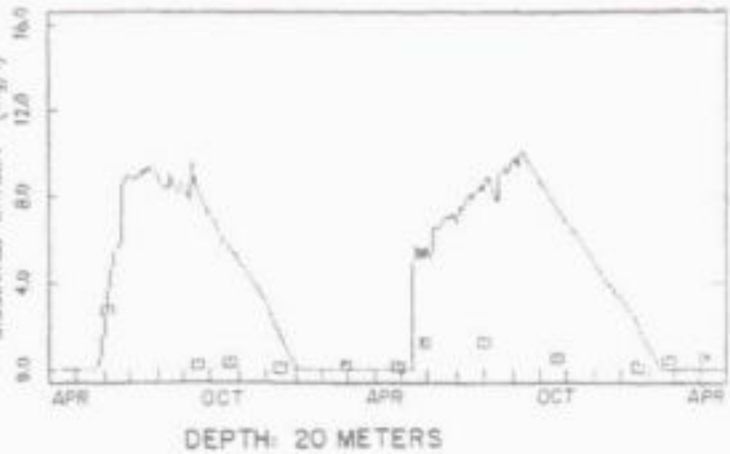
CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3 CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73$m^2 d^{-1}$ SYNTHESIZED TSS



DEPTH: 0.0 METERS



DEPTH: 5 METERS

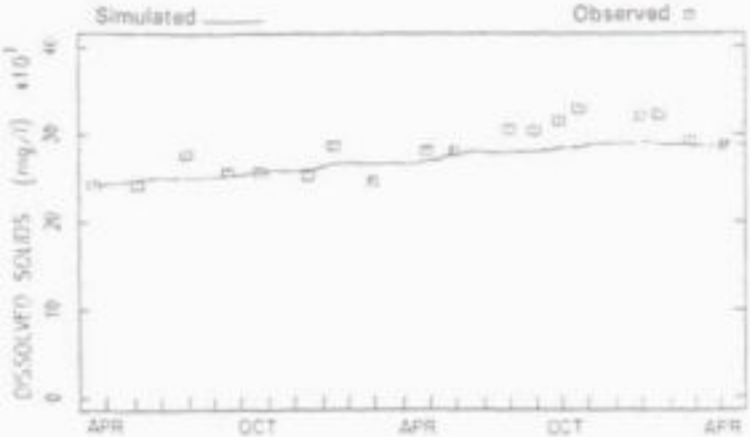


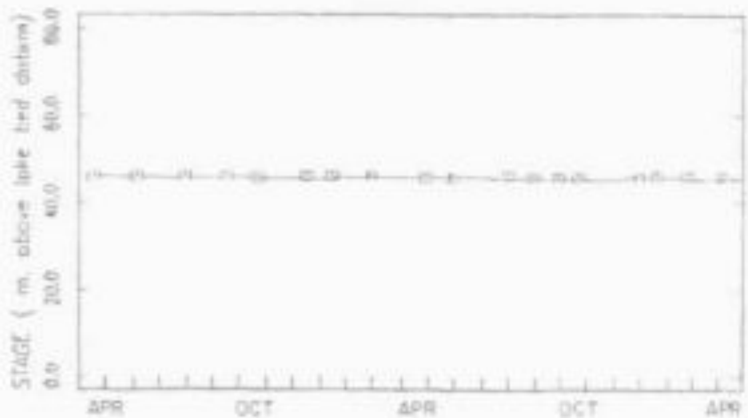
DEPTH: 20 METERS

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with corrected model.	FIGURE 3.15e

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3 CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ SYNTHESIZED TSS





NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with corrected model.	FIGURE 3.15 F

concentration was only occasionally measured in the hypolimnion, and then not always at the same depth, so that it is not always possible to test the model performance in the hypolimnetic zone.

Regarding the surface simulation of chlorophyll-a and dissolved phosphate concentrations, it still deviates significantly from the observed values. Regarding the simulation of dissolved oxygen (Figure 3.15e), the simulation of algal growth has to be acceptable before attempting to improve the simulation of dissolved oxygen.

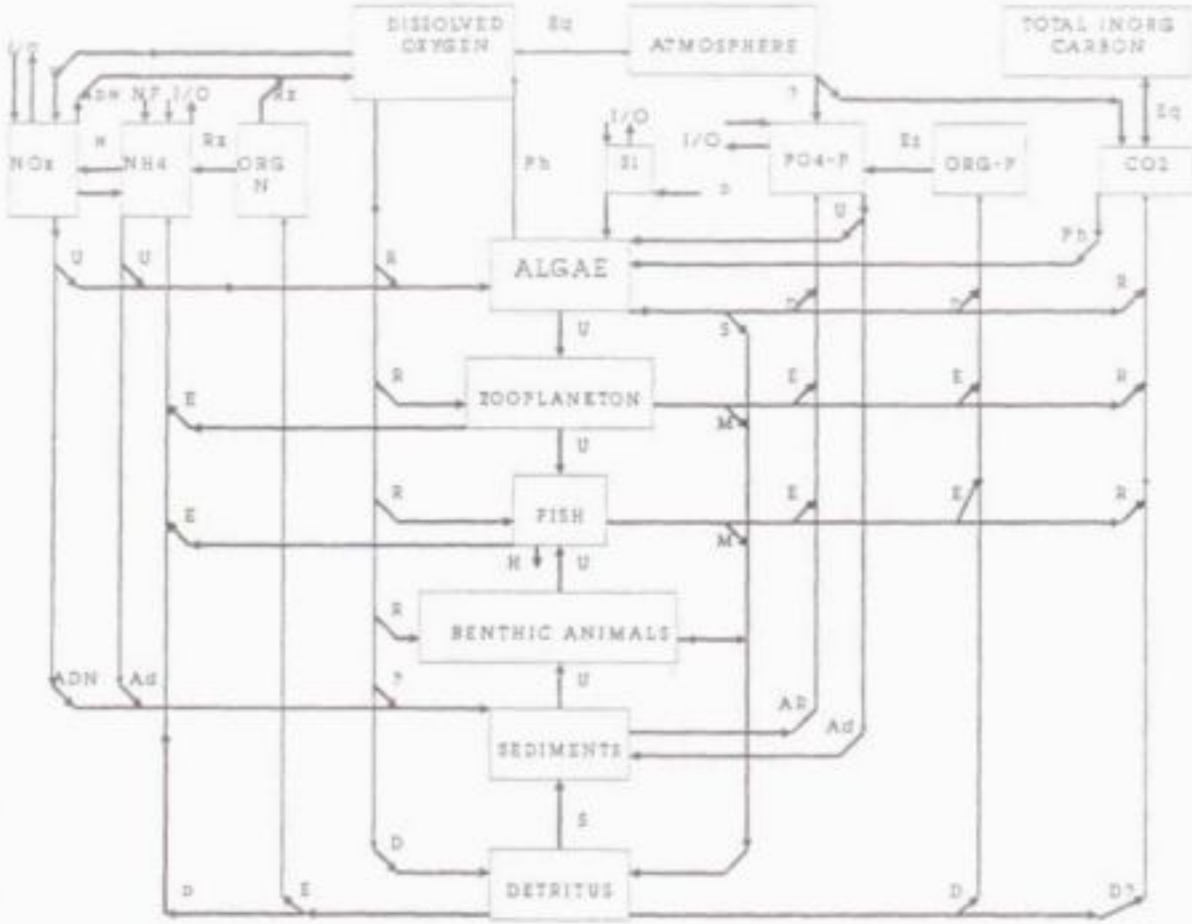
The excessive increase in **simulated** algal concentration during December 1980 cannot yet be explained. A thorough study of the data did not reveal any justification for the excessive increase. There remains the possibility that algal growth may be nitrogen limited. Thus far, only phosphorus limited growth has been simulated. MINLAKE does make provision for the simulation of nitrogen limited growth. However, due to time constraints, this aspect has not yet been investigated.

There is a steady increase in simulated phosphorus concentration and even at the end of the two year simulation period, steady state conditions are not achieved. This may be because, in MINLAKE, the suspended and bottom sediment/phosphorus interactions are poorly developed. For example, phosphorus release from the bottom sediments is described by an empirical constant unrelated to temperature and the aerobic/anoxic state of the overlying water, very likely an inadequate representation. A literature study to obtain more insight into these processes and their temperature effect will be required before further simulations of the phosphorus/algal response can be attempted.

3.15 PROCESS FORMULATION

Usually, the primary water quality processes that occur in a reservoir are depicted in a diagram similar to the one in Figure 16(a). However, this diagram does not give any information as to the stoichiometric relationship between compounds, or the kinetic rates of the different processes. A task group of the International Association on Water Pollution and Control has recently proposed a matrix method for presenting the processes and the compounds on which they act in biological systems (Henze, 1987). The processes are listed in the first column of the matrix, while the compounds are listed in the first row. The intersect cell defines the stoichiometric relationship and the kinetics of the associated process are listed in the last column.

To illustrate this approach, a part of such a matrix, showing three of the processes that affect phosphorus concentration in MINLAKE, is depicted in Figure 16b. The matrix forms an easily comprehended fingerprint of the processes, their interactive kinetics and stoichiometry. The matrix can be readily expanded to include additional processes and compounds and the system can be solved by a computerised calculation technique which remains the same irrespective of the size of the matrix. This approach can be applied to the water quality processes in reservoirs with advantage.



Ad	Adsorption
ADN	Anaerobic denitrification
AR	Aerobic release
D	Bacterial decay
DN	Denitrification
E	Excretion
Eq	Equilibrium
Ez	Enzymatic reaction
H	Harvesting
I/O	Inflow and outflow
M	Mortality
N	Nitrification
NF	Nitrogen fixation
Ph	Photosynthesis
R	Respiration
Rx	Chemical reduction
S	Settling
U	Nutrient uptake

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Diagram of primary water quality processes

FIGURE 3.16a

	Dissolved PO4-P ($PO4_D$)	Particulate (stored) P (P_s)	PO4-P adsorbed ($PO4_A$)	
Phosphate adsorption	-1		+1	$PO_A = k\ PO_D^{1/n}$
Phosphate uptake	-1	+1		$U = U_{max} \frac{Q_m - P_s}{Q_m - K_Q} \cdot \frac{PO_D}{K_s + PO_D}$
Photosynthesis		-1		$\mu = \mu_{max} \frac{P_s - K_Q}{P_s}$

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Matrix representation of primary water quality processes	FIGURE 3.16b

3.16 SENSITIVITY ANALYSIS

A full statistical sensitivity analysis has not been done due to time constraints. However, in calibrating MINLAKE it was observed that:

MINLAKE is extremely sensitive to:

- wind speed
- sediment phosphorus release rate
- hypolimnetic eddy diffusion
- maximum growth rate
- non-predatory mortality
- minimum intracellular phosphorus concentration

MINLAKE is not very sensitive to:

- changes in solar radiation
- wind direction/fetch - a behaviour possibly applicable only to small and medium size reservoirs
- effect of temperature on algal growth

3.17 CONCLUSIONS: APPLICATION OF MINLAKE

3.17.1 Hydrodynamic behaviour

The hydrodynamic aspects, as represented in MINLAKE, are relatively straight forward and have a well founded basis in theory. The hydrodynamic behaviour of Roodeplaat Dam can be adequately simulated with the MINLAKE model. Very likely this model should be adequate for simulating the hydrodynamic behaviour of other reservoirs in South Africa of similar or smaller size, provided that acceptable hydrometeorlogical databases are available.

3.17.2 Water quality behaviour

MINLAKE appears to have considerable potential for the simulation of water quality behaviour. In particular, it allows for simulation of:

* growth of up to three algal classes
* both phosphorus and nitrogen limited growth
* light limited algal growth
* effect of temperature on algal growth
* zooplankton growth

The degree in which adequate simulation of the water quality behaviour will be achieved is not yet clear, for the following reasons:

* There is not yet certainty that the water quality processes included in the model are adequately formulated; this aspect will require intensive and extensive study.

* Phosphorus-sediment interaction is not included in the model, an interaction which has been mooted to be of significant importance in South African reservoirs (DWAF, 1981) - MINLAKE incorporates only a sediment phosphorus release coefficient which has to be set empirically by the user.

3.17.3 MINLAKE software

The MINLAKE software is reasonably user-friendly and easy to use:

- The program is structured in two parts: The main program, incorporating 40 clearly defined subroutines and a reservoir specific program. This structure facilitates changes to the program, and decreases compilation time.

- The MINLAKE program is compiled using a Microsoft (Version 3.31 or higher) compiler. This compiler is readily available in South Africa.

- Debugging of data files is facilitated considerably by the use of the data listing files provided with the MINLAKE program.

The following deficiencies have been identified:

- there are coding errors in the main program.

- tracking of errors in the main program is complicated because all the common block variables are not listed in the manual; and variables are often renamed in the program, without this being indicated.

- some formulations are hardwired into the main program, eg. astronomical day length is formulated for a single northern latitude, without indicating that the formulation does not apply to other latitudes.

3.18 RECOMMENDATIONS

3.18.1 MINLAKE

The following modifications are required in the MINLAKE model:

- Sediment-phosphorus interaction, which may be very important under South African conditions, should be incorporated into the model.

- Simulation of pH should be included.

- In the source code, the units of all the input variables and constants should be converted to SI units to facilitate the use of MINLAKE for users outside the USA.

- The complex interactions between the various processes governing the hydrodynamic/water quality response are often difficult to comprehend. These can be depicted more clearly by a matrix representation of processes, compounds and their kinetic formulations. The processes in MINLAKE should be restructured in such a matrix. This approach may find application in all water quality models.

The following need further investigation:

- Nitrogen limited algal growth should be taken into account; up to the present only phosphorus limited growth has been considered, but the model response indicates that nitrogen limitation may be present.

- Optimum values for the algal specific calibration coefficients under South African conditions, should be determined.

- The model performance should be tested under reduced data input, such as smoothed weekly, monthly or even cyclic seasonal values for certain input variables, with the effect of perturbations (storm events) on the reservoir superimposed at different parts of the hydrological cycle.

  Such a study could assist in:

  a) identifying variables of significant/insignificant importance.
  b) establishing whether certain input variables could to be measured on a daily, monthly, or cyclic seasonal basis, and still satisfy the requirements of the model.
  c) establishing whether site specific data are essential, or whether regional data will suffice for certain variables.
  d) providing information on operational strategy when storm events occur at different periods during the annual cycle.

3.18.2 Data

A shortlist of reservoirs should be compiled where hydrodynamic or hydrodynamic water quality models are likely to be applied; and a monitoring strategy should be devised for these reservoirs. In such a strategy, particular attention should be accorded to the following:

- Wind speed - this is one of the most important driving forces in applications where simulation of the vertical distribution of substances is important. Such simulations are possible only with models having a spatial dimension of one or greater.

- Hypolimnetic sampling - integrated or grab samples of selected water quality variables should be taken at selected depths down to the bottom of the reservoir, at regular intervals. Measurements down the profile should always be at the same set of depths. Sampling intervals can range from monthly to quarterly.

* Inorganic suspended sediment should be measured routinely in these reservoirs, and in the rivers associated with them. A number of determinations of sediment composition/fall velocity, under stratified as well as fully mixed conditions, should also be undertaken for the sediments in each of the reservoirs.

* At present, the data required for modelling have to be obtained from various institutions. Although different models incorporate different sets of variables, in different formats, the basic input data requirements tend to be the same. The establishment of a 'modelling data bank' at an appropriate institution, linked to the Computing Centre for Water Research (CCWR), from where modellers can obtain data for various reservoirs, is proposed.

3.19 REFERENCES

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APPENDIX A3.1

INFLOW AND METEOROLOGICAL DATA AVAILABLE FOR ROODEPLAAT DAM

THE AVAILABILITY OF METEOROLOGICAL DATA
FOR ROODEPLAAT DAM 1980-1983

MONTH	TEMP °C	DEWPOINT °C	PRECIP mm	WIND km/h	DIR	%SUN	RAD Various
1980 1	**	**	**	**	**	**	**
2	**	**	**	**	**	**	**
3	**	**	**	**	**	**	**
4	**	**	**	**	**	**	**
5	**	**	**	6	7	**	**
6	**	**	**	**	**	**	**
7	**	**	**	**	**	**	**
8	**	**	**	**	**	**	**
9	**	**	**	**	**	**	**
10	**	**	**	**	**	**	**
11	**	**	**	**	8	**	**
12	**	**	**	**	3	**	**
1981 1	**	**	**	4	18	**	**
2	**	**	**	**	11	**	**
3	**	**	**	**	**	**	**
4	**	**	**	**	**	**	**
5	**	**	**	**	**	**	**
6	**	**	**	**	**	**	12
7	**	**	**	**	**	**	**
8	**	**	**	3	3	5	**
9	**	**	**	**	3	**	**
10	**	**	**	**	**	**	**
11	**	**	**	**	**	**	**
12	**	**	**	**	**	**	**

MONTH	TEMP	DEWPOINT	PRECIP	WIND SPEED	DIR	%SUN	RAD
1982 1	**	**	**	**	**	**	**
2	**	**	**	**	**	**	**
3	**	**	**	6	**	3	**
4	**	**	**	9	9	**	**
5	**	**	**	**	4	**	**
6	**	**	**	**	**	**	**
7	**	**	**	**	**	**	**
8	**	**	**	**	**	**	**
9	**	**	**	**	**	**	**
10	**	**	**	4	**	**	**
11	**	**	**	7	6	**	**
12	**	**	**	8	6	**	**
1983 1	**	**	**	**	**	**	**
2	**	**	**	**	**	**	**
3	**	**	**	**	**	**	**
4	**	**	**	**	**	**	**
5	**	**	**	**	**	**	**
6	**	**	**	**	**	**	**
7	**	**	**	**	**	**	**
8	**	**	**	3	3	3	**
9	**	**	**	**	**	13	**
10	**	**	**	**	**	3	**

** : Data is available

Number : Number of days of missing data (three or more consecutive days)

AVAILABILITY OF INFLOW DATA FOR PIENAARS RIVER

MONTH	FLOW m^3/s	TEMP °C	PO4 mg/l	BOD	TSS mg/l	TDS mg/l	NO3 mg/l	NH4 mg/l	CHLa mg/l
1980 1	**	31	4			4	4	4	
2	**	29	**			**	**	**	
3	**	31	**			**	**	**	
4	**	30	**			**	**	**	
5	**	31	10			10	10	10	
6	**	30	19			19	19	19	
7	**	12	14			14	14	14	
8	**	**	18			18	18	18	
9	**	**	**			**	**	**	
10	**	**	**			**	**	**	
11	**	**	**			**	**	**	
12	**	**	6			6	6	6	
1981 1	**	**	**			**	**	**	
2	**	**	**			**	**	**	
3	**	3	8			8	8	8	
4	**	**	**			**	**	**	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	**	**			**	**	**	
9	**	**	18			18	18	18	
10	**	**	**			**	**	**	
11	**	**	29			29	29	29	
12	**	**	9			9	9	9	

MONTH	FLOW	TEMP	PO4	BOD	TSS	TDS	NO3	NH4	CHLa
1982 1	**	**	**			**	**	**	
2	**	**	**			**	**	**	
3	**	**	**			**	**	**	
4	**	**	**			**	**	**	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	4	**			**	**	**	
9	**	**	**			**	**	**	
10	**	**	20			20	20	20	
11	**	**	23			23	23	23	
12	**	**	3			3	3	3	
1983 1	**	**	16			16	16	16	
2	**	5	9			9	9	9	
3	**	**	**			**	**	**	
4	**	**	4			4	4	4	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	**	**			**	**	**	
9	**	3	3			3	3	3	
10	**	**	**			**	**	**	
11	**	**	**			**	**	**	
12	**	**	**			**	**	**	

** : Data is available

NUMBER : Number of days of missing data (three or more consecutive days)

BLANK : The variable was not monitored

AVAILABILITY OF INFLOW DATA FOR HARTBEESSPRUIT

MONTH	FLOW m^3/s	TEMP °C	PO4 mg/l	BOD	TSS mg/l	TDS mg/l	NO3 mg/l	NH4 mg/l	CHLa mg/l
1980 1	**	31	4			4	4	4	
2	**	29	**			**	**	**	
3	**	31	**			**	**	**	
4	**	30	**			**	**	**	
5	**	31	5			5	5	5	
6	**	30	19			19	19	19	
7	**	12	14			14	14	14	
8	**	**	18			18	18	18	
9	**	**	**			**	**	**	
10	**	**	5			5	5	5	
11	**	**	**			**	**	**	
12	**	**	5			5	5	5	
1981 1	**	**	**			**	**	**	
2	**	**	5			5	5	5	
3	**	3	8			8	8	8	
4	**	**	**			**	**	**	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	**	**			**	**	**	
9	**	**	20			20	20	20	
10	**	**	**			**	**	**	
11	**	12	29			29	29	29	
12	**	**	9			9	9	9	

MONTH	FLOW	TEMP	PO4	BOD	TSS	TDS	NO3	NH4	CHLa
1982 1	**	**	**			**	**	**	
2	**	**	**			**	**	**	
3	**	**	**			**	**	**	
4	**	**	4			4	4	4	
5	**	**	3			3	3	3	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	4	**			**	**	**	
9	**	11	10			10	10	10	
10	**	10	29			29	29	29	
11	**	**	23			23	23	23	
12	**	**	3			3	3	3	
1983 1	**	**	27			27	27	27	
2	**	7	10			10	10	10	
3	**	20	20			20	20	20	
4	**	18	17			17	17	17	
5	**	27	20			20	20	20	
6	**	14	17			17	17	17	
7	**	14	14			14	14	14	
8	**	15	15			15	15	15	
9	**	25	26			26	26	26	
10	**	**	10			10	10	10	
11	**	**	**			**	**	**	
12	**	**	3			3	3	3	

** : Data is available

NUMBER : Number of days of missing data (three or more consecutive days)

BLANK : The variable was not monitored

AVAILABILITY OF INFLOW DATA FOR EDENDALESPRUIT

MONTH	FLOW cfs	TEMP °C	PO4 mg/l	BOD	TSS mg/l	TDS mg/l	NO3 mg/l	NH4 mg/l	CHLa mg/l
1980 1	**	31	4			4	4	4	
2	**	29	**			**	**	**	
3	**	31	**			**	**	**	
4	**	30	**			**	**	**	
5	**	31	6			6	6	6	
6	**	30	19			19	19	19	
7	**	12	14			14	14	14	
8	**	**	18			18	18	18	
9	**	**	**			**	**	**	
10	**	**	**			**	**	**	
11	**	**	**			**	**	**	
12	**	**	9			9	9	9	
1981 1	**	**	**			**	**	**	
2	**	**	5			5	5	5	
3	**	3	6			6	6	6	
4	**	**	**			**	**	**	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	**	**			**	**	**	
9	**	**	20			20	20	20	
10	**	**	**			**	**	**	
11	**	6	29			29	29	29	
12	**	9	9			9	9	9	

MONTH	FLOW	TEMP	PO4	BOD	TSS	TDS	NO3	NH4	CHLa
1982 1	**	**	**			**	**	**	
2	**	8	8			8	8	8	
3	**	25	25			25	25	25	
4	**	30	30			30	30	30	
5	**	31	31			31	31	31	
6	**	30	30			30	30	30	
7	**	27	27			27	27	27	
8	**	4	**			**	**	**	
9	**	**	**			**	**	**	
10	**	27	29			29	29	29	
11	**	30	30			30	30	30	
12	**	31	31			31	31	31	
1983 1	**	24	29			29	29	29	
2	**	28	28			28	28	28	
3	**	31	31			31	31	31	
4	**	30	30			30	30	30	
5	**	31	31			31	31	31	
6	**	30	30			30	30	30	
7	**	31	31			31	31	31	
8	**	31	31			31	31	31	
9	**	30	30			30	30	30	
10	**	31	31			31	31	31	
11	**	8	9			9	9	9	
12	**	**	**			**	**	**	

** : The data is available

NUMBER : The number of days of missing data (three or more consecutive days)

BLANK : The variable was not monitored

APPENDIX A3.2

ALGAL AND CLIMATE SPECIFIC CALIBRATION COEFFICIENTS FOR ALGAL SPECIES COMMON IN WATER QUALITY MODELLING IN SOUTH AFRICA

ALGAL AND CLIMATE SPECIFIC CALIBRATION COEFFICIENTS FOR ALGAL SPECIES COMMON IN WATER QUALITY MODELLING IN SOUTH AFRICA

* Value used to obtain latest MINLAKE simulation results (Section 3.14)

CALIBRATION COEFFICIENT	UNITS	VALUE	REFERENCE
Extinction coefficient of water	m^{-1}	0.55 to 1.99*	Pieterse (1990)
Specific extinction coefficient of phytoplankton	$m^2\ g^{-1}$ Chla	12*	FRD (1985)
Wind function coefficient		25.6*	MINLAKE (1988)
Wind sheltering coefficient		0.95*	MINLAKE (1988)
Sediment oxygen depletion rate	$g\ m^2\ day^{-1}$	1.0*	MINLAKE (1988)
Sediment phosphorus release coefficient	$g\ m^2\ day^{-1}$	0.001*	DWAF (1981)
Detrital decay rate	day^{-1}	0.07*	MINLAKE (1988)
Detrital settling rate	$m\ day^{-1}$	0.05*	Orlob (1983) Canale (1976)
Algal respiration rate	day^{-1}	0.03 0.08*	Orlob (1983) Canale (1976)
Algal mortality rate	day^{-1}	0.003 to 0.17 0.07*	EPA (1985)
Algal settling rate:	$m\ day^{-1}$		
Blue-green algae		0.002* 0.0	Orlob (1983) Canale (1976)
Green algae		0.02 0.02	Orlob (1983) Canale (1976)
Diatoms		0.03	Canale (1976)

CALIBRATION COEFFICIENT	UNITS	VALUE	REFERENCE
Maximum phosphorus uptake rate:	day^{-1}		
Blue-greens			
non N-fixing		0.0035	Orlob (1983)
N-fixing		0.042	Canale (1976)
Greens		0.059	"
Diatoms		0.133	"
Microsystis		0.024	"
		0.12	Bierman (1977)
Half saturation coefficient for phosphorus uptake	$mg\ l^{-1}$		
Microsystis		0.006	Bierman (1977)
			Canale (1976)
Blue-green		0.0025*	EPA (1985)
Greens		0.0025 to 0.47	
Minimum intracellular phosphorus concentration needed for growth:	moles P $cell^{-1}$		
Microsystis		$0.58*10^{-15}$	Bierman (1977)
Blue-greens (non N-fixing)		$0.58*10^{-15}$	Canale (1976)
Blue-greens (N-fixing)		$0.13*10^{-14}$	"
Greens		$0.2*10^{-14}$	"
Diatoms		$0.2*10^{-14}$	Orlob (1983)
		0.075 to 0.15	Reynolds (1984)
Blue-greens	mg P mg^{-1} Chla	0.34	

CALIBRATION COEFFICIENTS	UNITS	VALUE	REFERENCE
Maximum intracellular phosphorus storage capacity	mg P mg^{-1} Chla		
Blue-greens		1.0 to 1.5	Orlob (1983)
Phytoplankton mass per cell	mg dry weight cell^{-1}		
Microsystis		$0.25*10^{-7}$	Bierman (1977)
Maximum nitrogen uptake rate:	day^{-1}		
Blue-greens		0.0096	Orlob (1983)
Non N-fixing		0.04	Canale (1976)
N-fixing		0.04	"
Greens		0.06	"
Diatoms		0.015	"
Microsystis		0.072	Bierman (1977)
Half saturation coefficient for nitrogen uptake:	mg l^{-1}		
Blue-greens		0.015	Canale (1976)
Minimum intracellular nitrogen concentration needed for growth:	moles cell^{-1}		
Microsystis		$0.52*10^{-13}$	Bierman (1977)
Blue-greens			Canale (1976)
N-fixing		$0.52*10^{-13}$	
non-N-fixing		$0.85*10^{-13}$	
Greens		$0.52*10^{-13}$	
Diatoms		1.0 to 2.0	Orlob (1983)
		$0.52*10^{-13}$	

CALIBRATION COEFFICIENTS	UNITS	VALUE	REFERENCES
Maximum intracellular nitrogen to chlorophyll-a ratio: Blue-greens	mg N mg^{-1} Chla	4.0 to 5.0	Orlob (1983)
Half saturation coefficient for preferential uptake of ammonium over nitrate:	mg l^{-1}	<0.025	MINLAKE (1988)
Maximum nutrient saturated growth rate: Blue-greens Non N-fixing N-fixing	day^{-1}	1.6 1.1 1.1 1.9 1.6	Orlob (1983) Canale (1976) Canale (1976) Orlob (1983) Canale (1976)
Green algae		0.25 0.24	Bierman (1977) Reynolds (1984)
Microsystis Unicellular culture Colonial culture		1.11 0.48 0.25*	Reynolds (1984) Reynolds (1984)
Upper temperature at which algal growth is reduced 90% : Blue-greens	°C	45*	Orlob (1983)
Lower temperature at which growth is reduced 90 % : Microsystis	°C	15*	FRD (1985)

CALIBRATION COEFFICIENT	UNITS	VALUE	REFERENCE
Optimum temperature for algal growth:	°C		
Blue-greens		33	Orlob (1983)
Microsystis		35*	Bierman (1977)
Half saturation coefficient for light limited growth.	$\mu E\ m^{-2}\ s^{-1}$	250*	Megard (1984)
Light inhibition coefficient	$\mu E\ m^{-2}\ s^{-1}$	1900*	Megard (1984)

* Value used to obtain latest MINLAKE simulation results (Section 3.14).

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APPENDIX A3.3

DATABASE DEVELOPMENT FOR HARTBEESPOORT DAM

A3.1 RESERVOIR DESCRIPTION

Hartbeespoort Dam lies in a summer rainfall region with an average annual rainfall of about 700 mm. The reservoir is located 37 km West of Pretoria at the confluence of the Crocodile and Magalies Rivers. The Crocodile River is the principal source of water for the reservoir and is largely supplemented by treated effluent from the extensively urbanised areas in its upper catchment.

The point of inflow of the two rivers, the shape of the reservoir, the sampling point and wind measurement stations, are shown in Figure 3.17. Further characteristics of Hartbeespoort Dam are presented in Table A3.1. Area, volume, and maximum and mean depth is indicated for full supply level.

TABLE A3.1 : CHARACTERISTICS OF HARTBEESPOORT DAM

Area	2000 ha
Volume	194,6 x 10^6 m^6
Maximum depth	31,1 m
Mean depth	9,6 m
Height above sea level	1131,2 m
Annual inflow	234 x 10^6 m^3
Annual outflow	228 x 10^6 m^3

A3.2 DATABASE DEVELOPMENT

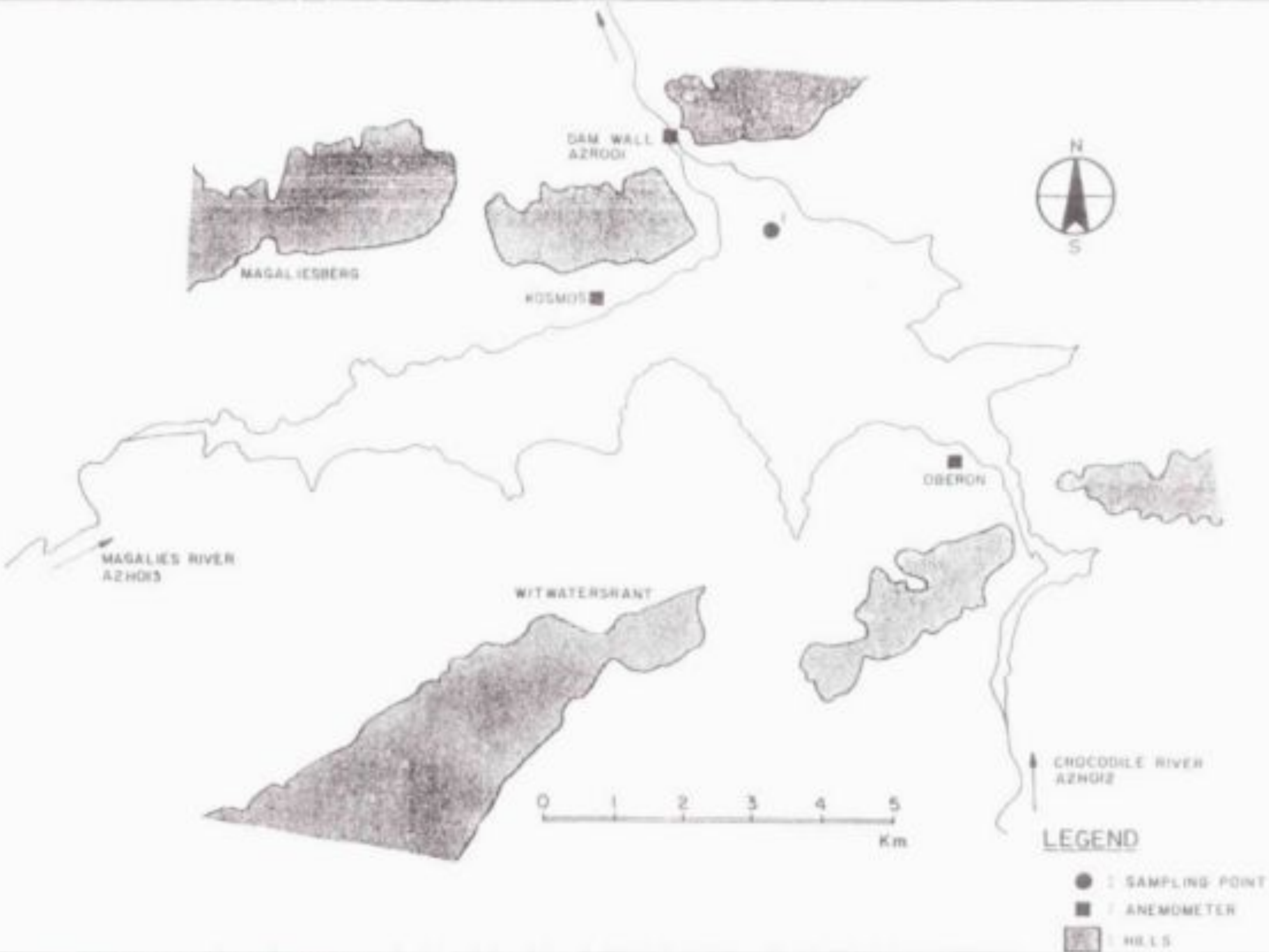
A3.2.1 Meteorological and inflow data

The various meteorological and inflow data sets were mostly obtained from the same institutions and in the same form as for Roodeplaat Dam (see Table 3.2). Additional data on wind speed and direction were obtained from the CSIR (Division of Water Technology).

Processing of meteorological and inflow data: From Table 3.2 it is evident that the required data had to be obtained from various state departments, and that the available data sets were not in a readily usable format. Only river flow rate and chemical water quality parameters were available in computerised format. Computer data capturing from photostat copies of original records was required in the case of river water temperature, sun hours and solar radiation, and because of the format of the data this was a laborious process. Where photostat copies of original recorder charts were obtained (i.e. wind speed and direction, air temperature and humidity) digitising of the raw data was required.

Two meteorological variables required by the model, viz. dew point temperature and percentage sun hours, were not available. These variables were calculated as described in Section 3.11.1.

Infilling of missing meteorological and inflow data: Though the required data were available on a daily basis for extensive periods during January 1984 to December 1986, there were still some periods in between where no data were available. However, infilling of data was possible. The same rationale as for Roodeplaat Dam (see Section 3.11.1) was used for the infilling of missing data of solar radiation, sun hours, inflow water temperature, and concentrations of dissolved phosphate, total dissolved salts and inorganic suspended sediments.



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Map of Hartbeespoort Dam

FIGURE 3.17

the reservoir. Concentrations of dissolved phosphate, nitrate-nitrite, ammonia, TDS and chlorophyll-a also were measured, but not always down to the bottom of the reservoir. Depth profile data were obtained from the Division for Water Technology, CSIR.

Calibration coefficients and reservoir constants: A total of 24 calibration coefficients on the process behaviour, and 12 constants on the physical characteristics of Hartbeespoort Dam, are required by the program (Table 3.5). Values for the constants describing the physical characteristics of Hartbeespoort Dam were obtained from the Department of Water Affairs. In sofar as the calibration coefficients are concerned, only a few of these could be estimated from the literature on studies that had been done previously on Hartbeespoort Dam. Although a range of values for each calibration coefficient is given in the manual, these are often of restricted use; for instance, the 12 coefficients relating to algal growth are algal and climate specific, and there is little indication in the manual as to the values for specific algal species in a given climate. As a starting point, where the value of a calibration coefficient could not be determined for Hartbeespoort Dam, the default value suggested for Lake Riley was used. The calibration coefficients, and the values that were used, are listed in Table 3.5.

A3.3 PRELIMINARY MINLAKE SIMULATIONS

MINLAKE was implemented on Hartbeespoort Dam using the preliminary data set and provisional parameter set described above. It became clear very soon that the data sets required in-depth investigation in terms of anomalies and apparent errors. Particularly the wind and inflow time series were suspect. A pragmatic decision was subsequently made to concentrate all MINLAKE investigations on Roodeplaat Dam, as described in Chapter 3.

CHAPTER 3

APPLICATION OF A ONE-DIMENSIONAL WATER QUALITY MODEL : MINLAKE

by

A Venter, A Görgens, A Bath and G Marais

Contents | Page:

APPENDICES

PART 1
GENERAL DESCRIPTION OF THE MINLAKE MODEL

3.1 INTRODUCTION

The MINLAKE model is a dynamic one-dimensional water quality model for lakes and reservoirs. It was developed by the University of Minnesota (St Anthony Falls Hydraulic Laboratory). The model is intended to be used to simulate some of the physical, chemical and biological variables that describe the existing hydrodynamic and water quality behaviour of a lake/reservoir, and to provide a method to test the feasibility of different reservoir management alternatives that will affect the eutrophic state of the reservoir (MINLAKE, 1988). The variables being simulated include water temperature, dissolved oxygen, phosphate, nitrogen, chlorophyll-a and suspended solids as a function of depth and time. The reservoir is treated spatially as a series of horizontal layers; each layer is considered to be homogeneously mixed, with the relevant components and states to be uniform within the layer. The model requires limnological field data for calibration and verification, and the time step is one day.

3.2 MODEL DESCRIPTION

The model deals interactively with its hydrodynamic and water quality components. The hydrodynamic behaviour has a dominating influence on the water quality response, whereas the water quality has a relatively weaker interactive effect on the hydrodynamics. This feature implies that the inputs affecting the hydrodynamic behaviour are of primary importance. Of these inputs the wind and solar radiation are the major hydrodynamic driving forces. Because the driving forces originating from the water quality response are relatively weaker, it allows the hydrodynamic behaviour to be simulated to an acceptable level even though the water quality simulation may still be inadequate. Hence, in evaluating the MINLAKE model it is necessary first to obtain satisfactory correlation between the observed and simulated hydrodynamic variables before attempting to deal with the water quality aspects.

A quantitative, detailed exposition of the formulation of the physical/chemical /biological processes is not feasible for this part of the report, accordingly only the principal ones and the manner of their application in MINLAKE will be considered here. (See Schematic diagram, Figure 3.1). Modifications originating from our application of the model will be discussed with the simulation results in Sections 3.12 and 3.13.

3.2.1 Hydrodynamic sub-model

The evaluation of the temperature in each layer and the distribution of temperature with depth forms the principal outcome against which the hydrodynamic response can be evaluated. In simulating a depth profile of temperature, consideration must be given to the amount of radiation energy reaching each layer; the amount of energy reaching each layer is affected by net solar radiation reaching the surface of the lake, diffusion, turbulent mixing due to wind (inter layer transport), inflows and outflows, and physical changes brought about by water quality variables (eg. algal concentration).

In greater detail, consider the model formulation of the hydrodynamic driving forces (MINLAKE, 1988):

Net radiation arriving at the surface of the lake/reservoir: In MINLAKE the net solar radiation energy retained at the surface of the reservoir is calculated each day from the balance between incoming heat from solar and long wave radiation, and the outflow of heat through convection, evaporation and back radiation. A fraction of net solar radiation reaching the surface of the reservoir is reflected, while the rest penetrates into the water.

Diffusion of both heat and water quality parameters between layers: In MINLAKE diffusion is computed separately in the epilimnion and hypolimnion. In the epilimnion the diffusion coefficient is formulated as a function of wind speed, and in the hypolimnion it is a function of the Brünt-Våsala frequency (Jassby and Powell, 1975). The vertical velocity of the diffusion rate for the suspended inorganic sediment component is computed from a formulation by Gibbs (MINLAKE, 1988). The settling velocity of algae and detritus must be specified.

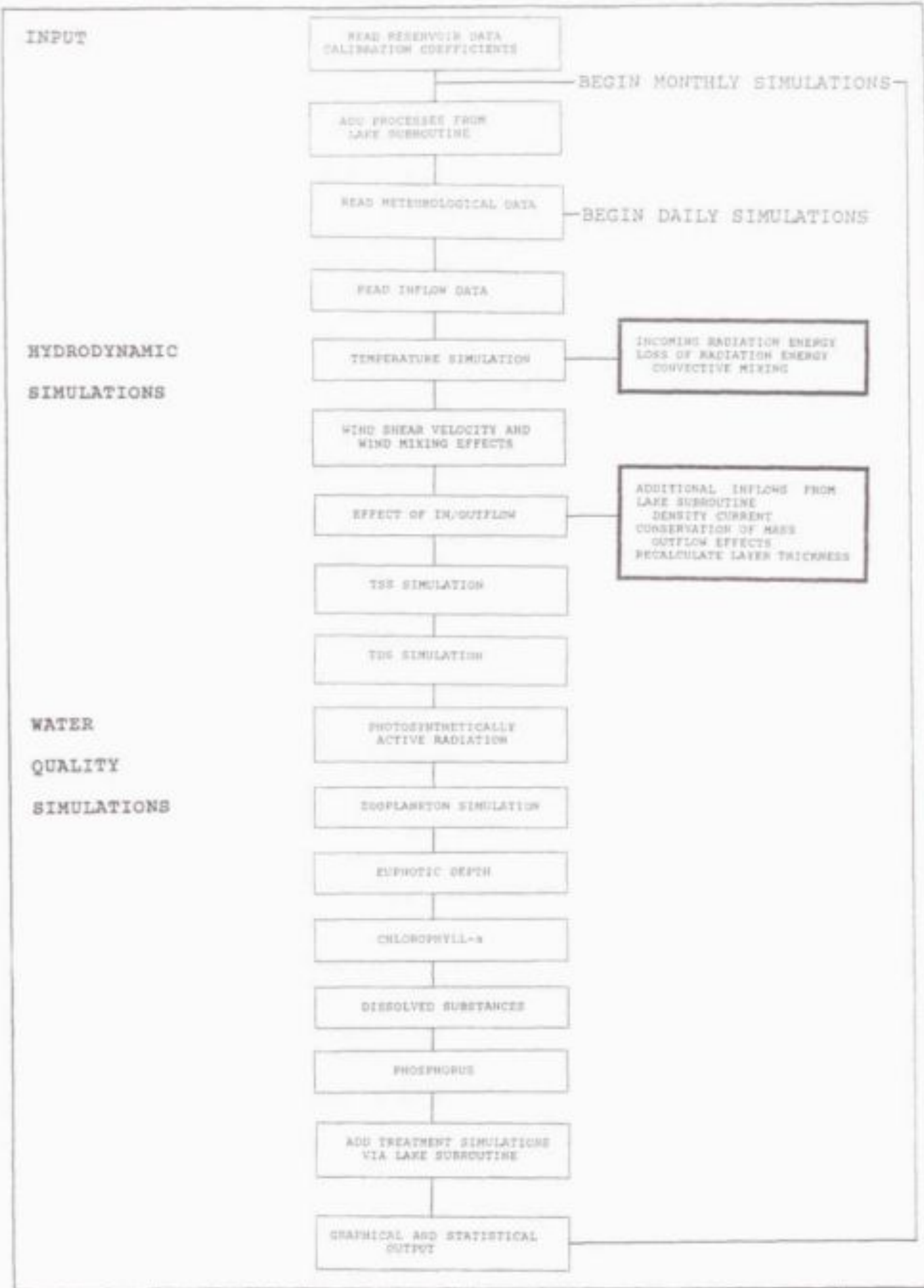

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FIGURE 3.1 Schematic representation of MINLAKE

Turbulent mixing of both heat and water quality parameters: The turbulence generated in a reservoir by wind or natural convection mixes the upper layers into a homogeneous surface layer. In MINLAKE the depth of wind mixing is determined daily after the heat budget had been calculated.

Effect of inflows and outflows: The vertical distribution of heat and water quality parameters will be affected by the temperature and density of inflowing water, as well as by the turbulence generated by in- and out-flowing water. In MINLAKE the inflowing water may flow into any layer, depending on the density of the inflowing layer. If the density of the inflow is equal or less than that of the surface mixed layer, the inflowing water will flow into the surface mixed layer and mix with it. If the density of the inflow is greater than that of the surface mixed layer, it plunges through layers of lower density until it reaches a layer of equal or greater density whereupon it mixes with that layer. Entrainment between layers due to turbulence created by in/outflows is calculated for each layer.

3.2.2 Water quality sub-model

The concentration of the different chemical/biological components in a layer is determined by the biological and physical processes that act on these components. For example, the concentration of dissolved phosphate in a layer will be affected by adsorption onto and desorption from inorganic suspended sediment, and therefore also by the concentration/settling velocity of inorganic sediment. Dissolved phosphate concentration is affected further by absorption and storage of dissolved phosphate by algae, principally, but also by other micro-organisms, excretion by zooplankton and fish, as well as bacterial decay of organic sediment. The concentration of various components in a layer and the processes that affect these are treated as follows in MINLAKE:

Inorganic suspended sediment: Inorganic suspended sediment may act as either a sink or a source of nutrients in a reservoir, therefore the simulation of inorganic suspended sediment must be acceptable before water quality parameters such as phosphorus concentration can be simulated. In MINLAKE an inorganic suspended sediment profile is calculated by taking inorganic sediment concentration, vertical mixing intensity, rate of deposition and time into account. Resuspension of bottom sediments is not taken into account.

Algal growth: In MINLAKE the concentration of algae is influenced by the combined effects of growth, diffusion, settling, respiration, mortality, and grazing by zooplankton. With regard to growth, absorption of nutrients (N and P) and growth are treated as two separate processes. The algae has the propensity to store absorbed phosphorus in excess of what is needed. Subsequent growth can take place from the stored P as phosphorus source, ie. growth is not governed directly by the concentration of dissolved P in the surrounding water. Although algae do not have the same capacity for storing nitrogen, nitrogen limited growth is calculated in the same way as phosphorus limited growth, using ammonia as substrate. In MINLAKE growth limitation by light, as well as the effect of temperature on growth, are also taken in account. Up to three different algal classes can be simulated, and three different methods of simulation are available, depending on the desired complexity level. More complex levels require more field data to calibrate the model.

Interactively, the concentration of inorganic suspended sediment and of algae affect the penetration of radiation, and hence energy transfer, to the different layers; and therefore affect the hydrodynamic response.

Nutrients: Phosphorus and nitrogen are the only nutrients simulated in MINLAKE. For nitrogen, nitrate-nitrite is modelled separately from ammonia. For phosphorus, total phosphorus is modelled separately from dissolved phosphate. Adsorption of dissolved phosphate by suspended inorganic sediment is not taken into account, nor is removal of phosphorus by settlement to the bottom. Phosphorus release from the bottom sediment must be specified.

Dissolved oxygen: Simulation of dissolved oxygen concentration is included in MINLAKE to aid the simulation of zooplankton movement and to provide information for lake management strategies.

Some of the processes described above are affected by radiation and most of them by temperature. The intensity of radiation and temperature in a layer is interactively dependent on data obtained from the hydrodynamic part of the model. The processes acting in a layer are also influenced by factors acting at the boundary of each layer, because there is transportation of variables (eg. algae and dissolved phosphate), into and out of the layer, by turbulent mixing and diffusion. In the MINLAKE model, processes acting on compounds in a layer are often approximated by simplified formulations with the use of calibration coefficients.

3.3 INPUT DATA REQUIREMENTS

Four types of data are required by MINLAKE, ie. meteorological, inflow/outflow, in-dam profile data, and physical reservoir constants. Furthermore, process coefficients for particular processes must also be provided. These coefficients usually act as calibration parameters.

3.3.1 Meteorological data

This group contains variables such as solar radiation (Langley) and wind speed (mph), which have been identified as the two main hydrodynamic driving forces in MINLAKE. Further meteorological data are:

- Air temperature (°F)
- Dew point temperature (°F)
- Precipitation (inches)
- Wind direction (degrees)
- Percentage sun

The units required are the units used by the National Weather Service in the USA. Meteorological data are needed on a daily basis. If site-specific meteorological data are not available, a site-specific meteorological database would need to be generated by interpolation from other databases.

3.3.2 Inflow/outflow daily time series

Regarding inflow, average **daily** flow rate (cfs) and temperature of inflowing water (°C) are essential variables for the hydrodynamic part of MINLAKE. Provision is made for data on the following water quality variables in the inflowing rivers:

- Dissolved oxygen (mg/l)
- Total dissolved solids (mg/l)
- Suspended inorganic sediment (mg/l)
- Dissolved phosphate (mg/l)
- Nitrate-nitrite (mg/l)
- Ammonium (mg/l)
- Chlorophyll-a (mg/l)

Only those variables that have been identified to affect the water quality of the reservoir significantly need to be included.

Regarding outflow, the flow rates of water being discharged, and of water flowing over the top of the dam wall, are entered as negative flow rates. Water quality variables are not specified in the outflow.

The original software makes provision for only one inflow/outflow. The model was subsequently modified to make provision for up to five inflows/outflows.

3.3.3 Reservoir data

In order to calibrate and verify the model, depth profiles of reservoir water quality variables of importance to the specific reservoir are required. Provision is made in the model for the following:

- Reservoir water temperature (°C)
- Dissolved oxygen (mg/l)
- Dissolved phosphate (mg/l)
- Total phosphorus (mg/l)
- Detritus as BOD (mg/l)
- Suspended inorganic solids (mg/l)
- Nitrate-nitrite nitrogen (mg/l)
- Ammonium nitrogen (mg/l)
- Three classes of chlorophyll-a (mg/l)

3.3.4 Physical reservoir constants

In MINLAKE, the following constants must be specified by the user for each reservoir:

- Width of each inflowing river
- Maximum width of the reservoir perpendicular to the inflowing river
- Height of reservoir bottom above sea level
- Height of discharge outlets above sea level
- Width of discharge outlet
- Initial height of the reservoir water level (stage) above sea level
- Downstream slope of each inflowing river
- Manning friction factor for each of the rivers

3.3.5 Calibration coefficients

In MINLAKE, many of the processes are simplified or even approximated, by the use of calibration coefficients. These must be specified by the user (*cf.* Table 3.5).

3.4 STRUCTURE OF MINLAKE

3.4.1 Data input

The input data required are represented in three separate computer files, ie. a meteorological file containing the meteorological data; an inflow file containing river water quality data, and an input file containing observed profiles of reservoir water quality variables, calibration coefficients, as well as various reservoir specific constants.

3.4.2 Data output

Data output from the MINLAKE model is in the form of graphics and statistics, as well as in file format. Graphics, consisting of profiles as well as time-series, and statistics are displayed during operation of the model, and can be printed by request.

3.4.3 The model structure

The model is divided into two separate, but linked, computer programs. The first programme incorporates the main MINLAKE program, while the second program incorporates a lake specific subroutine.

Main MINLAKE program: The main program consists of 40 subroutines and two function routines (Figure 3.1). The subroutines calculate daily changes in states/concentration of various compounds, and the influence of inflows and outflows. The three input data files (see Section 3.3) are accessed from the main program via these subroutines. Graphical and tabular output, as well as all statistical calculations are also done in the main program. (The user manual suggests that there should be no need to make modifications to the main program; the program is constructed in such a way that, should modifications be required, it can be done via the lake specific subroutine).

The lake specific subroutine: The main program makes periodic calls to the subroutine which allows the user to change processes, add processes, or add inflows and outflows. Reservoir specific features such as depth-area relationships and the fetch of the lake are dealt with in the lake specific subroutine.

3.5 MINLAKE MANUAL

A user's manual is supplied with the MINLAKE package. The manual is relatively user-friendly. It gives an overview of the governing equations and the methods of solution used in MINLAKE, as well as more detailed descriptions in the appendices. The model structure, data input requirements, calibration procedure, statistical analysis of results and the use of the model to simulate some treatment scenarios are explained. A step by step example of running the model is given, including a description of the compiling procedure with the required compiler. Examples of both graphical and file output are given. Listings of the input and output data file, as well as a description of the various subroutines, are given in Appendices A and B.

3.5.1 Remarks

- Formulations as presented in the manual are not always correct. The references from where these formulations were obtained, had to be consulted. The references are listed in the manual, but all the references are not available in South Africa.

- Tracking of errors in the main program is complicated by the fact that all the common block variables are not listed in the manual. Also, variables are often renamed in the program, and this is not indicated in the manual.

- Some formulations, eg. astronomical day length, are hardwired into the main program for a specific latitude.

3.6 MINLAKE SOFTWARE

3.6.1 The model

The MINLAKE program can be used on personal computers with a DOS version of 3.0 or higher. The program is written in Fortran and must be compiled before it can be run. Compiling is facilitated by the structure of the program. Compiling can be a very time consuming procedure, but, according to the suppliers, there should be no need to recompile the main program, as no changes ought to be made to the main program. However, as will be shown later, apparent errors in the code and modifications deemed necessary, necessitated many recompilations of the main program. The lake specific subroutine must be recompiled whenever changes are made to this subroutine, but this is not time consuming as the subroutine is relatively short. After compilation of the lake specific subroutine, the subroutine must be linked to the main program; compiling and linking must be done separately. The program requires the Microsoft Fortran 3.31, 4.01 or 4.10 compiler and the PLOT88 graphics library. The compiler program is not supplied with the MINLAKE package, but it is freely available in South Africa.

3.6.2 Data input

The three data input files are standard ASCII data files, and the data format is in free form, ie. data files can be constructed without concern for the spacing between data. The only requirement is that columns of data must be separated by at least one blank space. The free form format is particularly suited to using spreadsheet programs, such as Lotus or Quattro, to construct data input files.

The MINLAKE package also contains data file listing programs for each of the three data files. Errors in the data files will cause an error exit when the MINLAKE program is run. Considerable time can be spent in debugging data files, not only because the data files usually are quite large, but also because the data file containing an error often cannot be determined from the error exit code. The debugging of data files is facilitated by the use of the data listing programs provided. These programs list the contents of a data file to the screen, allowing the user to view the data. Errors in the data file will cause the data listing program to stop at the line where the error occurs.

Remarks: It is recommended that, whenever an error exit occurs, the first step in tracking the error that caused the exit, should be the listing of the data files with the data listing program. An error exit is usually caused by an error in the data files.

To provide a bench mark example, test data files for each of the three data files, and for the lake specific subroutine are supplied for Lake Riley in Minnesota. This allows the user to gain familiarity with the MINLAKE program before attempting to run the program with their own input.

3.6.3 Software implementation

Implementing the model presented no problem. As a test, both the main program and the lake specific subroutine, as received from the supplier, were recompiled and linked. Compilation time for the main program on a 386 personal computer is approximately six minutes. Compilation of the lake specific subroutine is done in a few seconds, while linking of the two files also takes a few seconds only.

3.6.4 Graphics support software

To overcome a number of shortcomings in the MINLAKE graphical routine, the DYPLOT package was developed by Ninham Shand Inc. as part of this project. The package enables plotting of time-series with depth of any one of eight different MINLAKE output variables. The resultant graph can be displayed on screen or printed (Figure 3.5b)

3.7 APPLICATION OF THE BENCH MARK TEST DATA SET - LAKE RILEY

A test run was done using the bench mark test data set for Lake Riley in Minnesota, provided by the supplier, to:

- ensure that the model performs according to the supplier's specifications
- gain familiarity with the graphic output and the operating instructions

Test data for a six month period were supplied. The model was run with the test data sets according to the instructions in the manual. The model operated satisfactorily, and visually the graphical responses generated appeared identical to those provided in the manual. It was therefore accepted that the model implementation was correct.

3.8 GENERAL TASKS

In investigating the applicability of the MINLAKE model to South African reservoirs, the approach was as follows:

* Investigate if there are reservoirs in South Africa with databases that satisfy the requirements of the model, and to select at least one reservoir with an adequate, or near adequate database for intensive study.

* Transform the data and units of measurement of all relevant data relating to the selected reservoir into the format required by the model.

* Calibrate the model optimally by:
  a) following the calibration sequence recommended in the model instruction.
  b) selecting optimal values of each of the calibration coefficients ($\pm$ 24 in number) from a literature study, using as a starting point the range of values for each coefficient suggested in the manual.

* Enquire into the causes for deviations between simulated and observed results by:
  a) critically evaluating the process formulations and constants.
  b) checking for the presence of programming errors.

* Modify the model and correct any errors identified, and resimulate the reservoir response.

* Evaluate the applicability of the model and propose further action.

3.9 RESERVOIR SELECTION

Two reservoirs were selected for the evaluation of MINLAKE, ie. Roodeplaat Dam and Hartbeespoort Dam.

Roodeplaat Dam was selected for evaluation of MINLAKE for the following reasons:

- When the data requirements of the MINLAKE model were compared to the data that was measured at Roodeplaat Dam, it was found that the measurements at Roodeplaat Dam matched most of the MINLAKE data requirements. Monthly depth profiles of temperature and dissolved oxygen, as well as surface measurements of several other water quality parameters in the dam, were available. Flow rate, and a few water quality parameters were measured on a daily basis in the inflowing rivers. Meteorological data also were measured on a daily basis for extensive periods.

- Roodeplaat Dam receives both secondary treated domestic wastewater effluent, and run-off from agricultural land. It is a popular recreational site and a source of irrigation water, and consequently there is concern about the water quality in the dam. In 1976 Roodeplaat Dam was ranked as the third most eutrophic water body in a study of 98 South African impoundments (Toerien, 1976).

Hartbeespoort Dam was selected for the following reasons:

- Extensive research has been done on Hartbeespoort Dam by the CSIR and various universities and the data that were measured at Hartbeespoort Dam matched most of the data requirements of the MINLAKE model. Weekly depth profiles of temperature, dissolved oxygen, electrical conductivity, dissolved phosphate, chlorophyll-a and light distribution were taken. Flow rate and a few water quality parameters were measured on a daily basis in the inflowing rivers. Meteorological data were also measured on a daily basis for extensive periods.

- Hartbeespoort Dam receives both urban effluent, and runoff from agricultural land. It is a source of irrigation, as well as raw water, and is a popular recreation site. The dam can be classified as hypertrophic, with outbreaks of aesthetically undesirable hyperscums, and toxic algae, eg. *Microsystis* (FRD, 1985).

Remark: Regarding Hartbeespoort Dam, it was soon discovered that the inflow volumes were too low for the first few years of available data, and that a factor of approximately 1,45 was required before a reasonable mass balance could be achieved. Problems with the inflow records of the gauges on the two inflowing rivers, as well as with the outflow records, have been encountered in the past (Bosman, personal communication, 1991). Further investigation into this matter is required, which was not possible within the scope of this study. Attention was therefore focused on Roodeplaat Dam in evaluating the MINLAKE model. The database development for Hartbeespoort Dam is summarised in Appendix 3.3.

PART 2

APPLICATION OF THE MINLAKE MODEL TO ROODEPLAAT DAM

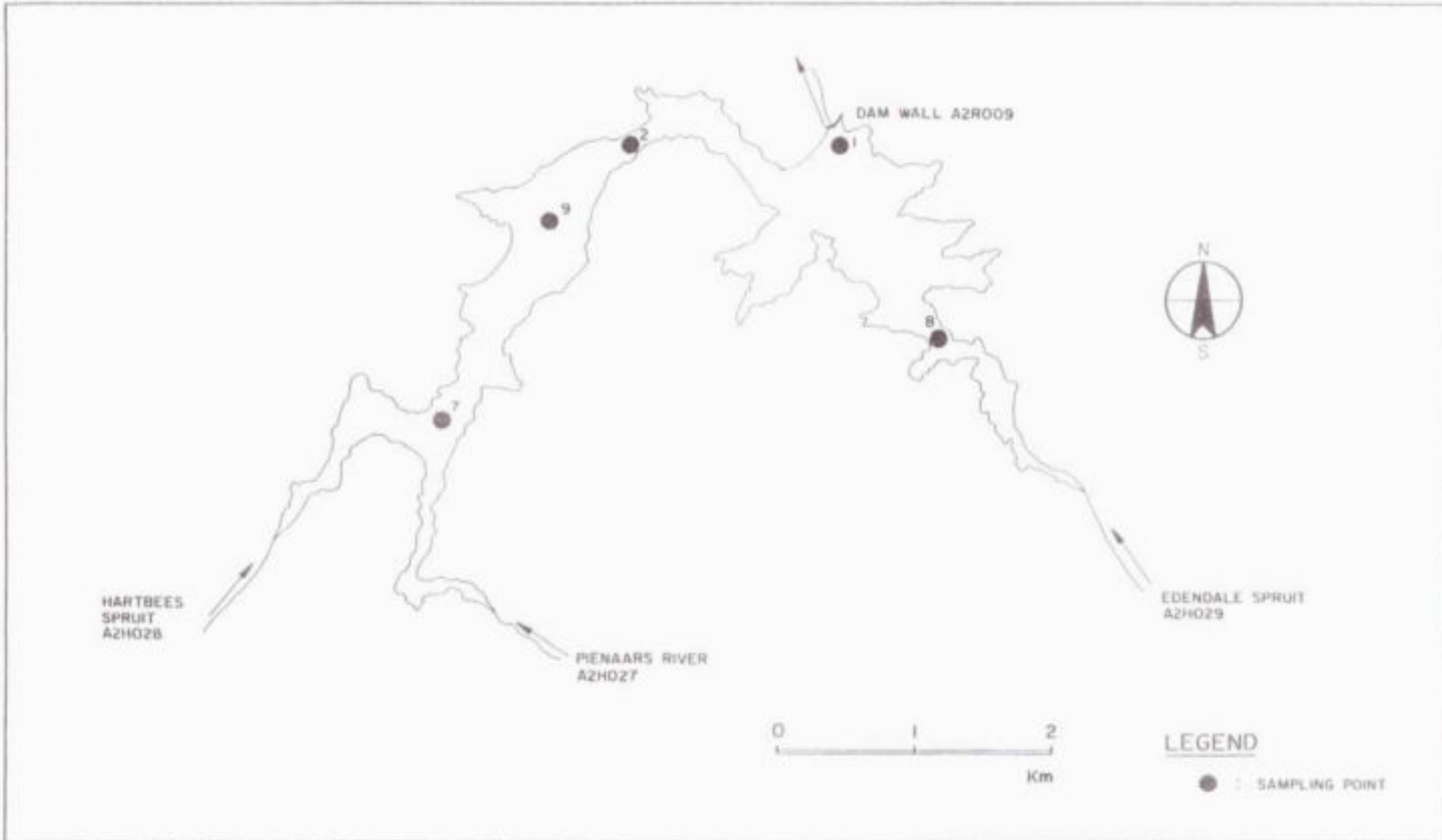
3.10 RESERVOIR DESCRIPTION

Roodeplaat Dam is situated 20 km north of Pretoria (23°58'S; 27°43'E). The reservoir lies in a summer rainfall region with an average annual rainfall of about 700 mm. Three rivers, the Pienaars River, Edendalespruit and Hartbeesspruit, discharge into the reservoir. The Pienaars River flows through Mamelodi Township and then past the Baviaanspoort sewage works which treats effluent from the Township. This river is the major nutrient source of Roodeplaat Dam, contributing up to 75% of the annual dissolved nitrogen load and up to 87% of the annual phosphorus load. Edendalespruit receives run-off from agricultural and grassland, while Hartbeesspruit originates in the urban areas of Pretoria, whereafter it flows through the industrial area of Silverton. The river inflow is strongly seasonal with flooding of the system during the rainy season in summer (Butty and Walmsley, 1979).

The point of inflow for each river, as well as the shape of the dam and the different sampling points, is shown in Figure 3.2. Further characteristics of Roodeplaat Dam are presented in Table 3.1. Area, volume, and maximum and mean depth are indicated at full supply level.

TABLE 3.1 : CHARACTERISTICS OF ROODEPLAAT DAM

Area	396 ha
Volume	41,9 x 10^6 m^3
Maximum depth	43 m
Mean depth	10,6 m
Height above sea level	1214 m
Annual inflow	59,01 x 10^6 m^3
Annual outflow	55,68 x 10^6 m^3



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Map of Roodeplaat Dam showing sampling points

FIGURE 3.2

3.11 DATABASE DEVELOPMENT FOR ROODEPLAAT DAM

3.11.1 Meteorological and inflow data

Retrieval of meteorological and inflow data: A summary of various institutions where meteorological and inflow data were obtained, the format of the obtained data, and the units of measurement, as opposed to the units required by MINLAKE, is given in Table 3.2.

TABLE 3.2 : SUMMARY OF UNITS AND FORMAT OF OBTAINED DATA AND INSTITUTIONS WHERE DATA WERE OBTAINED

Variable	Measured Unit	Required Unit	Institution*	Format of obtained data
River flow rate	m^3s^{-1}	cfs	DWAF	Floppy disks
River water temperature	°C	°C	DWAF/HRI	Copy of original handwritten record
PO_4,NO_3, NH_4, TDS	mg l^{-1}	mg l^{-1}	DWAF	Floppy disks
Air temperature	°C	°F	DWAF/HRI	Photostat copy of recorder charts
Dew point (calculated from humidity)	°C	°F	DWAF/HRI	Photostat copy of recorder charts
Precipitation	mm	inches	DWAF/HRI	Photostat copy of handwritten record
Wind speed	km h^{-1}	mph	DWAF/HRI	Mostly photostat copies of undigitised wind run chart
Wind direction	degrees	degrees	DWA/HRI	Mostly photostat copies of undigitised wind direction chart
Sun hours	hours	% sun	DWAF/HRI	Photostat copy of handwritten record
Solar radiation	Watt-hr m^{-2} Joule m^{-2}	Langley (cal cm^{-2})	DWAF/HRI WB	Photostat copy of original records

*Institutions:

DWAF : Department of Water Affairs and Forestry Head Office, Pretoria.

DWAF (HRI) : Hydrological Research Institute, Department of Water Affairs and Forestry, Roodeplaat Dam.

WB : The Weather Bureau, Department of the Environment, Pretoria.

Processing of meteorological and inflow data: From Table 3.2 it is evident that the data that were needed were lodged with various state departments, and that the data were not in a readily usable format. Only river flow rate and chemical water quality parameters were available in computerised format. Where photostat copies of original records were obtained, (ie. river water temperature, sun hours and solar radiation), these had to be computerised. Because of the format of, for instance, solar radiation, this was often a laborious process. Where photostat copies of original recorder charts were obtained (ie. wind speed and direction, air temperature and humidity), these had to be digitised.

Two meteorological variables required by the model, dew point temperature and percentage sun hours, were not available, and therefore had to be calculated. Daily dew point temperature was calculated from daily relative humidity data, using the Clausius-Clapeyron formulation (Barrow, 1973). Percentage sun is defined as the number of hours of observed sunshine per day, divided by the maximum number of hours of sunshine possible (astronomical day length). Observed sunshine data were obtained from the Department of Water Affairs and Forestry (HRI). Tables of the astronomical day length for Pretoria, as well as a general formula for calculating astronomical day length at any latitude, were obtained from the Observatory in Cape Town.

Infilling of missing meteorological and inflow data: Though the required data were available on a daily basis for extensive periods during 1980 to 1984, there were still some periods in between where no data were available. The worst period was April to November 1984. No radiation data were available for this period, as well as no river water quality data for Hartbeesspruit and Edendalespruit. The study period therefore had to be limited to January 1980 to December 1983. A summary of the availability of required inflow data, as well as meteorological data, is given in Appendix 3.1

Even though there were still some data missing from the period 1980 to 1983, infilling of data was possible. Table 3.3 gives a summary of the inflow and meteorological variables that needed infilling, the variables that were used to aid in the infilling, and the relationship that existed between the variables.

TABLE 3.3 : INFILLING OF METEOROLOGICAL AND WATER QUALITY VARIABLES

Parameter with missing data	Parameter used for infilling	Condition	R^2	X-coeff	Infilling technique
Water temp (Edendale)	Average air temp	-	0.80	0.96	Linear regression
Water temp (Hartbees)	Average air temp	-	0.80	0.92	Linear regression
Water temp (Pienaars)	Average air temp	-	0.86	0.96	Linear regression
ln** PO_4 (Pienaars)	ln flow	May-Nov flow $< 0.22 m^3 s^{-1}$	0.00	0.006	Interpolation
		May-Nov flow $> 0.22 m^3 s^{-1}$	0.40	-0.68	Program*
		Dec-April flow $< 0.25 m^3 s^{-1}$	0.04	0.66	Interpolation
		Dec-April flow $> 0.25 m^3 s^{-1}$	0.40	-0.79	Program
ln PO_4 (Hartbees)	ln flow	-	0.22	0.29	Program
ln PO_4 (Edendale)	ln flow	-	0.31	0.39	Program
ln TDS (Pienaars)	ln flow	-	0.52	-0.24	Program
ln TDS (Hartbees)	ln flow	-	0.30	-0.23	Program
ln TDS (Edendale)	ln flow	-	0.72	-0.13	Program
Wind speed	Wind speed (Forum)***	Aug-Dec	0.44	0.22	Linear regression
Wind dir.	Wind dir. (Forum)	-			
%Sun hours	Radiation	-	0.84	0.005	Linear regression
Radiation	% Sun hours	-	0.84	166	Linear regression

* Program refers to the three-stage technique discussed below.

** 'ln' refers to the natural logarithm.

*** Forum refers to the Forum Building in Pretoria, the site where the wind data used for infilling, were measured.

Exhaustive efforts were made to find relationships between variables with missing values and other variables with more complete values. Daily flow was often used for infilling, as the flow records were complete (only three days missing from the entire record). When daily flow was used for infilling other data, it was done with the aid of a three-stage time-dependent seasonal technique.

- **First stage:** Infilling was done with a time-dependent seasonal non-linear regression of grab sample against daily flow, for days with flow above a certain truncation level, but with the infilled values weighed by proximity to a grab sample value at either end of the missing period

- **Second stage:** Data for days with flows below the truncation level was filled in by linear interpolation.

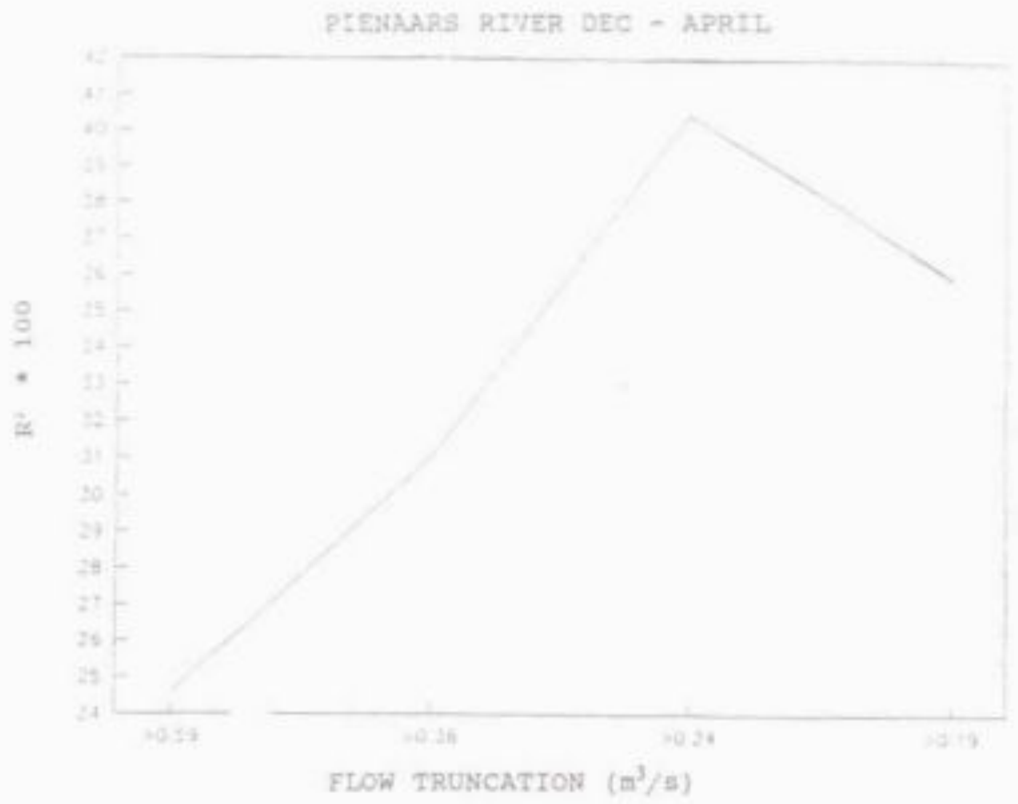
- **Third stage:** The grab sample values are imbedded in the created series and discontinuities and seasonal transitions are smoothed.

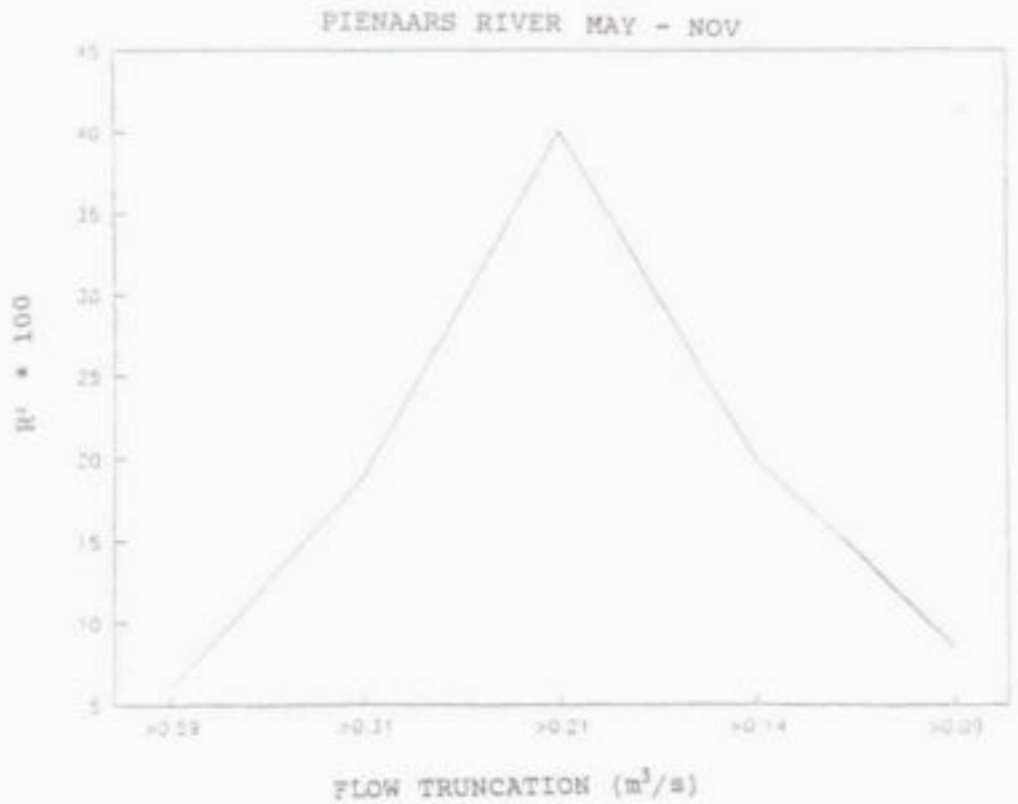
Water temperature: The water temperature was determined from the 'average' air temperature as follows: The 'average' air temperature for a specific day was defined as the mean of the true average air temperature for that day and the true average air temperature for the preceding day. A satisfactory correlation of 0.96 was found between water temperature and this 'average' air temperature.

Dissolved phosphate concentration: Missing dissolved phosphate concentrations were filled in with the aid of river flow rate data. The best regression between phosphate concentration and river flow rate was obtained using the natural logarithm of the two variables. It was found that the regression for Pienaars River differed from the other two rivers. This difference is probably due to a point source of dissolved phosphate to the Pienaars River, namely effluent from a sewage works upstream from measuring point. A definite seasonal phosphorus/flow trend could be discerned in the regression analysis, for flows greater than 0.22 $m^3 s^{-1}$ for the period May to November, and for flows greater than 0.25 $m^3 s^{-1}$ for the period December to April (Table 3.3). The truncation level of the flow influenced the value of R^2 significantly, as may be seen in Figure 3.3 - a graphical representation of R^2 against truncation level. The final infilling was done with the aid of the three-stage technique mentioned previously, for the period May to November (flow > 0.22 $m^3 s^{-1}$) and for the period December to April (flow > 0.25 m^3s^{-1}). Below these flows linear interpolation were used. No annual trend could be established.

The other two rivers did not show any seasonal phosphorus/flow dependence. In spite of exhaustive efforts, no discernible cause for the spread of data could be identified. The linear regression coefficient was low, ≈ 0.2 and ≈ 0.3 (Table 3.3). However, in view of the much lower dissolved phosphate concentration in these two rivers, the regression relationship between flow and dissolved phosphate was accepted.

Total dissolved salts: Although a very good linear regression between TDS and conductivity was found for each river, the regression relationship could not be used for infilling TDS data from conductivity data, because both TDS and conductivity were monitored at the same time, or both not at all. The missing values therefore had to be filled in with the aid of river flow rate, using the aforementioned three-stage approach. The regression relationship between TDS and river flow rate was also described best by the natural logarithm of the two variables. The regression coefficients for Pienaars River and Edendalespruit were reasonable (R^2 = 0.52 and 0.72 respectively) but the R^2-value for Hartbeesspruit was low, ≈ 0.3.





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Graphical representation of R^2 against truncation level

FIGURE 3.3

Inorganic suspended sediment (TSS): No data on inorganic sediment concentration were available. TSS is modelled as an implicit part of the processes that govern water quality and temperature distribution in a reservoir, therefore it was vital that some estimate of TSS be made in order to simulate the behaviour of the reservoir.

The approach to find surrogate TSS data went through two phases: In the first phase, time-series data on the concentration of total suspended matter (TSM) in the reservoir were available. TSM is defined as comprising dead and alive phyto- and zooplankton, as well as inorganic suspended sediment and detritus (DWAF, 1988). TSM concentration was measured three times per week at points 1, 2, 7 and 8 in the reservoir. (See Figure 3.2). Point 7 is near the confluence of Pienaars River and Hartbeesspruit and therefore it was concluded that TSM concentration at this point very likely approximated the weighted average TSM concentration of Pienaars River and Hartbeesspruit. The TSM data at point 8 should adequately reflect the TSM concentration of Edendalespruit. Point 1 is well away from the effect of inflows and consequently TSM data at this point were used as field data to compare the simulated and observed TSS/TSM results. Missing time-series TSM data were filled in by linear interpolation. Section 3.13.1 below gives an account of the results achieved with this data and the eventual rejection of this data.

The second phase of the search for surrogate TSS data centred on the synthesising of daily TSS concentrations by use of the daily inflow record, as well as unit streampower theory. The unit streampower equation, based on daily flows, as developed by Rooseboom, was calibrated against the surveyed sediment volume in Roodeplaat Dam for the period 1959 to 1980.

Wind speed: Monitoring of wind speed data was done at Roodeplaat Dam. The data were not complete (see Appendix 3.1). To infill the missing data, it was found that, for the windy period, August to December, a slight correlation ($R^2 = 0.4$) existed between the daily wind speed measured at Forum Building in Pretoria and wind speed measured at Roodeplaat Dam. For this period, infilling of missing data was done using the regression relationship between the wind speeds at the two locations. During the low wind period, January to July, the

3.13 WATER QUALITY SIMULATION RESULTS

Using the improved hydrodynamic response discussed above, a water quality simulation was done using the default calibration coefficients as shown in Table 3.5. In Figure 3.12 (a) the simulated and observed algal, soluble phosphorus, and TSS/TSM concentrations are depicted. The simulated water quality variables still deviated considerably from those observed. Clearly this deviation cannot be attributed to inadequate hydrodynamic simulations. One may identify two possible causes for these differences:

1. Algal growth in Roodeplaat Dam could be phosphorus or nitrogen limited at different periods.
2. Our TSS/TSM time-series data approximation are inadequate.

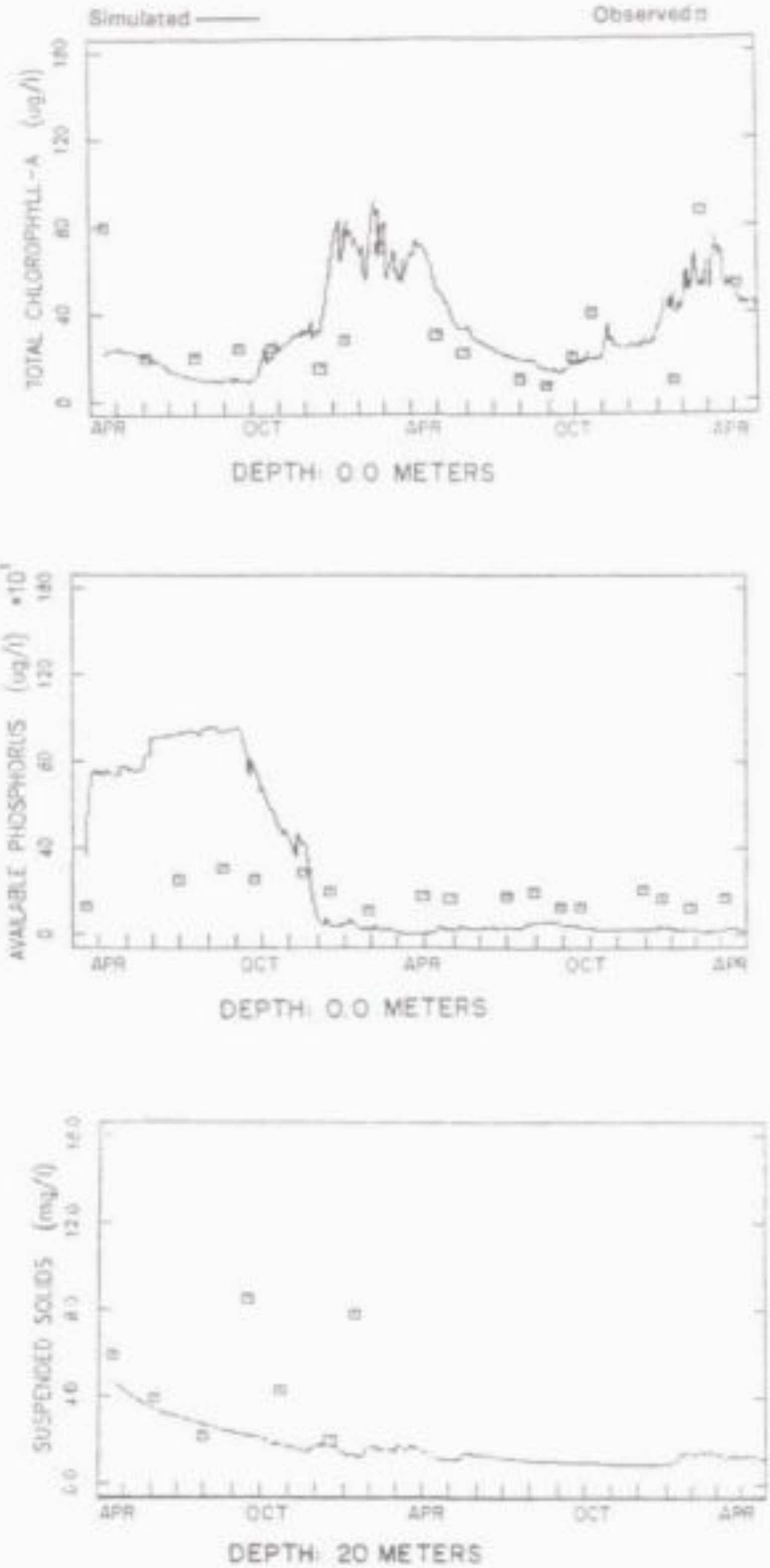
With regard to possible phosphorus/nitrogen limitation of algal growth, only phosphorus limited algal growth has been simulated. Clearly it would be desirable to simulate both phosphorus and nitrogen growth limitation.

3.13.1 The effect of TSS/TSM

Whereas TSS/TSM was shown to be of little importance in simulation of water temperature profiles, this is not the case with regard to water quality. TSS may act as a source/sink of nutrients in a reservoir, and the literature indicates that this has a relatively large effect on algal growth. Therefore the simulation of TSS has to be acceptable before the rest of the water quality parameters such as phosphorus and algal growth could be simulated. As discussed in Section 3.11, TSS concentration in the inflows to Roodeplaat Dam was not measured, nor was it measured in the reservoir. It was therefore necessary to find an associated or surrogate parameter from which it would be possible to approximate the TSS in the inflows and in the reservoir. It was stated in Section 3.11 that the TSM time-series data near the point of confluence of the Pienaars and Hartbeesspruit Rivers in the reservoir were taken to approximate the TSS in these rivers. The TSS for Edendalespruit was

RODEPLAAT DAM - APRIL 1980 TO APRIL 1982

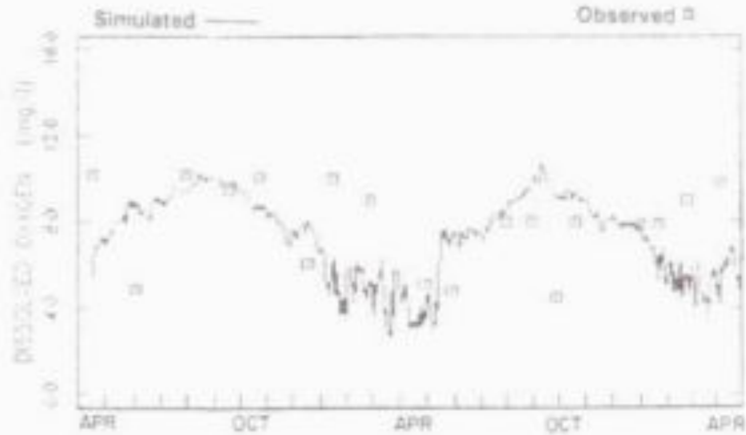
CONDITIONS : WINDSPEED AT 10m, EDDY COEFFICIENT = 1.73m² d⁻¹ TSS = TSM



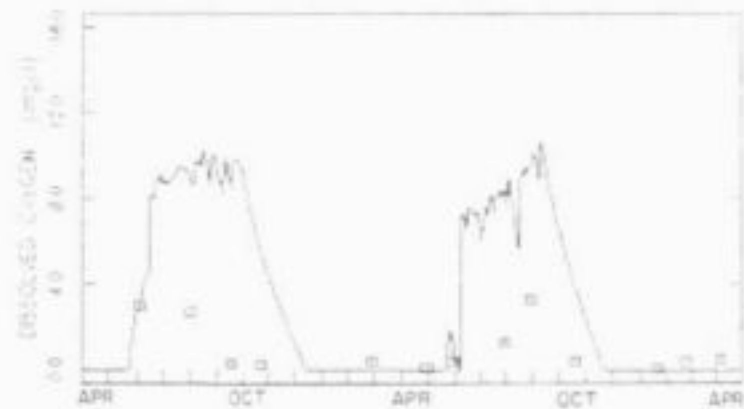
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with eddy diffusion coefficient calculated for Roodeplaat Dam	FIGURE 3.12a

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m^2 d^{-1} TSS = TSM



DEPTH: 0.0 METERS



DEPTH: 20 METERS

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with eddy diffusion coefficient calculated for Roodeplaat Dam	FIGURE 3.12b

approximated by the time-series TSM data at point 8 in the reservoir (see Figure 3.2). TSM data at point 1 (away from the inflow) was assumed to approximate TSS in the reservoir.

A preliminary study was made as to the effect of TSS/TSM on algal growth and soluble phosphorus concentration by doing a simulation with TSS/TSM equal to zero in the inflowing rivers. The results are shown in Figure 3.13. Clearly TSS/TSM has a marked effect, therefore it was necessary to improve the reliability of our TSS data approximations.

When the TSM data, serving as surrogate for TSS data, were compared with the flow data it did not reflect the relationship usually expected between TSS and flow. Upon investigation it was found that (DWAF (HRI), personal communication, 1992):

- Total Suspended Matter at measuring point 1 at Roodeplaat Dam consists of only algal biomass, and not phyto- and zooplankton, inorganic suspended sediment and detritus, as defined in TR 136: Analytical Methods Manual (DWAF (HRI), 1988)

- The assumption that TSM concentration at measuring point 8 approximated the weighted average TSM concentration of Pienaars River and Hartbeesspruit is incorrect.

It was concluded that TSM cannot serve as a reliable measure of TSS, and therefore, as explained in Section 3.11, another surrogate TSS data set was synthesised by means of the unit stream power equation. A run was done with this TSS data; the results are shown in Figure 3.14(a) to (e). As there were no TSS field data, a comparison of the simulated and observed TSS concentrations was not possible, but it is to be expected that the TSS concentration in the reservoir should follow a seasonal trend as it is related to daily inflow from the three rivers. The simulated TSS does seem to follow a seasonal pattern. The effect of TSS on, for example, the simulation of dissolved phosphorus, is indicated in Figure 3.14e, a depth/time graph of dissolved phosphorus simulations, with and without TSS.

When simulations, using the surrogate TSS data thus generated, were compared with the TSS/TSM based data set, there was no significant improvement in correlation between observed and simulated temperatures (*cf.* Figure 3.11a and 3.14a). The simulation of the mixed layer depth improved slightly (*cf.* Fig 3.11b and 3.14b). The simulated concentrations of both available phosphorus and chlorophyll-a still deviated significantly from the observed concentrations in trend and value, but the optimum values of all the calibration coefficients had not yet been ascertained.

3.13.2 Calibration coefficients

In Section 3.11.2 it was stated that 24 calibration coefficients need to be estimated. Only a few of these could be estimated from literature on studies that had been done on Roodeplaat Dam, as listed in Table 3.5. The rest (marked with an * in the table), need to be determined from literature on algal growth and water quality modelling studies. The coefficients relating to algal growth (12 in number) are algal and climate specific. Many parts of South Africa have a subtropical climate, and the dominating algal species often is *Microsystis aureginosa*, which prefers higher water temperatures. However, most of the work to establish values for the calibration coefficients was done in the temperate climates of the northern hemisphere, where *Microsystis* appears to be one of the species of lesser importance. From the literature, values for 11 of the 12 required algal specific calibration coefficients could be obtained; very likely these values are not optimal, particularly those relating to temperature and light, as some of these had to be determined by extrapolation for the temperature range in South Africa. In Appendix 3.2 algal and climate specific values for the calibration coefficients for a number of algal species common in water quality modelling, are listed, as well as the literature sources from which these values were derived.

3.13.3 Coding errors

While the calibration coefficients were being investigated, it was noted that daily calculation of **astronomical day length** was hardwired in the MINLAKE source code. The formulation is not in terms of northern or southern latitude, but derived values for Lake Riley are inserted as constants, consequently the formulation does not apply elsewhere. The astronomical day length is an important parameter in calculating algal growth and an error in its formulation could lead to significant error in the simulation of algal concentration.

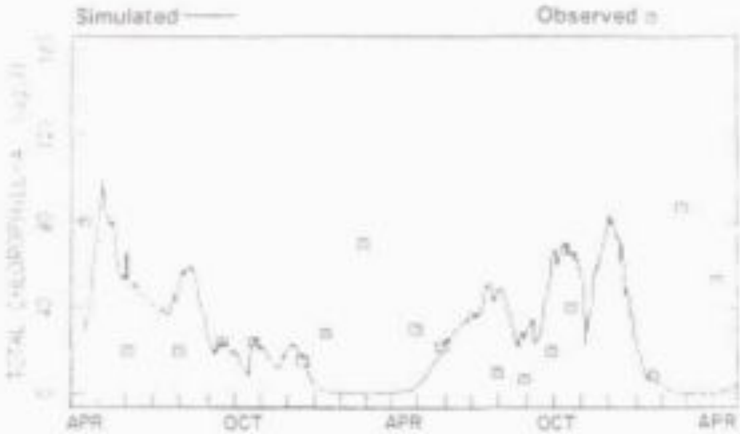
Accordingly, as an interim measure, the constants were adjusted to give the astronomical day length for the southern latitude of Roodeplaat Dam. (This formulation needs to be generalised for any latitude, north or south).

It was also discovered that the symbol for astronomical day length was coded, in error, for the symbol for dew point temperature in the expression to calculate daily vapour pressure of the air. This could affect the temperature simulation.

Also, in the expression relating algal growth rate with temperature, the minimum temperature below which algal growth would not occur, was hardwired as 0 °C. In South Africa, however, the minimum temperature below which algal growth does not occur, appears to be approximately 10 to 12 °C. We reformulated the formulation containing the hardwired value so that the appropriate minimum temperature can now be specified by the user.

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m^2 d^{-1} ZERO TSS



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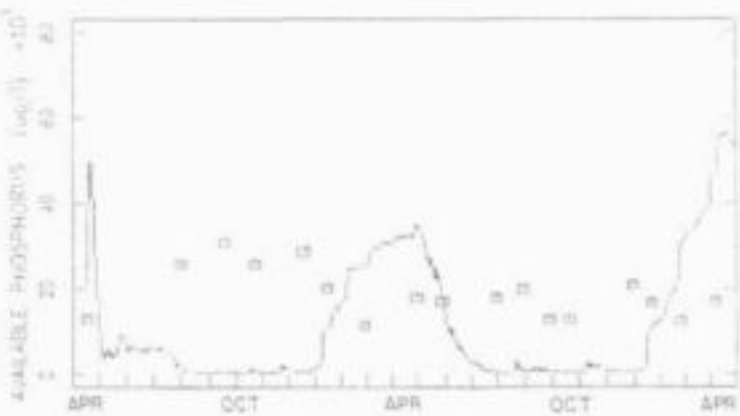
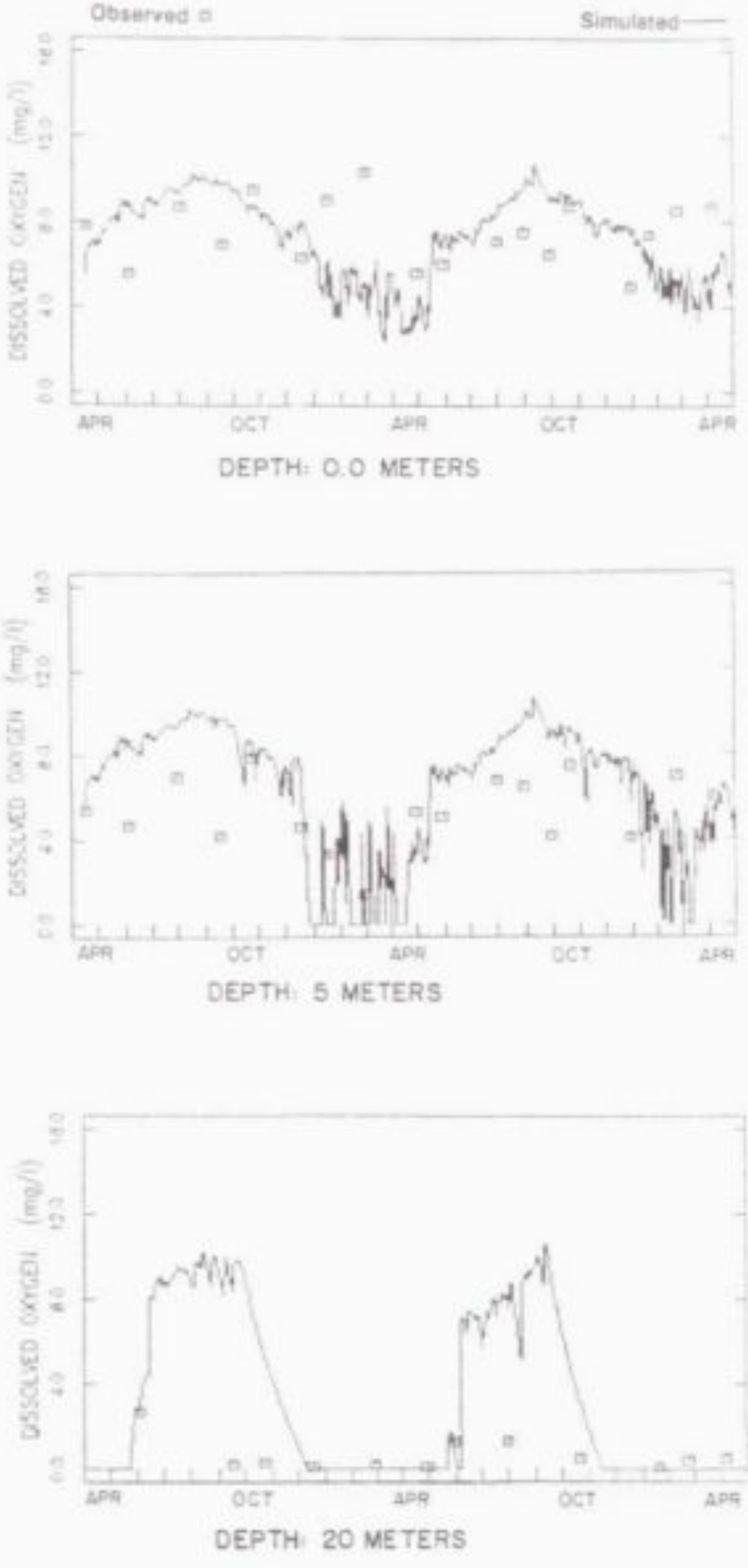


DEPTH: 0.0 METERS

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with zero TSS concentration in the inflow.	FIGURE 3.13a

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

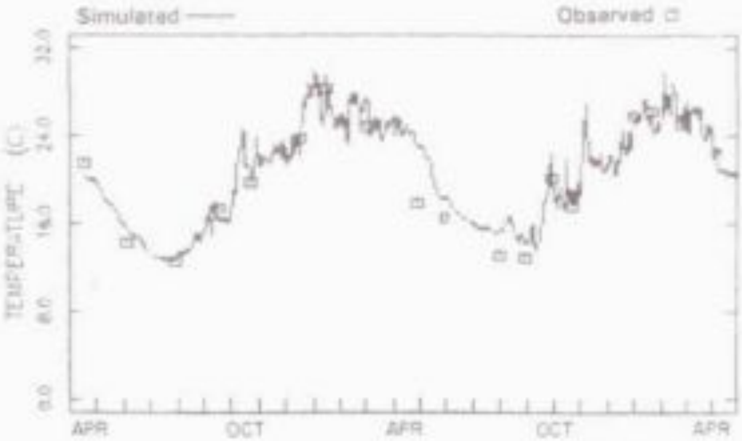
CONDITIONS : WINDSPEED AT 10m EDDY COEFFICIENT = 1.73m^2 d^{-1} ZERO TSS



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with zero TSS concentration in the inflow.	FIGURE 3.13b

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73$m^2 d^{-1}$ SYNTHESIZED TSS



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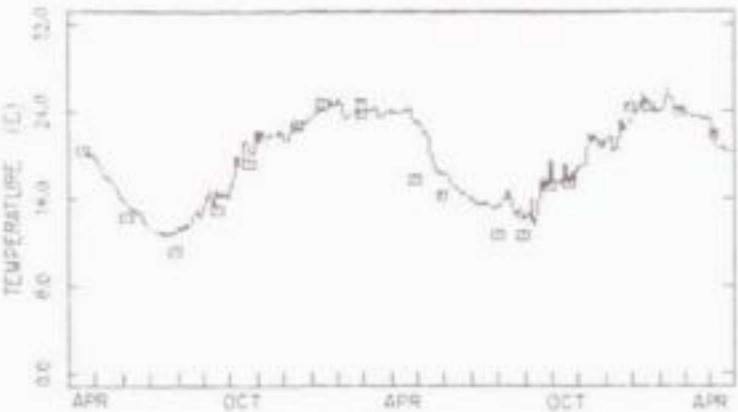

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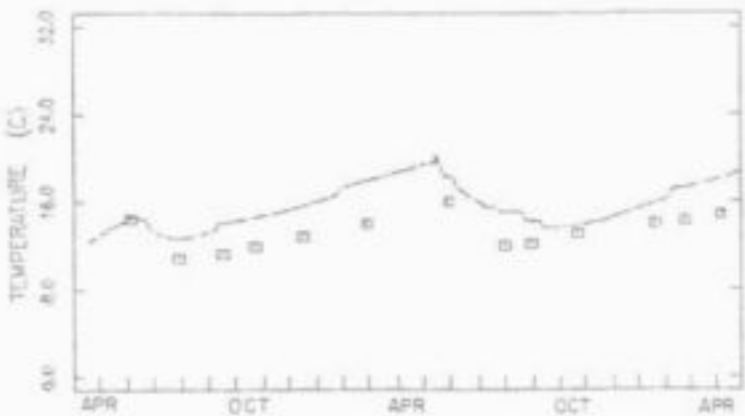
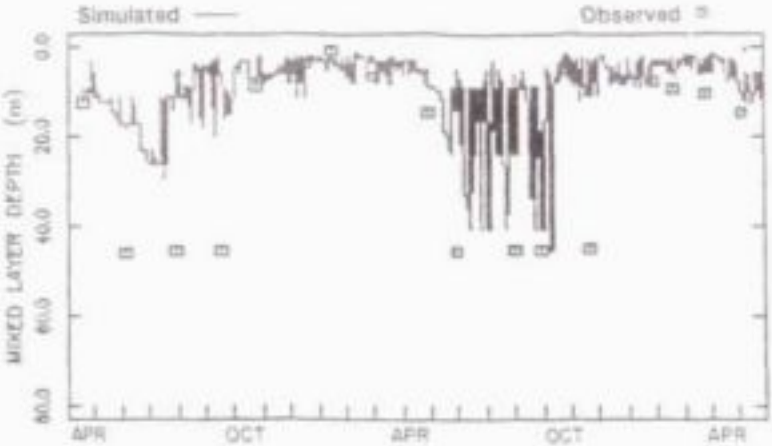


DEPTH: 20 METERS

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed temperature obtained with synthezised TSS concentration in the inflow.	FIGURE 3.14a

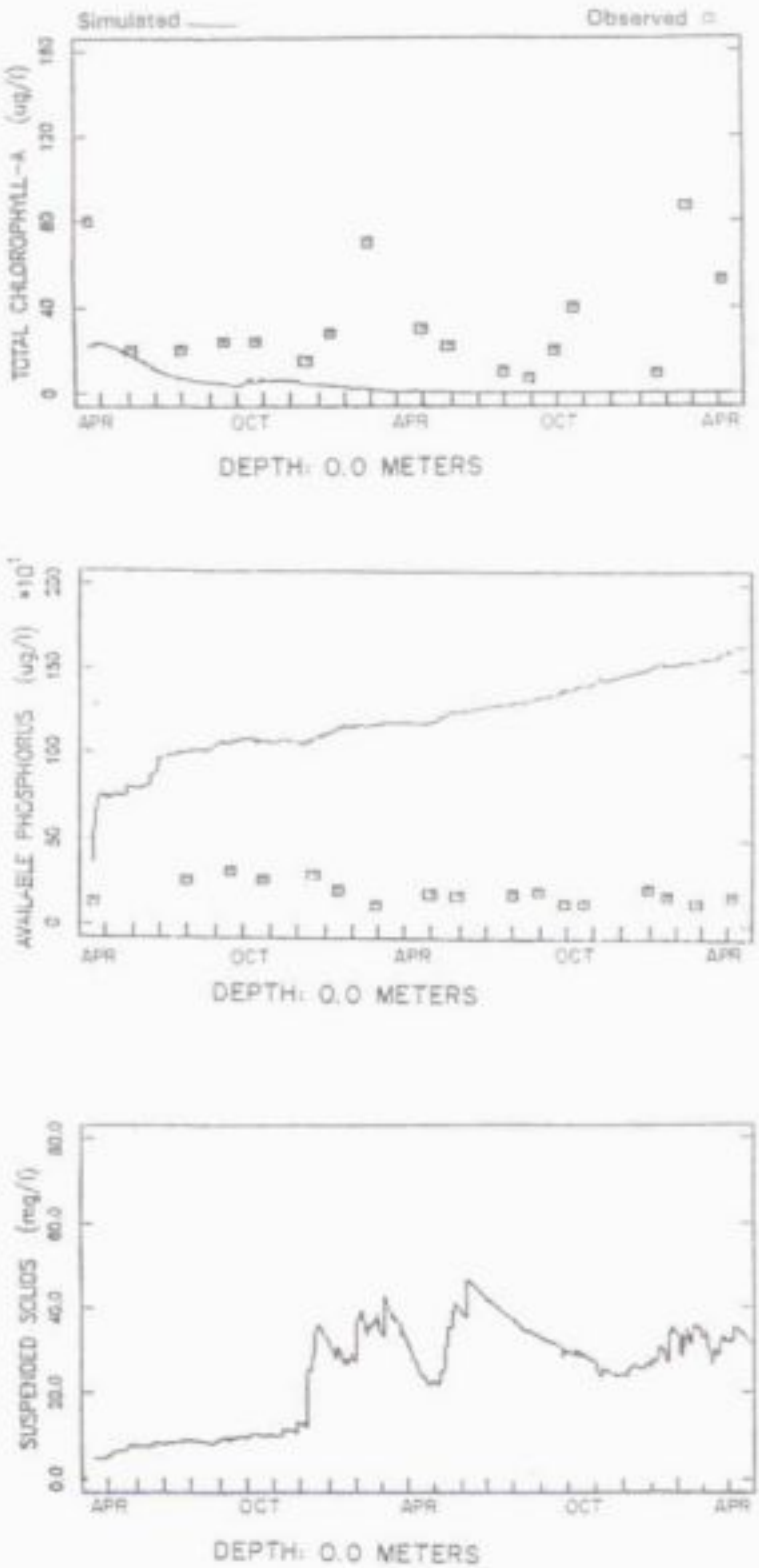
ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed mixed layer depth obtained with synthezised TSS	FIGURE 3.14b

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

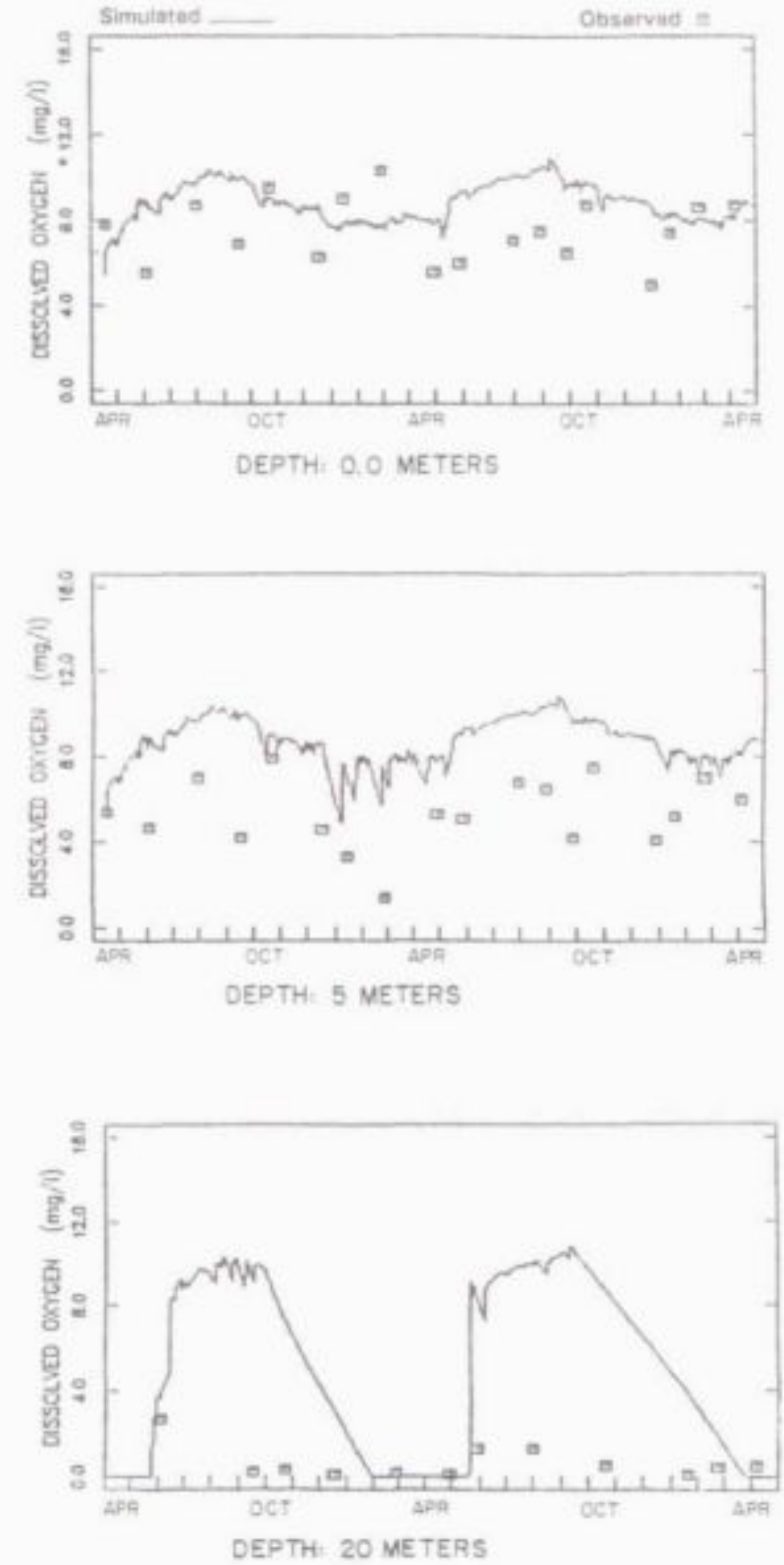
CONDITIONS : WINDSPEED AT 10m, EDDY COEFFICIENT = 1.73m² d⁻¹ SYNTHESIZED TSS



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with synthezised TSS in the inflow.	FIGURE 3.14C

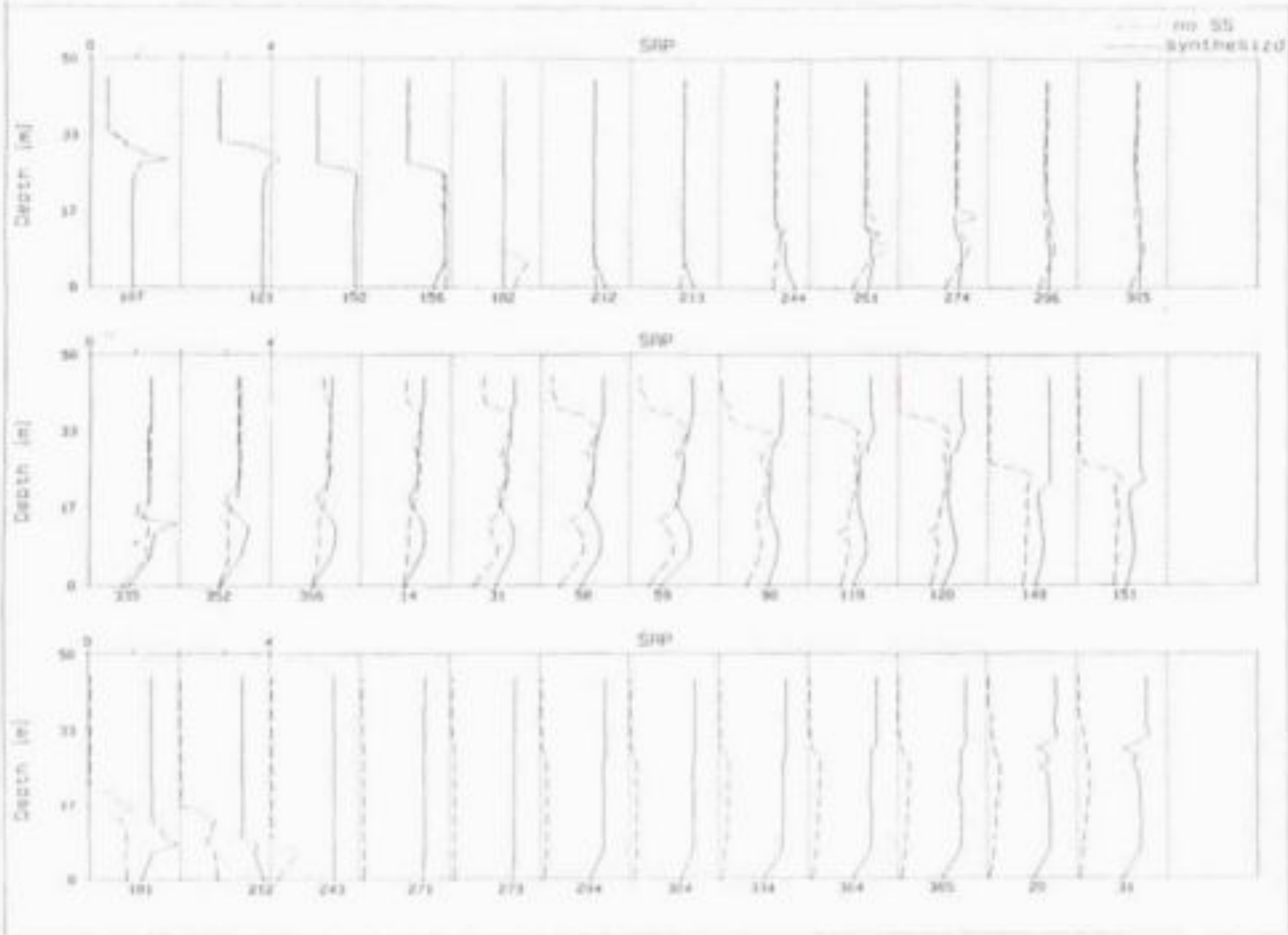
ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m^2 d^{-1} SYNTHESIZED TSS



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with synthezised TSS in the inflow.	FIGURE 3.14 d

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Depth / time graph of simulated phosphorus concentrations with and without suspended sediment concentration	FIGURE 3.14c

3.14 LATEST SIMULATION RESULTS

The latest simulation results for the selected variables are shown in Figures 3.15a to 3.15f. These results were obtained with:

- coding errors that have been identified, corrected in the source code.
- input wind speed adapted to that at 10 m (as required by the model).
- TSS data synthesised as discussed in Section 3.11.
- calibration coefficients as indicated in Appendix 3.2.
- the rest of the input data as used previously.

3.14.1 Hydrodynamic simulation results

The simulated and observed temperatures (Figures 3.15a and 3.15b) show excellent correspondence at the surface, and at 5 m and 20 m. The temperature simulation can be regarded as very satisfactory.

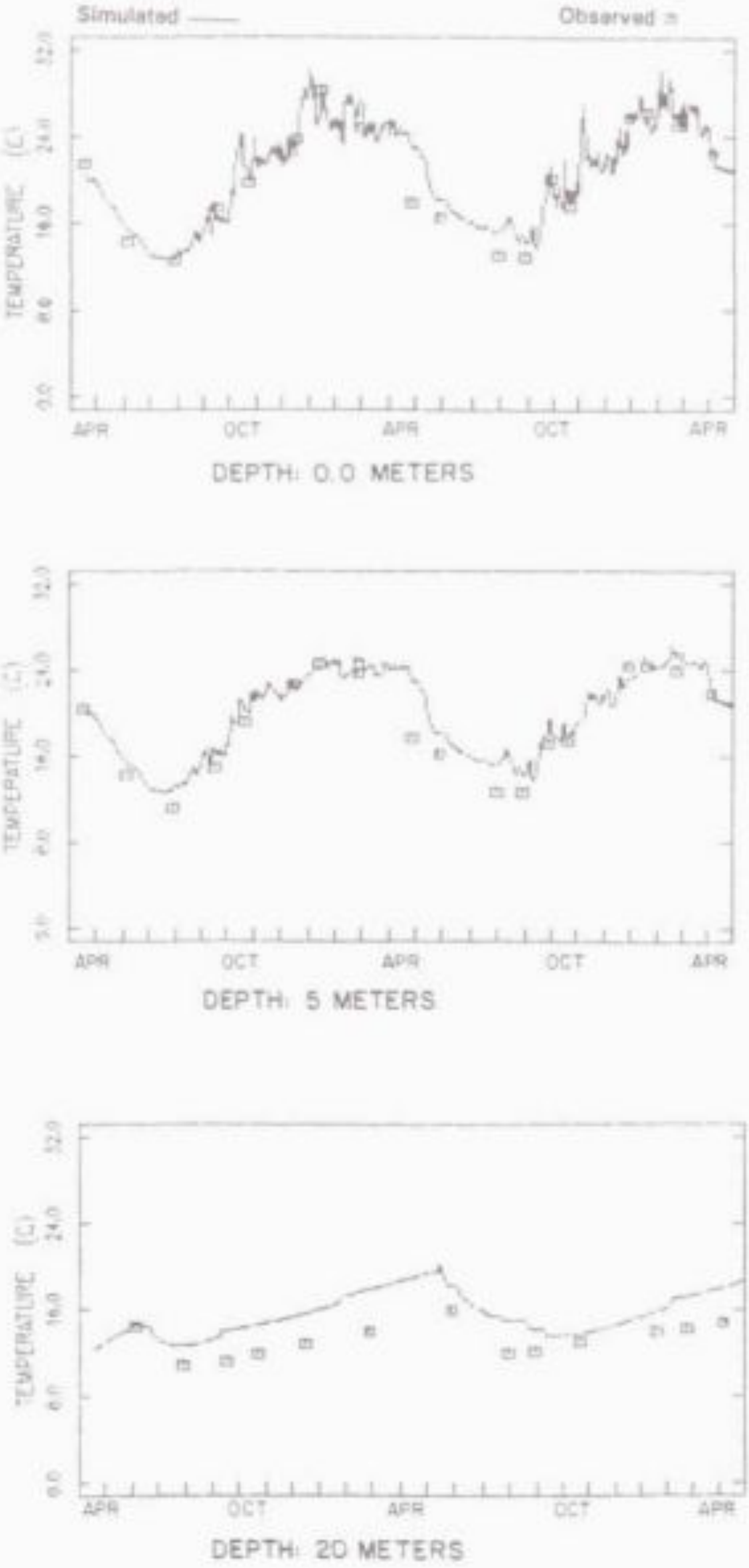
Some discrepancy still exists between the simulated and observed mixed layer depth. First indications are that this may be linked to the TSS concentration. It is difficult to assess the TSS simulation as there is no observed TSS data. However, in Figures 3.15b and 3.15d it can be seen that, during the period where mixed layer depth is inadequately simulated, the simulated TSS concentration is lower than during the rest of the simulation period. This aspect will need further study, the synthesised TSS concentration may have to be re-evaluated.

3.14.2 Water quality simulation results

For the purposes of calibration, the developers of MINLAKE suggest that the simulation of hypolimnetic phosphorus needs to be acceptable before dissolved phosphate/algal growth in the photic zone can be resolved. However, for Roodeplaat Dam, dissolved phosphate

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

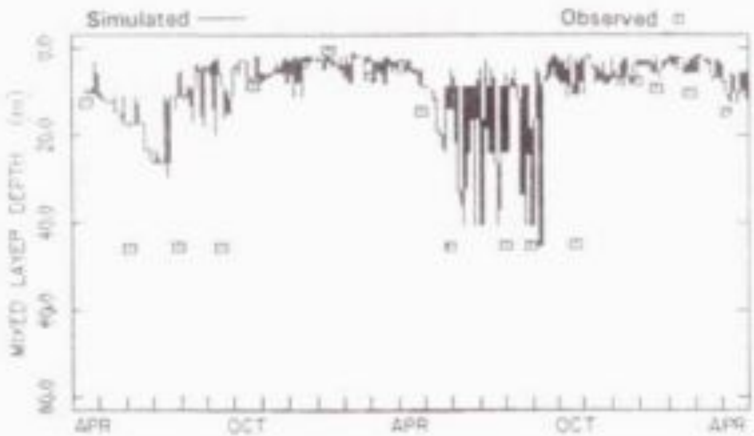
CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3. CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ SYNTHESIZED TSS



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed temperature obtained with corrected model	FIGURE 3.15a

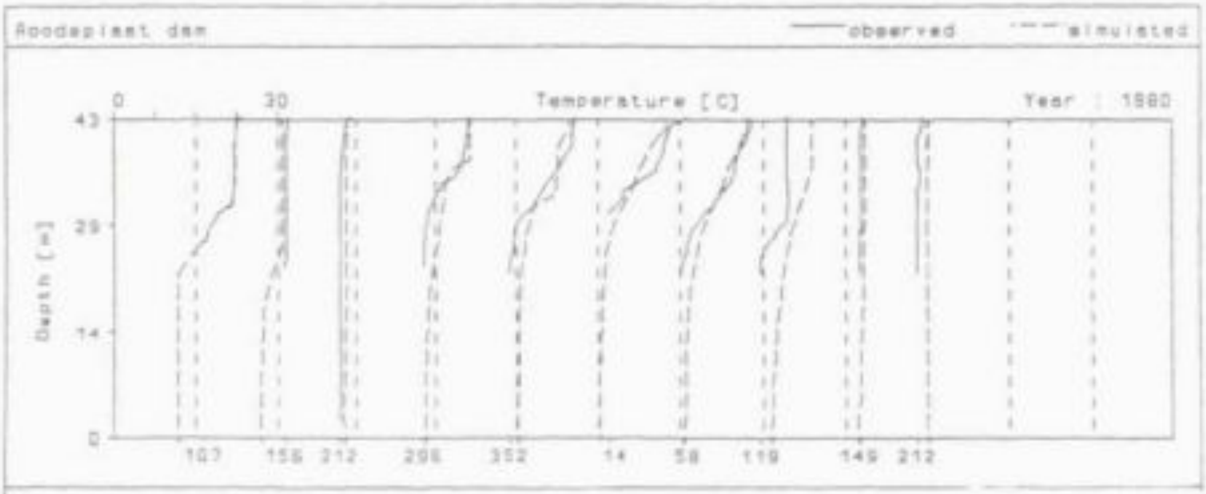
ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3, CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73$m^2 d^{-1}$ SYNTHESIZED TSS



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed mixed layer depth obtained with corrected model.	FIGURE 3.15b

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982



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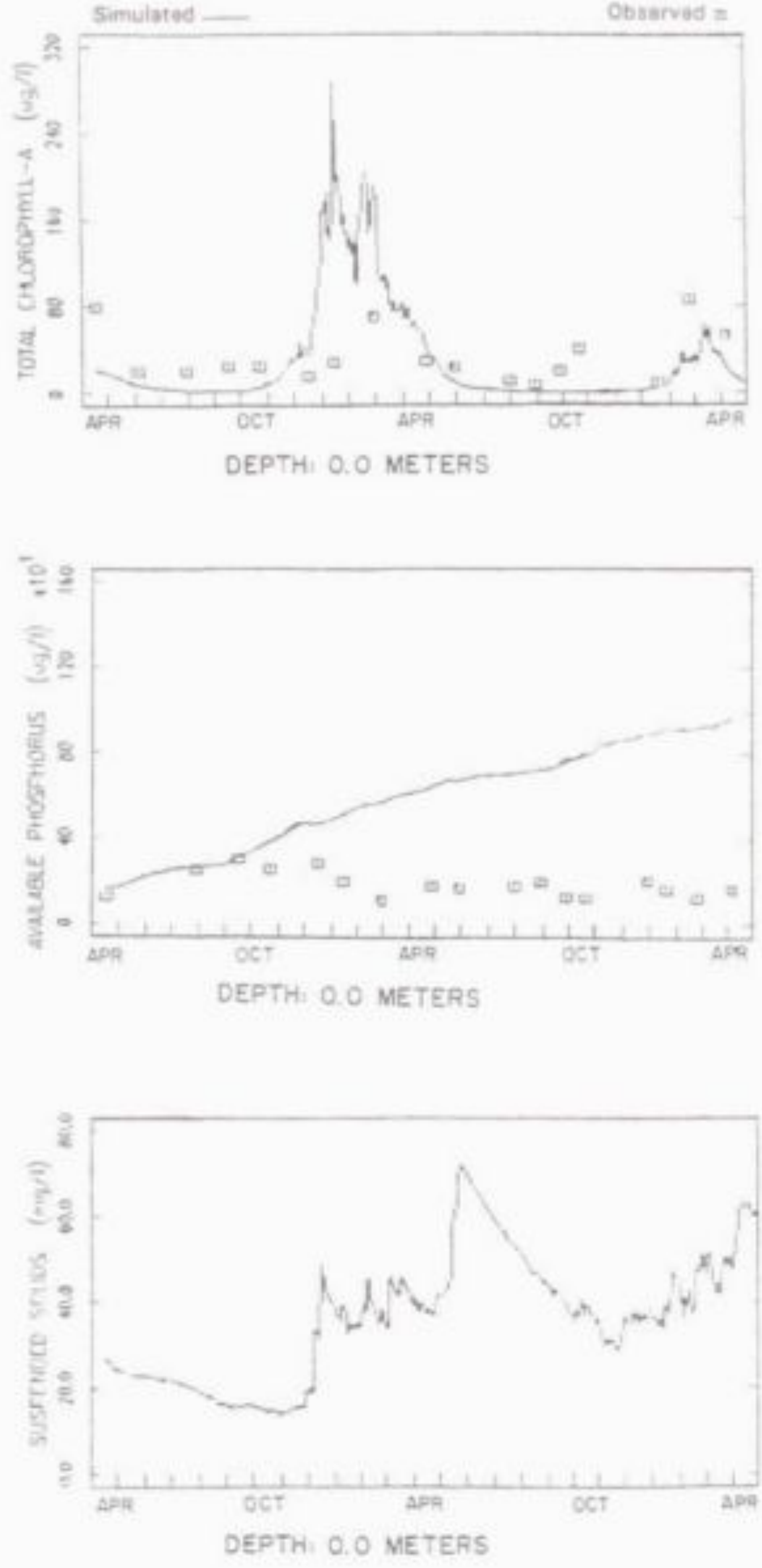
WATER RESEARCH COMMISSION

Plot of simulated vs observed temperatures with depth

FIGURE 3.15c

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

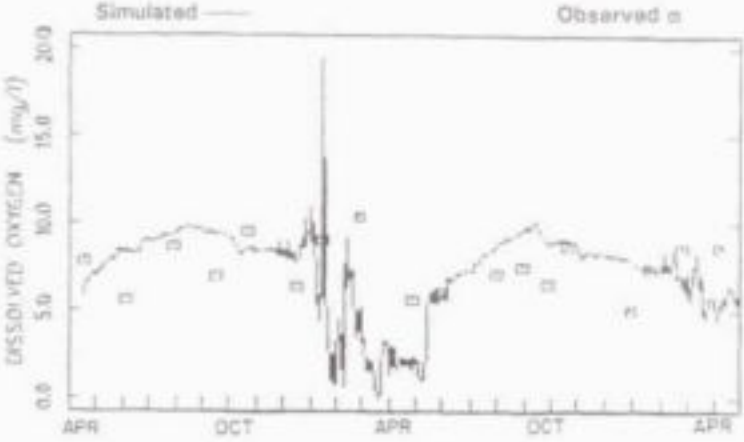
CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3 CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73$m^2 d^{-1}$ SYNTHESIZED TSS



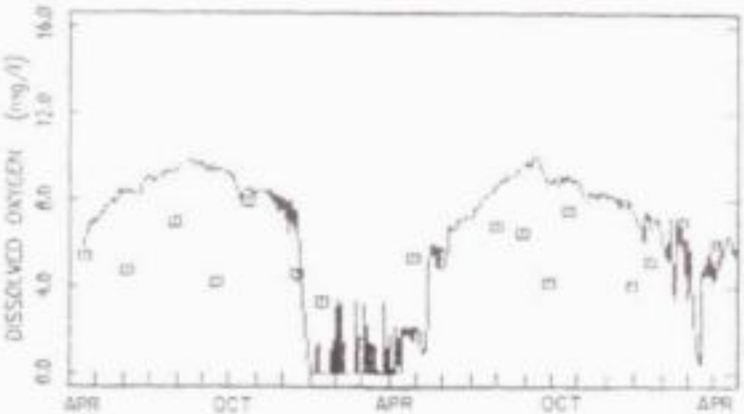
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with corrected model.	FIGURE 3.15d

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

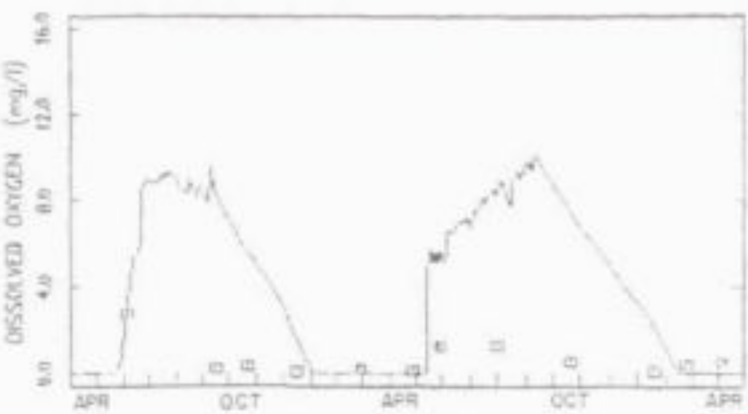
CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3, CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ SYNTHESIZED TSS



DEPTH: 0.0 METERS



DEPTH: 5 METERS

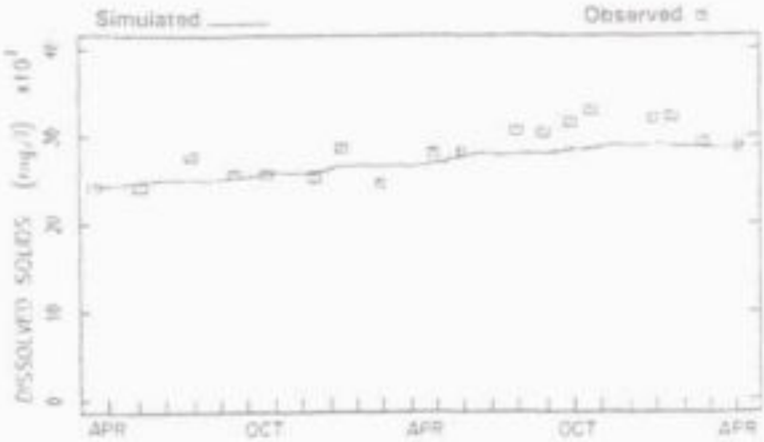


DEPTH: 20 METERS

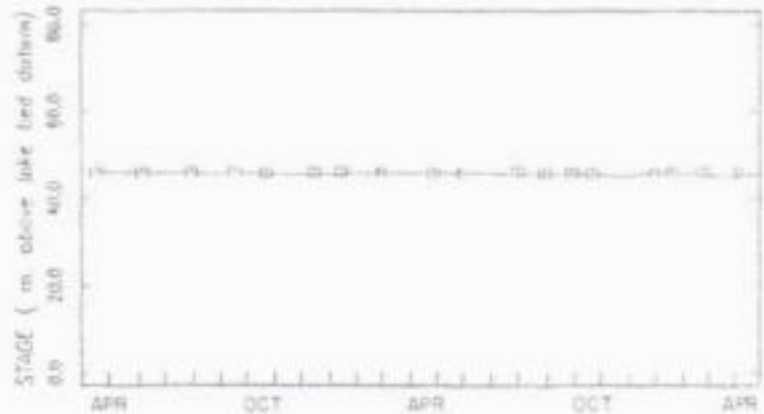
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with corrected model.	FIGURE 3.15e

ROODEPLAAT DAM - APRIL 1980 TO APRIL 1982

CONDITIONS : COEFFICIENTS AS IN APPENDIX 3.3 CODING ERRORS CORRECTED.
WINDSPEED AT 10m. EDDY COEFFICIENT = 1.73m² d⁻¹ SYNTHESIZED TSS



DEPTH: 0.0 METERS



HENNAM SNAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Plot of simulated vs. observed water quality variables obtained with corrected model.	FIGURE 3.15 F

concentration was only occasionally measured in the hypolimnion, and then not always at the same depth, so that it is not always possible to test the model performance in the hypolimnetic zone.

Regarding the surface simulation of chlorophyll-a and dissolved phosphate concentrations, it still deviates significantly from the observed values. Regarding the simulation of dissolved oxygen (Figure 3.15e), the simulation of algal growth has to be acceptable before attempting to improve the simulation of dissolved oxygen.

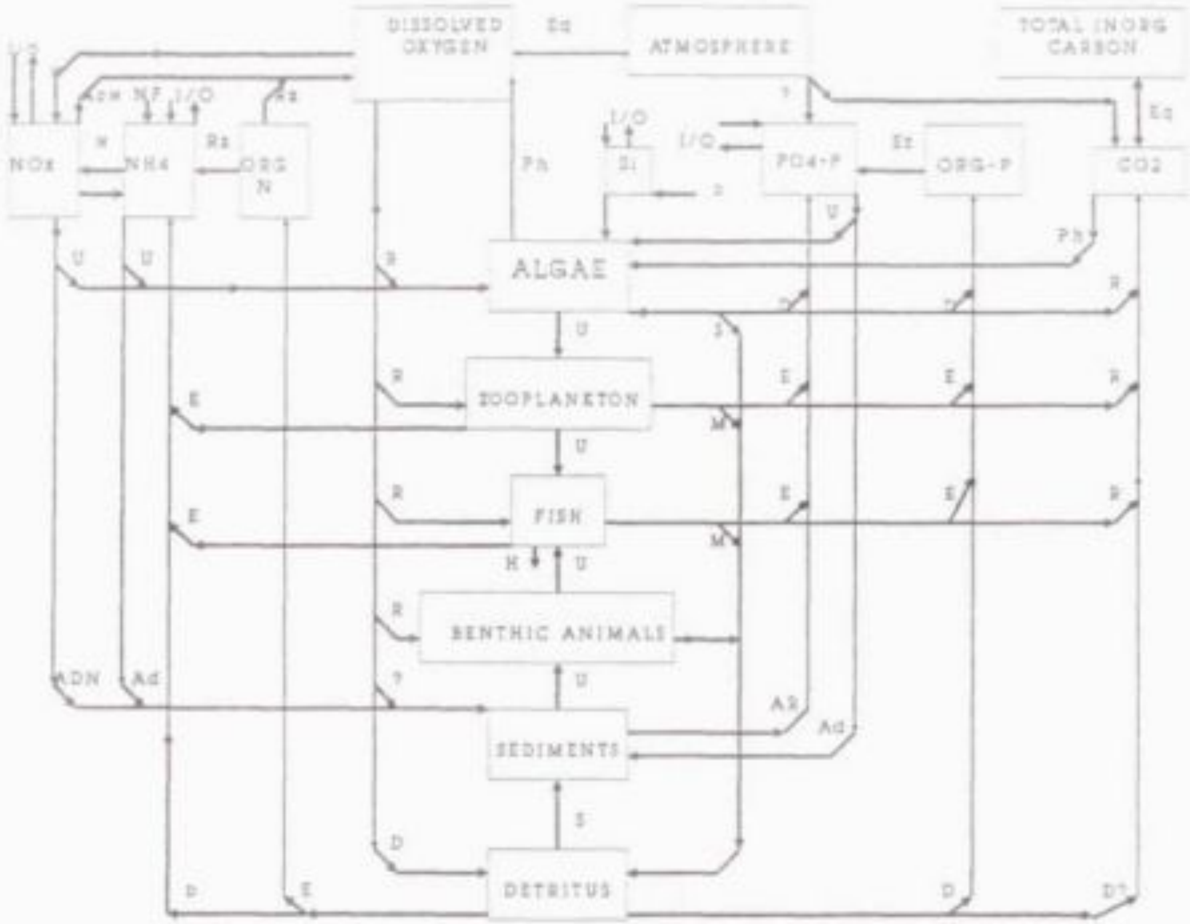
The excessive increase in **simulated** algal concentration during December 1980 cannot yet be explained. A thorough study of the data did not reveal any justification for the excessive increase. There remains the possibility that algal growth may be nitrogen limited. Thus far, only phosphorus limited growth has been simulated. MINLAKE does make provision for the simulation of nitrogen limited growth. However, due to time constraints, this aspect has not yet been investigated.

There is a steady increase in simulated phosphorus concentration and even at the end of the two year simulation period, steady state conditions are not achieved. This may be because, in MINLAKE, the suspended and bottom sediment/phosphorus interactions are poorly developed. For example, phosphorus release from the bottom sediments is described by an empirical constant unrelated to temperature and the aerobic/anoxic state of the overlying water, very likely an inadequate representation. A literature study to obtain more insight into these processes and their temperature effect will be required before further simulations of the phosphorus/algal response can be attempted.

3.15 PROCESS FORMULATION

Usually, the primary water quality processes that occur in a reservoir are depicted in a diagram similar to the one in Figure 16(a). However, this diagram does not give any information as to the stoichiometric relationship between compounds, or the kinetic rates of the different processes. A task group of the International Association on Water Pollution and Control has recently proposed a matrix method for presenting the processes and the compounds on which they act in biological systems (Henze, 1987). The processes are listed in the first column of the matrix, while the compounds are listed in the first row. The intersect cell defines the stoichiometric relationship and the kinetics of the associated process are listed in the last column.

To illustrate this approach, a part of such a matrix, showing three of the processes that affect phosphorus concentration in MINLAKE, is depicted in Figure 16b. The matrix forms an easily comprehended fingerprint of the processes, their interactive kinetics and stoichiometry. The matrix can be readily expanded to include additional processes and compounds and the system can be solved by a computerised calculation technique which remains the same irrespective of the size of the matrix. This approach can be applied to the water quality processes in reservoirs with advantage.



Ad	Adsorption	I/O	Inflow and outflow
ADN	Anaerobic denitrification	M	Mortality
AR	Aerobic release	N	Nitrification
D	Bacterial decay	NF	Nitrogen fixation
DN	Denitrification	Ph	Photosynthesis
E	Excretion	R	Respiration
Eq	Equilibrium	Rx	Chemical reduction
Ez	Enzymatic reaction	S	Settling
H	Harvesting	U	Nutrient uptake

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Diagram of primary water quality processes

FIGURE 3.16a

	Dissolved PO4-P ($PO4_D$)	Particulate (stored) P (P_s)	PO4-P adsorbed ($PO4_A$)	
Phosphate adsorption	-1		+1	$PO_A = k\ PO_D^{1/n}$
Phosphate uptake	-1	+1		$U = U_{max} \frac{Q_m - P_s}{Q_m - K_Q} \cdot \frac{PO_D}{K_s + PO_D}$
Photosyn-thesis		-1		$\mu = \mu_{max} \frac{P_s - K_Q}{P_s}$

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Matrix representation of primary water quality processes

FIGURE 3.16b

3.16 SENSITIVITY ANALYSIS

A full statistical sensitivity analysis has not been done due to time constraints. However, in calibrating MINLAKE it was observed that:

MINLAKE is extremely sensitive to:

- wind speed
- sediment phosphorus release rate
- hypolimnetic eddy diffusion
- maximum growth rate
- non-predatory mortality
- minimum intracellular phosphorus concentration

MINLAKE is not very sensitive to:

- changes in solar radiation
- wind direction/fetch - a behaviour possibly applicable only to small and medium size reservoirs
- effect of temperature on algal growth

3.17 CONCLUSIONS: APPLICATION OF MINLAKE

3.17.1 Hydrodynamic behaviour

The hydrodynamic aspects, as represented in MINLAKE, are relatively straight forward and have a well founded basis in theory. The hydrodynamic behaviour of Roodeplaat Dam can be adequately simulated with the MINLAKE model. Very likely this model should be adequate for simulating the hydrodynamic behaviour of other reservoirs in South Africa of similar or smaller size, provided that acceptable hydrometeorlogical databases are available.

3.17.2 Water quality behaviour

MINLAKE appears to have considerable potential for the simulation of water quality behaviour. In particular, it allows for simulation of:

- growth of up to three algal classes
- both phosphorus and nitrogen limited growth
- light limited algal growth
- effect of temperature on algal growth
- zooplankton growth

The degree in which adequate simulation of the water quality behaviour will be achieved is not yet clear, for the following reasons:

- There is not yet certainty that the water quality processes included in the model are adequately formulated; this aspect will require intensive and extensive study.

- Phosphorus-sediment interaction is not included in the model, an interaction which has been mooted to be of significant importance in South African reservoirs (DWAF, 1981) - MINLAKE incorporates only a sediment phosphorus release coefficient which has to be set empirically by the user.

3.17.3 MINLAKE software

The MINLAKE software is reasonably user-friendly and easy to use:

- The program is structured in two parts: The main program, incorporating 40 clearly defined subroutines and a reservoir specific program. This structure facilitates changes to the program, and decreases compilation time.

- The MINLAKE program is compiled using a Microsoft (Version 3.31 or higher) compiler. This compiler is readily available in South Africa.

- Debugging of data files is facilitated considerably by the use of the data listing files provided with the MINLAKE program.

The following deficiencies have been identified:

- there are coding errors in the main program.

- tracking of errors in the main program is complicated because all the common block variables are not listed in the manual; and variables are often renamed in the program, without this being indicated.

- some formulations are hardwired into the main program, eg. astronomical day length is formulated for a single northern latitude, without indicating that the formulation does not apply to other latitudes.

3.18 RECOMMENDATIONS

3.18.1 MINLAKE

The following modifications are required in the MINLAKE model:

* Sediment-phosphorus interaction, which may be very important under South African conditions, should be incorporated into the model.

* Simulation of pH should be included.

* In the source code, the units of all the input variables and constants should be converted to SI units to facilitate the use of MINLAKE for users outside the USA.

* The complex interactions between the various processes governing the hydrodynamic/water quality response are often difficult to comprehend. These can be depicted more clearly by a matrix representation of processes, compounds and their kinetic formulations. The processes in MINLAKE should be restructured in such a matrix. This approach may find application in all water quality models.

The following need further investigation:

* Nitrogen limited algal growth should be taken into account; up to the present only phosphorus limited growth has been considered, but the model response indicates that nitrogen limitation may be present.

* Optimum values for the algal specific calibration coefficients under South African conditions, should be determined.

- The model performance should be tested under reduced data input, such as smoothed weekly, monthly or even cyclic seasonal values for certain input variables, with the effect of perturbations (storm events) on the reservoir superimposed at different parts of the hydrological cycle.

  Such a study could assist in:

  a) identifying variables of significant/insignificant importance.
  b) establishing whether certain input variables could to be measured on a daily, monthly, or cyclic seasonal basis, and still satisfy the requirements of the model.
  c) establishing whether site specific data are essential, or whether regional data will suffice for certain variables.
  d) providing information on operational strategy when storm events occur at different periods during the annual cycle.

3.18.2 Data

A shortlist of reservoirs should be compiled where hydrodynamic or hydrodynamic water quality models are likely to be applied; and a monitoring strategy should be devised for these reservoirs. In such a strategy, particular attention should be accorded to the following:

- Wind speed - this is one of the most important driving forces in applications where simulation of the vertical distribution of substances is important. Such simulations are possible only with models having a spatial dimension of one or greater.

- Hypolimnetic sampling - integrated or grab samples of selected water quality variables should be taken at selected depths down to the bottom of the reservoir, at regular intervals. Measurements down the profile should always be at the same set of depths. Sampling intervals can range from monthly to quarterly.

- Inorganic suspended sediment should be measured routinely in these reservoirs, and in the rivers associated with them. A number of determinations of sediment composition/fall velocity, under stratified as well as fully mixed conditions, should also be undertaken for the sediments in each of the reservoirs.

- At present, the data required for modelling have to be obtained from various institutions. Although different models incorporate different sets of variables, in different formats, the basic input data requirements tend to be the same. The establishment of a 'modelling data bank' at an appropriate institution, linked to the Computing Centre for Water Research (CCWR), from where modellers can obtain data for various reservoirs, is proposed.

3.19 REFERENCES

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APPENDIX A3.1

INFLOW AND METEOROLOGICAL DATA AVAILABLE FOR ROODEPLAAT DAM

THE AVAILABILITY OF METEOROLOGICAL DATA
FOR ROODEPLAAT DAM 1980-1983

MONTH	TEMP °C	DEWPOINT °C	PRECIP mm	WIND km/h	DIR	%SUN	RAD Various
1980 1	**	**	**	**	**	**	**
2	**	**	**	**	**	**	**
3	**	**	**	**	**	**	**
4	**	**	**	**	**	**	**
5	**	**	**	6	7	**	**
6	**	**	**	**	**	**	**
7	**	**	**	**	**	**	**
8	**	**	**	**	**	**	**
9	**	**	**	**	**	**	**
10	**	**	**	**	**	**	**
11	**	**	**	**	8	**	**
12	**	**	**	**	3	**	**
1981 1	**	**	**	4	18	**	**
2	**	**	**	**	11	**	**
3	**	**	**	**	**	**	**
4	**	**	**	**	**	**	**
5	**	**	**	**	**	**	**
6	**	**	**	**	**	**	12
7	**	**	**	**	**	**	**
8	**	**	**	3	3	5	**
9	**	**	**	**	3	**	**
10	**	**	**	**	**	**	**
11	**	**	**	**	**	**	**
12	**	**	**	**	**	**	**

MONTH	TEMP	DEWPOINT	PRECIP	WIND SPEED	DIR	%SUN	RAD
1982 1	**	**	**	**	**	**	**
2	**	**	**	**	**	**	**
3	**	**	**	6	**	3	**
4	**	**	**	9	9	**	**
5	**	**	**	**	4	**	**
6	**	**	**	**	**	**	**
7	**	**	**	**	**	**	**
8	**	**	**	**	**	**	**
9	**	**	**	**	**	**	**
10	**	**	**	4	**	**	**
11	**	**	**	7	6	**	**
12	**	**	**	8	6	**	**
1983 1	**	**	**	**	**	**	**
2	**	**	**	**	**	**	**
3	**	**	**	**	**	**	**
4	**	**	**	**	**	**	**
5	**	**	**	**	**	**	**
6	**	**	**	**	**	**	**
7	**	**	**	**	**	**	**
8	**	**	**	3	3	3	**
9	**	**	**	**	**	13	**
10	**	**	**	**	**	3	**

** : Data is available

Number : Number of days of missing data (three or more consecutive days)

AVAILABILITY OF INFLOW DATA FOR PIENAARS RIVER

MONTH	FLOW m^3/s	TEMP °C	PO4 mg/l	BOD	TSS mg/l	TDS mg/l	NO3 mg/l	NH4 mg/l	CHLa mg/l
1980 1	**	31	4			4	4	4	
2	**	29	**			**	**	**	
3	**	31	**			**	**	**	
4	**	30	**			**	**	**	
5	**	31	10			10	10	10	
6	**	30	19			19	19	19	
7	**	12	14			14	14	14	
8	**	**	18			18	18	18	
9	**	**	**			**	**	**	
10	**	**	**			**	**	**	
11	**	**	**			**	**	**	
12	**	**	6			6	6	6	
1981 1	**	**	**			**	**	**	
2	**	**	**			**	**	**	
3	**	3	8			8	8	8	
4	**	**	**			**	**	**	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	**	**			**	**	**	
9	**	**	18			18	18	18	
10	**	**	**			**	**	**	
11	**	**	29			29	29	29	
12	**	**	9			9	9	9	

MONTH	FLOW	TEMP	PO4	BOD	TSS	TDS	NO3	NH4	CHLa
1982 1	**	**	**			**	**	**	
2	**	**	**			**	**	**	
3	**	**	**			**	**	**	
4	**	**	**			**	**	**	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	4	**			**	**	**	
9	**	**	**			**	**	**	
10	**	**	20			20	20	20	
11	**	**	23			23	23	23	
12	**	**	3			3	3	3	
1983 1	**	**	16			16	16	16	
2	**	5	9			9	9	9	
3	**	**	**			**	**	**	
4	**	**	4			4	4	4	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	**	**			**	**	**	
9	**	3	3			3	3	3	
10	**	**	**			**	**	**	
11	**	**	**			**	**	**	
12	**	**	**			**	**	**	

** : Data is available

NUMBER : Number of days of missing data (three or more consecutive days)

BLANK : The variable was not monitored

AVAILABILITY OF INFLOW DATA FOR HARTBEESSPRUIT

MONTH	FLOW m^3/s	TEMP °C	PO4 mg/l	BOD	TSS mg/l	TDS mg/l	NO3 mg/l	NH4 mg/l	CHLa mg/l
1980 1	**	31	4			4	4	4	
2	**	29	**			**	**	**	
3	**	31	**			**	**	**	
4	**	30	**			**	**	**	
5	**	31	5			5	5	5	
6	**	30	19			19	19	19	
7	**	12	14			14	14	14	
8	**	**	18			18	18	18	
9	**	**	**			**	**	**	
10	**	**	5			5	5	5	
11	**	**	**			**	**	**	
12	**	**	5			5	5	5	
1981 1	**	**	**			**	**	**	
2	**	**	5			5	5	5	
3	**	3	8			8	8	8	
4	**	**	**			**	**	**	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	**	**			**	**	**	
9	**	**	20			20	20	20	
10	**	**	**			**	**	**	
11	**	12	29			29	29	29	
12	**	**	9			9	9	9	

MONTH	FLOW	TEMP	PO4	BOD	TSS	TDS	NO3	NH4	CHLa
1982 1	**	**	**			**	**	**	
2	**	**	**			**	**	**	
3	**	**	**			**	**	**	
4	**	**	4			4	4	4	
5	**	**	3			3	3	3	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	4	**			**	**	**	
9	**	11	10			10	10	10	
10	**	10	29			29	29	29	
11	**	**	23			23	23	23	
12	**	**	3			3	3	3	
1983 1	**	**	27			27	27	27	
2	**	7	10			10	10	10	
3	**	20	20			20	20	20	
4	**	18	17			17	17	17	
5	**	27	20			20	20	20	
6	**	14	17			17	17	17	
7	**	14	14			14	14	14	
8	**	15	15			15	15	15	
9	**	25	26			26	26	26	
10	**	**	10			10	10	10	
11	**	**	**			**	**	**	
12	**	**	3			3	3	3	

** : Data is available

NUMBER : Number of days of missing data (three or more consecutive days)

BLANK : The variable was not monitored

AVAILABILITY OF INFLOW DATA FOR EDENDALESPRUIT

MONTH	FLOW cfs	TEMP °C	PO4 mg/l	BOD	TSS mg/l	TDS mg/l	NO3 mg/l	NH4 mg/l	CHLa mg/l
1980 1	**	31	4			4	4	4	
2	**	29	**			**	**	**	
3	**	31	**			**	**	**	
4	**	30	**			**	**	**	
5	**	31	6			6	6	6	
6	**	30	19			19	19	19	
7	**	12	14			14	14	14	
8	**	**	18			18	18	18	
9	**	**	**			**	**	**	
10	**	**	**			**	**	**	
11	**	**	**			**	**	**	
12	**	**	9			9	9	9	
1981 1	**	**	**			**	**	**	
2	**	**	5			5	5	5	
3	**	3	6			6	6	6	
4	**	**	**			**	**	**	
5	**	**	**			**	**	**	
6	**	**	**			**	**	**	
7	**	**	**			**	**	**	
8	**	**	**			**	**	**	
9	**	**	20			20	20	20	
10	**	**	**			**	**	**	
11	**	6	29			29	29	29	
12	**	9	9			9	9	9	

MONTH	FLOW	TEMP	PO4	BOD	TSS	TDS	NO3	NH4	CHLa
1982 1	**	**	**			**	**	**	
2	**	8	8			8	8	8	
3	**	25	25			25	25	25	
4	**	30	30			30	30	30	
5	**	31	31			31	31	31	
6	**	30	30			30	30	30	
7	**	27	27			27	27	27	
8	**	4	**			**	**	**	
9	**	**	**			**	**	**	
10	**	27	29			29	29	29	
11	**	30	30			30	30	30	
12	**	31	31			31	31	31	
1983 1	**	24	29			29	29	29	
2	**	28	28			28	28	28	
3	**	31	31			31	31	31	
4	**	30	30			30	30	30	
5	**	31	31			31	31	31	
6	**	30	30			30	30	30	
7	**	31	31			31	31	31	
8	**	31	31			31	31	31	
9	**	30	30			30	30	30	
10	**	31	31			31	31	31	
11	**	8	9			9	9	9	
12	**	**	**			**	**	**	

** : The data is available

NUMBER : The number of days of missing data (three or more consecutive days)

BLANK : The variable was not monitored

APPENDIX A3.2

ALGAL AND CLIMATE SPECIFIC CALIBRATION COEFFICIENTS FOR ALGAL SPECIES COMMON IN WATER QUALITY MODELLING IN SOUTH AFRICA

ALGAL AND CLIMATE SPECIFIC CALIBRATION COEFFICIENTS FOR ALGAL SPECIES COMMON IN WATER QUALITY MODELLING IN SOUTH AFRICA

* Value used to obtain latest MINLAKE simulation results (Section 3.14)

CALIBRATION COEFFICIENT	UNITS	VALUE	REFERENCE
Extinction coefficient of water	m^{-1}	0.55 to 1.99*	Pieterse (1990)
Specific extinction coefficient of phytoplankton	$m^2\ g^{-1}$ Chla	12*	FRD (1985)
Wind function coefficient		25.6*	MINLAKE (1988)
Wind sheltering coefficient		0.95*	MINLAKE (1988)
Sediment oxygen depletion rate	$g\ m^{2}\ day^{-1}$	1.0*	MINLAKE (1988)
Sediment phosphorus release coefficient	$g\ m^{2}\ day^{-1}$	0.001*	DWAF (1981)
Detrital decay rate	day^{-1}	0.07*	MINLAKE (1988)
Detrital settling rate	$m\ day^{-1}$	0.05*	Orlob (1983) Canale (1976)
Algal respiration rate	day^{-1}	0.03 0.08*	Orlob (1983) Canale (1976)
Algal mortality rate	day^{-1}	0.003 to 0.17 0.07*	EPA (1985)
Algal settling rate:	$m\ day^{-1}$		
Blue-green algae		0.002* 0.0	Orlob (1983) Canale (1976)
Green algae		0.02 0.02	Orlob (1983) Canale (1976)
Diatoms		0.03	Canale (1976)

CALIBRATION COEFFICIENT	UNITS	VALUE	REFERENCE
Maximum phosphorus uptake rate:	day^{-1}		
Blue-greens			
non N-fixing		0.0035	Orlob (1983)
N-fixing		0.042	Canale (1976)
Greens		0.059	"
Diatoms		0.133	"
Microsystis		0.024	"
		0.12	Bierman (1977)
Half saturation coefficient for phosphorus uptake	$mg\ l^{-1}$		
Microsystis		0.006	Bierman (1977)
			Canale (1976)
Blue-green		0.0025*	EPA (1985)
Greens		0.0025 to 0.47	
Minimum intracellular phosphorus concentration needed for growth:	moles P $cell^{-1}$		
Microsystis		$0.58*10^{-15}$	Bierman (1977)
Blue-greens (non N-fixing)		$0.58*10^{-15}$	Canale (1976)
Blue-greens (N-fixing)		$0.13*10^{-14}$	"
Greens		$0.2*10^{-14}$	"
Diatoms		$0.2*10^{-14}$	Orlob (1983)
		0.075 to 0.15	Reynolds (1984)
Blue-greens	mg P mg^{-1} Chla	0.34	

CALIBRATION COEFFICIENTS	UNITS	VALUE	REFERENCE
Maximum intracellular phosphorus storage capacity	mg P mg^{-1} Chla		
Blue-greens		1.0 to 1.5	Orlob (1983)
Phytoplankton mass per cell	mg dry weight $cell^{-1}$		
Microsystis		$0.25*10^{-7}$	Bierman (1977)
Maximum nitrogen uptake rate:	day^{-1}		
Blue-greens		0.0096	Orlob (1983)
Non N-fixing		0.04	Canale (1976)
N-fixing		0.04	"
Greens		0.06	"
Diatoms		0.015	"
Microsystis		0.072	Bierman (1977)
Half saturation coefficient for nitrogen uptake:	mg l^{-1}		
Blue-greens		0.015	Canale (1976)
Minimum intracellular nitrogen concentration needed for growth:	moles $cell^{-1}$		
Microsystis		$0.52*10^{-13}$	Bierman (1977)
Blue-greens			Canale (1976)
N-fixing		$0.52*10^{-13}$	
non-N-fixing		$0.85*10^{-13}$	
Greens		$0.52*10^{-13}$	
Diatoms		1.0 to 2.0 $0.52*10^{-13}$	Orlob (1983)

CALIBRATION COEFFICIENTS	UNITS	VALUE	REFERENCES
Maximum intracellular nitrogen to chlorophyll-a ratio: Blue-greens	mg N mg^{-1} Chla	4.0 to 5.0	Orlob (1983)
Half saturation coefficient for preferential uptake of ammonium over nitrate:	mg l^{-1}	<0.025	MINLAKE (1988)
Maximum nutrient saturated growth rate: Blue-greens Non N-fixing N-fixing	day^{-1}	1.6 1.1 1.1 1.9 1.6	Orlob (1983) Canale (1976) Canale (1976) Orlob (1983) Canale (1976)
Green algae		0.25 0.24	Bierman (1977) Reynolds (1984)
Microsystis Unicellular culture Colonial culture		1.11 0.48 0.25*	Reynolds (1984) Reynolds (1984)
Upper temperature at which algal growth is reduced 90% : Blue-greens	°C	45*	Orlob (1983)
Lower temperature at which growth is reduced 90 % : Microsystis	°C	15*	FRD (1985)

CALIBRATION COEFFICIENT	UNITS	VALUE	REFERENCE
Optimum temperature for algal growth:	°C		
Blue-greens		33	Orlob (1983)
Microsystis		35*	Bierman (1977)
Half saturation coefficient for light limited growth.	$\mu E\ m^{-2}\ s^{-1}$	250*	Megard (1984)
Light inhibition coefficient	$\mu E\ m^{-2}\ s^{-1}$	1900*	Megard (1984)

* Value used to obtain latest MINLAKE simulation results (Section 3.14).

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APPENDIX A3.3

DATABASE DEVELOPMENT FOR HARTBEESPOORT DAM

A3.1 RESERVOIR DESCRIPTION

Hartbeespoort Dam lies in a summer rainfall region with an average annual rainfall of about 700 mm. The reservoir is located 37 km West of Pretoria at the confluence of the Crocodile and Magalies Rivers. The Crocodile River is the principal source of water for the reservoir and is largely supplemented by treated effluent from the extensively urbanised areas in its upper catchment.

The point of inflow of the two rivers, the shape of the reservoir, the sampling point and wind measurement stations, are shown in Figure 3.17. Further characteristics of Hartbeespoort Dam are presented in Table A3.1. Area, volume, and maximum and mean depth is indicated for full supply level.

TABLE A3.1 : CHARACTERISTICS OF HARTBEESPOORT DAM

Area	2000 ha
Volume	194,6 x 10^6 m^6
Maximum depth	31,1 m
Mean depth	9,6 m
Height above sea level	1131,2 m
Annual inflow	234 x 10^6 m^3
Annual outflow	228 x 10^6 m^3

A3.2 DATABASE DEVELOPMENT

A3.2.1 Meteorological and inflow data

The various meteorological and inflow data sets were mostly obtained from the same institutions and in the same form as for Roodeplaat Dam (see Table 3.2). Additional data on wind speed and direction were obtained from the CSIR (Division of Water Technology).

Processing of meteorological and inflow data: From Table 3.2 it is evident that the required data had to be obtained from various state departments, and that the available data sets were not in a readily usable format. Only river flow rate and chemical water quality parameters were available in computerised format. Computer data capturing from photostat copies of original records was required in the case of river water temperature, sun hours and solar radiation, and because of the format of the data this was a laborious process. Where photostat copies of original recorder charts were obtained (i.e. wind speed and direction, air temperature and humidity) digitising of the raw data was required.

Two meteorological variables required by the model, viz. dew point temperature and percentage sun hours, were not available. These variables were calculated as described in Section 3.11.1.

Infilling of missing meteorological and inflow data: Though the required data were available on a daily basis for extensive periods during January 1984 to December 1986, there were still some periods in between where no data were available. However, infilling of data was possible. The same rationale as for Roodeplaat Dam (see Section 3.11.1) was used for the infilling of missing data of solar radiation, sun hours, inflow water temperature, and concentrations of dissolved phosphate, total dissolved salts and inorganic suspended sediments.

	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Map of Hartbeespoort Dam	FIGURE 3.17

the reservoir. Concentrations of dissolved phosphate, nitrate-nitrite, ammonia, TDS and chlorophyll-a also were measured, but not always down to the bottom of the reservoir. Depth profile data were obtained from the Division for Water Technology, CSIR.

Calibration coefficients and reservoir constants: A total of 24 calibration coefficients on the process behaviour, and 12 constants on the physical characteristics of Hartbeespoort Dam, are required by the program (Table 3.5). Values for the constants describing the physical characteristics of Hartbeespoort Dam were obtained from the Department of Water Affairs. In sofar as the calibration coefficients are concerned, only a few of these could be estimated from the literature on studies that had been done previously on Hartbeespoort Dam. Although a range of values for each calibration coefficient is given in the manual, these are often of restricted use; for instance, the 12 coefficients relating to algal growth are algal and climate specific, and there is little indication in the manual as to the values for specific algal species in a given climate. As a starting point, where the value of a calibration coefficient could not be determined for Hartbeespoort Dam, the default value suggested for Lake Riley was used. The calibration coefficients, and the values that were used, are listed in Table 3.5.

A3.3 PRELIMINARY MINLAKE SIMULATIONS

MINLAKE was implemented on Hartbeespoort Dam using the preliminary data set and provisional parameter set described above. It became clear very soon that the data sets required in-depth investigation in terms of anomalies and apparent errors. Particularly the wind and inflow time series were suspect. A pragmatic decision was subsequently made to concentrate all MINLAKE investigations on Roodeplaat Dam, as described in Chapter 3.

CHAPTER 4
APPLICATION OF A TWO-DIMENSIONAL WATER QUALITY MODEL: CE-QUAL-W2

by
A J Bath

Contents

4.1 INTRODUCTION

Model overview Many waterbodies exhibit significant multi-dimensional water quality variation caused by the interplay of hydrodynamic, biological and chemical processes. Water movement and mixing processes are closely linked to other mechanisms determining the quality of the water. The ability to link the multi-dimensional hydrodynamic and transport simulations with algorithms to predict constituent kinetics are shown to be critical to many water quality investigations. CE-QUAL-W2 is a two-dimensional, laterally averaged, hydrodynamic and water quality simulation model. The model assumes lateral homogeneity, and is suited to relatively long and narrow waterbodies which exhibit gradients in water quality in both the longitudinal and vertical directions. The model is designed to simulate the water quality and hydrodynamics in rivers, reservoirs and estuaries (Cole, 1991). In South Africa, reservoirs are generally long and narrow which provides an ideal opportunity to test the predictive ability of CE-QUAL-W2. This chapter describes the use of CE_QUAL_W2 to simulate the water quality of (1) Inanda Dam, situated in the Province of Natal and (2) the Vaal Barrage, situated on the border of the Transvaal and Orange Free State.

Model background CE-QUAL-W2 has been under development since 1975. The original model was known as LARM - **L**aterally **A**veraged **R**eservoir **M**odel (Edinger and Buchak, 1975). The first use of LARM was on reservoirs with no branches. Subsequent modifications to the model allowed for multiple branches and the ability to simulate estuarine boundary conditions. These modifications gave rise to the model known as GLVHT (**G**eneralised **L**ongitudinal-**V**ertical **H**ydrodynamics and **T**ransport model). The addition of the water quality algorithms by the United States Corps of Engineers resulted in version 1 of CE-QUAL-W2. Version 2 of the source code was modified to increase the computation efficiency and to decrease the storage requirements of the model. In addition, an algorithm has been added which calculates the maximum allowable time step and adjusts the time increments to maintain numerical stability. The format of the input and output files has also been changed to assist the user.

CE-QUAL-W2 uses a solution scheme that allows directly coupled and concurrent two-dimensional hydrodynamic and water quality simulations. The hydrodynamics are coupled with the water quality through relationships between density, water temperature and solids concentrations. The model employs the same time steps and spatial grid for concurrent hydrodynamic and water quality simulations. The solution scheme allows simulations to be made over time frames which, if necessary, can encompass a full stratification cycle i.e. a period of time up to, and exceeding, one year.

The model is particularly appropriate to reservoirs in South Africa where the main concern is water quality variations along the longitudinal and vertical axes, and where the lateral variation is comparatively small. A number of studies carried out in South africa and overseas show that the lateral influence on water quality is relatively small (Wells and Gordon, 1982; Thornton *et al.*, 1982).

Martin (1988) and Cole (1991) developed and tested CE-QUAL-W2 on Degray Lake which they show was ideally suited with pronounced longitudinal and vertical variation in water quality. DeGray Lake is representative of a large number of reservoirs which show dissolved oxygen depletions in the metalimnion (between epilimnion and hypolimnion) of the pool area and the hypolimnion of upstream regions during stratified periods.

This chapter describes CE-QUAL-W2 and application of the model using data for Inanda Dam in Natal, as well as the Vaal Barrage in the Transvaal. For Inanda Dam, the model was calibrated using water quality data collected during the beginning of 1990 and verified using data for the end of 1990. For the Vaal Barrage, the simulation period extended over the period July to November 1990. Section 4.2 describes the software, documentation, and hardware requirements of the model. Section 4.3 describes the selection of reservoirs and simulations performed. Section 4.4 and 4.5 describe the simulations for Inanda Dam and the Vaal Barrage.

4.2 MODEL DESCRIPTION

Conceptual Design CE-QUAL-W2 simulates time varying vertical and longitudinal distributions of thermal energy and selected biological and chemical constituents in a water body. The model is based on a *finite difference* solution of the laterally averaged equations of fluid motion (Buchak and Edinger, 1982) and include:

- The free surface wave equation
- Hydrostatic pressure
- Horizontal momentum
- Continuity
- Constituent transport
- An equation of state dealing with the density and constituents including temperature and solids concentration.

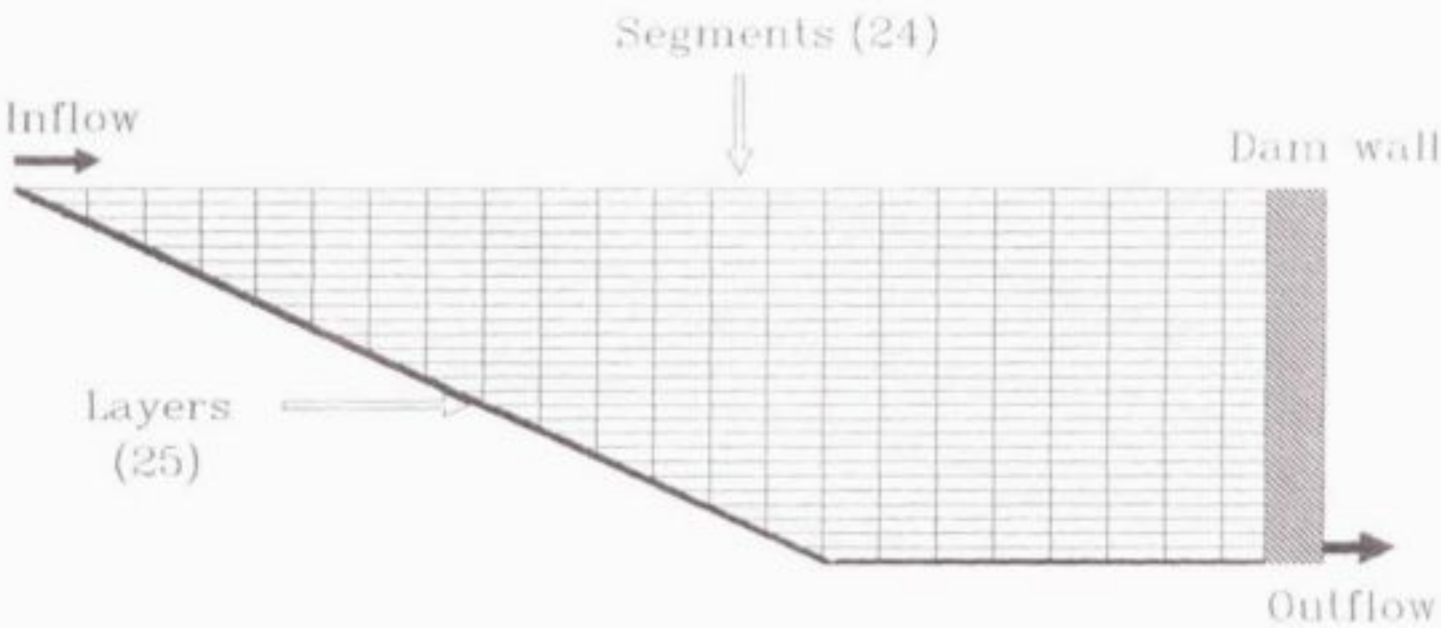
The unknowns include: the free water surface elevations, pressures, densities, horizontal and vertical velocities and chemical concentrations. The model permits the use of longer time steps and the affordable simulations of reasonable time periods for field applications (i.e stormflow periods, full stratification cycles). Explicit solution schemes are used to compute velocities and in the temperature and chemical/biological constituent calculations. CE-QUAL-W2 has the capability of including head or flow boundary conditions, branches, lateral inflows, multiple withdrawals and outlets.

The model is based on the following physical configuration of a reservoir. Along the main flow path, the reservoir is divided into a series of segments, each segment is divided into layers or cells, see Figure 4.1. The model predicts the average temperature for each model "cell" based on the inflow, outflow, solar radiation and surface heat exchange. The model predicts twenty water quality constituents in addition to temperature, density and circulation pattern. The chemical and biological constituents are simulated in three levels, and include:

Tracer Coliform Suspended solids	Level One
Total dissolved salts Dissolved organic matter - labile Dissolved organic matter - refractory Algae Detritus Orthophosphate Ammonia Nitrate Oxygen	Level Two
Inorganic carbon Alkalinity Carbon dioxide pH Sediment Iron	Level Three

The model is designed so that the user may specify the water quality variables of interest, providing flexibility in model application. Decay and decomposition reactions, shown in Figures 4.2 to 4.4, are described using first order kinetics. The user can simulate sediment decomposition by either first order decay or as a zero order sediment oxygen demand (SOD), see Figure 4.5. The user has the option of specifying different zero-order SOD rates for each segment in the reservoir. Sediment release of ammonia-nitrogen, phosphate-phosphorus and iron under anoxic conditions are modelled as zero order processes, Figures 4.3 and 4.5.

INANDA DAM



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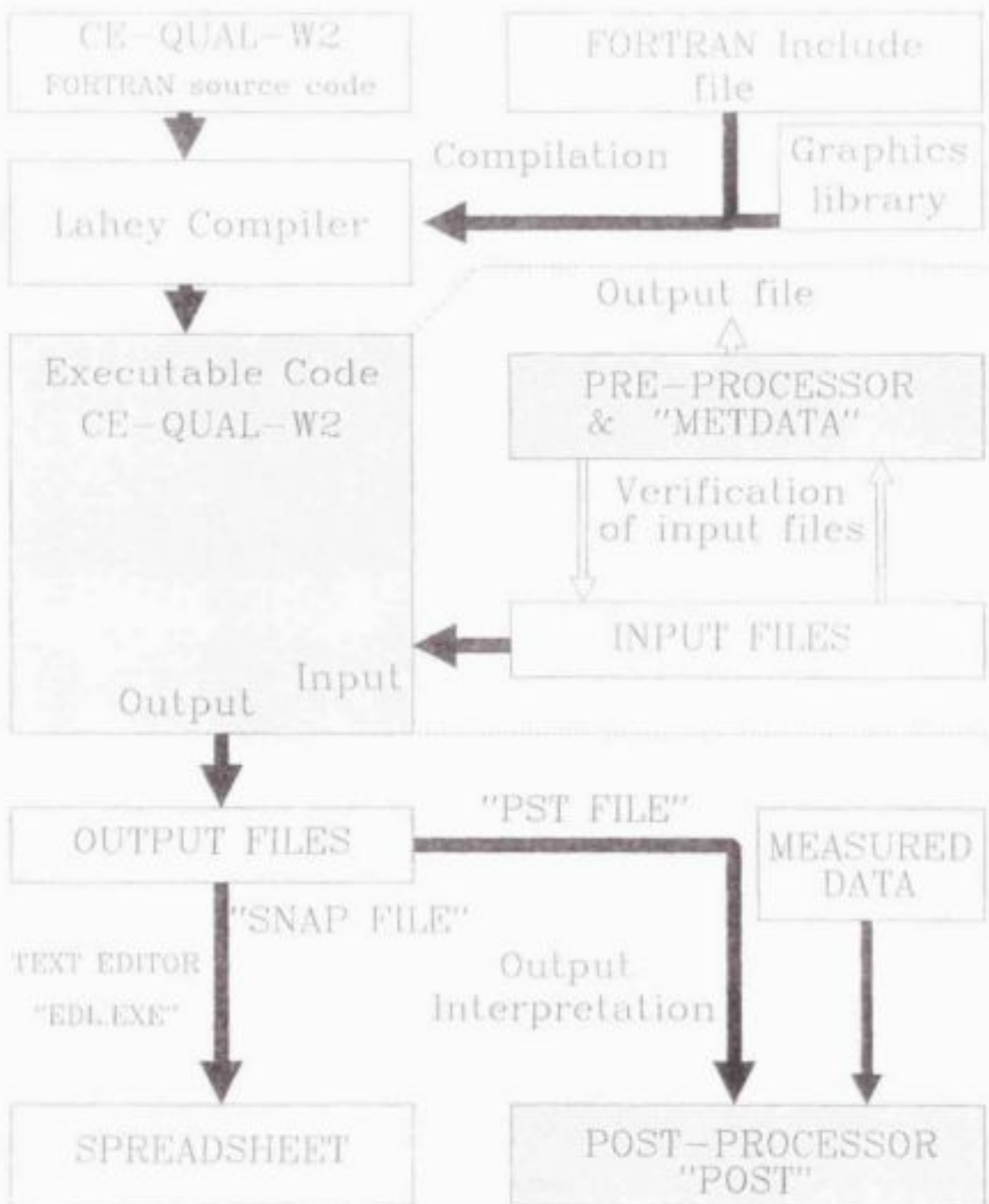
Inanda Dam: segment and layer configuration used in CE-QUAL-W2

FIGURE 4.1



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Software used in the compilation, run stream and processing of CE-QUAL-W2 data files.	FIGURE 4.6

Hardware Requirements The documentation states the minimum configuration of computer required for application of the model is a 80386 personal computer with 80387 coprocessor. The computer must have an extended memory of 4 Megabytes and hard disk with 10 to 15 Megabytes of available space. The DeGray Lake simulation covering a period of 251 days was run on a number of computers giving the following run times.

Computer:	Run time:
VAX 11/750	7 hours 29 minutes
VAX 8800	1 hour 12 minutes
Everex 80386/387 coprocessor 25 MHz	3 hours 39 minutes
Everex 80386/Weitek coprocessor 25 MHz	1 hour 32 minutes
Mecer 80386/387 Fasmath coprocessor 33 MHz	1 hour 59 minutes
Mecer 80486 33 MHz	56 minutes
Thomas 80486 33 MHz Weitek coprocessor	56 minutes

Based on the run times shown above, model simulations were performed on a Mecer 80486 33 MHz machine, and when available, simulations were also performed on a Thomas 80486 with Weitek coprocessor. Problems were experienced in that the FORTRAN code compiled with the Weitek option, produced the same run times as if the machine did not have the Weitek coprocessor. Tests were carried out to produce executable code which recognises and uses the 486 Weitek, unfortunately the Lahey only recognises a 386 Weitek. The developers of Lahey state that the new upgrade will make the code compatible with the 80486 processor and 80486 Weitek which will reduce computation times.

4.3 RESERVOIR SELECTION

To determine the predictive ability of CE-QUAL-W2 two reservoirs were selected, namely, Inanda Dam and the Vaal Barrage. These water bodies were selected because (1) they experience water quality problems, (2) both have an extensive water quality data base to calibrate and verify CE-QUAL-W2, and (3) both water bodies require the development of water quality management plans.

In general, water quality problems in South African reservoirs may be grouped into five categories, namely:

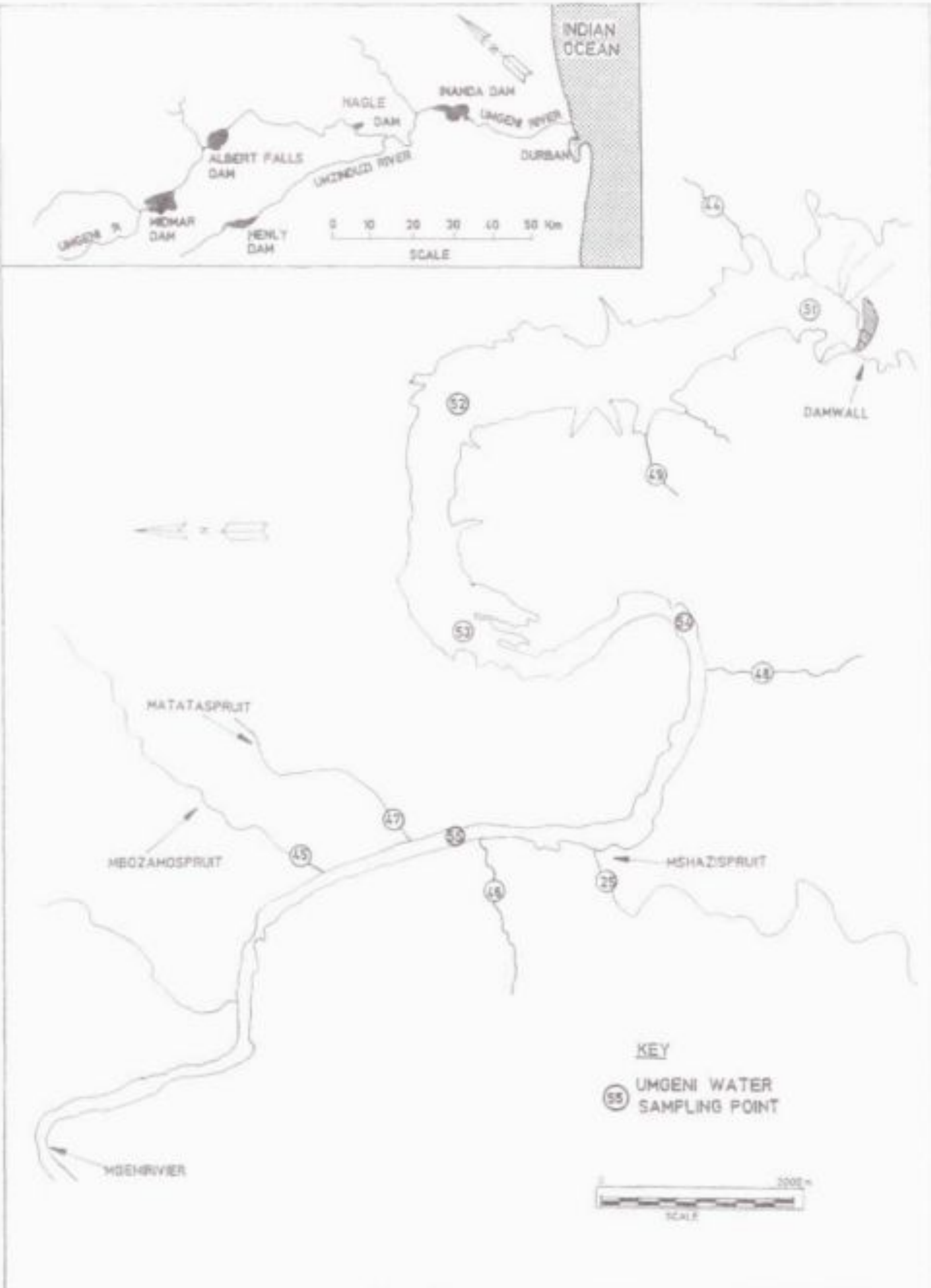
1. **Eutrophication** describes the development of a water body into a state in which the aerobic microbial decomposition of organic matter consumes more oxygen than is introduced into the system, resulting in an oxygen deficit. This definition extends beyond the early concepts of eutrophication as a phenomenon of increasing phytoplankton growth caused by enrichment with mineral nutrients. Increased nutrient loading remains the main cause of the massive growths of phytoplankton and water plants (Codd and Bell, 1985). Eutrophication results in increased water treatment costs, aesthetic problems, interference with recreation, taste and odour problems, problems for livestock watering, and clogging of irrigation canals (Walmsley and Butty, 1980). Eutrophication therefore has an adverse influence on all water use sectors including domestic, agricultural, industrial and recreation (Bath, 1989). The economic implications of eutrophication have not been determined in South Africa but the cost is expected to be high (Bruwer, 1979).

2. **Salinization** related problems occur through the increased loading of dissolved salts to a water body. Salinization results in problems for domestic, agricultural and industrial users of the water. Salinization has a direct influence on the industrial water users through scaling and corrosion of water reticulation systems. Salinization also influences the agricultural sector through damage to crops and soil.

3. **Microbiological** related problems are caused by the addition of runoff containing bacteriological contaminants. Microbiological contamination has most influence on the informal water user who takes water directly from a reservoir without treatment.

4. **Turbidity** related problems caused by the influx of suspended solids derived from surface erosion and riverine sources. High turbidity has a detrimental influence on all user groups as well as the aquatic environment. High turbidity in rivers reduces the operational life of the reservoirs to which they flow.

5. **Trace contaminants** a limited number of water bodies experience problems caused by dissolved organic compounds and trace metal contaminants. However, the occurrence of these problems is low when compared with the four groups described above.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Location map of Inanda Dam, and associated water quality monitoring points used by Umgeni Water.	FIGURE 4.7

at the points shown on Figure 4.7. The Umgeni River is the main inflow to Inanda Dam and sampled at point 26.1. Appendix A4.3 shows the format of the data files provided by Umgeni Water. CE-QUAL-W2 simulates 20 water quality constituents of which 16 are measured by Umgeni Water. The data set for Inanda Dam therefore allows a detailed calibration and testing of CE-QUAL-W2.

4.4.2 Model application: Inanda Dam

This section describes the application of CE-QUAL-W2 on Inanda Dam to examine the predictive abilities of the model, and where necessary adapt the model for use in South African conditions. In outline, the following approach was used

- Familiarisation of the Lahey compiler and programming environment.
- Compile and run the model with the test data set for DeGray Lake to verify the software and hardware configuration.
- Obtain data set for Inanda Dam, format and prepare the water quality and hydro-met data sets, and verify input data files using the CE-QUAL-W2 preprocessor.
- Test the model with different reservoir configurations and increasing levels of complexity. Figure 4.8 shows the four reservoir configurations used.
- Verify the output from the model against measured data for Inanda Dam using a postprocessor.

Application of the Lahey FORTRAN F77L EM/32 The FORTRAN environment comprises two sections. Firstly, the OS/386 which is the DOS extender which is loaded onto hard disk and uses 700 KBytes of space. Secondly, the FORTRAN F77L which consists of programs and utilities used to edit, debug and compile the source code. The F77L set of programs uses 2 MegaBytes of hard disk space. Once loaded onto hard disk, the OS/386 was tested to check that the program was installed correctly and operational. Test files were developed for this purpose. The FORTRAN programs were tested so that compiling, linking and binding could be carried out. Linking comprises the production of files with an extension of "EXP" which must be executed using the **UP** command. Binding comprises the production of executable files with the extension "EXE". Batch files were produced to simplify the compilation procedure.

INANDA DAM SIMULATIONS

(1) BASIC REPRESENTATION

1 Branch
1 Inflow
1 Outflow
26 Segments
25 Layers

(2) MODIFIED CHEMICAL REPRESENTATION

As above, plus:
detailed water quality boundary conditions

(3) MULTIPLE BRANCH REPRESENTATION

3 Branches
1 Inflow
1 Outflow
26 Segments
25 Layers
Detailed boundary conditions

(4) MULTIPLE INFLOW REPRESENTATION

3 Inflows

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Reservoir configurations used in the calibration and testing of CE-QUAL-W2 using data for Inanda Dam.	FIGURE 4.8

Application of the model using the DeGray Lake test data set The DeGray Lake test data set is provided to test and evaluate the configuration and setup of the hardware. CE-QUAL-W2 was compiled using the Lahey compiler, described above, in conjunction with the DeGray Lake "include" file. The preprocessor was compiled and used to verify the integrity of the input data files prior to the model being run. No errors were found in the input files. The output data file produced from the simulation was compared with the output file provided with the model, and showed the hardware was configured correctly. Application of the model with the test data set gave the run time shown in Section 4.2. The 80486 computers provided the shortest run time and hence were used for the calibration and verification of the model.

Appendix A4.5 shows the model output "snap" file. The interpretation and analysis of such an output file requires a postprocessor. Unfortunately, no postprocessor was available when the model was supplied from the US Corp of Engineers. The output file was compared with measured data using a number of programs such as text editors and spreadsheets, see Figure 4.6. An existing output managing program developed by Ninham Shand Inc., DYPLOT, was modified to provide comparison of measured and simulated data. The Post-processor is described in Appendix A4.2.

Preparation of data set for Inanda Dam The following data form input to the model

Geometric and bathymetric data

Boundary conditions

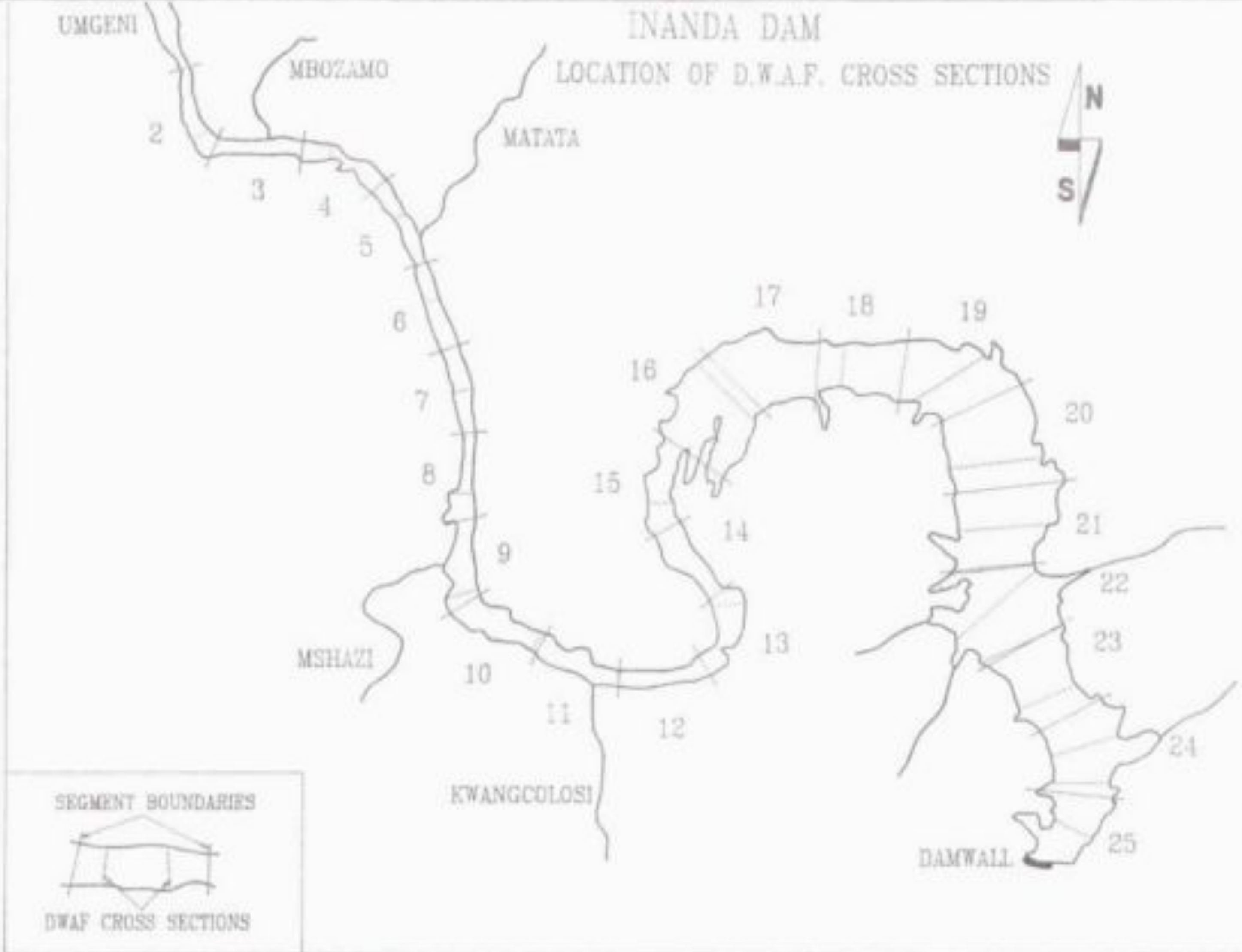
Hydraulic parameters

Kinetic parameters

Calibration and verification data

Geometric data An important task is assembling the geometric data used to represent the layout and volumetrics of the reservoir. These data are used to define the finite difference representation of the waterbody. The following data and information were used: (1) topographic maps (scale 1:50 000), (2) bathymetric cross-sections (DWA&F, 1990), see Figure 4.9, and (3) volume/area elevation tables and hydrographic survey (DWA&F, 1990). These data were processed as follows:

- The full supply level (FSL) of Inanda Dam was digitised on a Computer Aided Design (CAD) package using the hydrographic survey of Inanda Dam (DWA&F, 1990), see Figure 4.9.



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Inanda Dam: Segment layout used for CE-QUAL-W2, and location of cross-sectional data survey by the DWA&F (1990).

FIGURE 4.9

- As a guide to the choice of segment length and layer depth, the documentation states that segment lengths of 500 to 5000 metres and vertical layer depths of between 0.5 and 5 metre can be used. Figure 4.9 shows the FSL map of Inanda Dam divided into 25 segments with individual length of 750 metre. The segment layout was chosen to coincide with the location of water quality monitoring points used by Umgeni Water, see Figure 4.10.

- In the choice of number of layers, the maximum number of layers used in the DeGray Lake simulation was 36 giving a layer depth of 2 metre. In the Inanda Dam simulation a layer depth of 2 metre was used giving a total number of 25 layers. Figure 4.1 shows the configuration of layers and segments used in the Inanda Dam simulation.

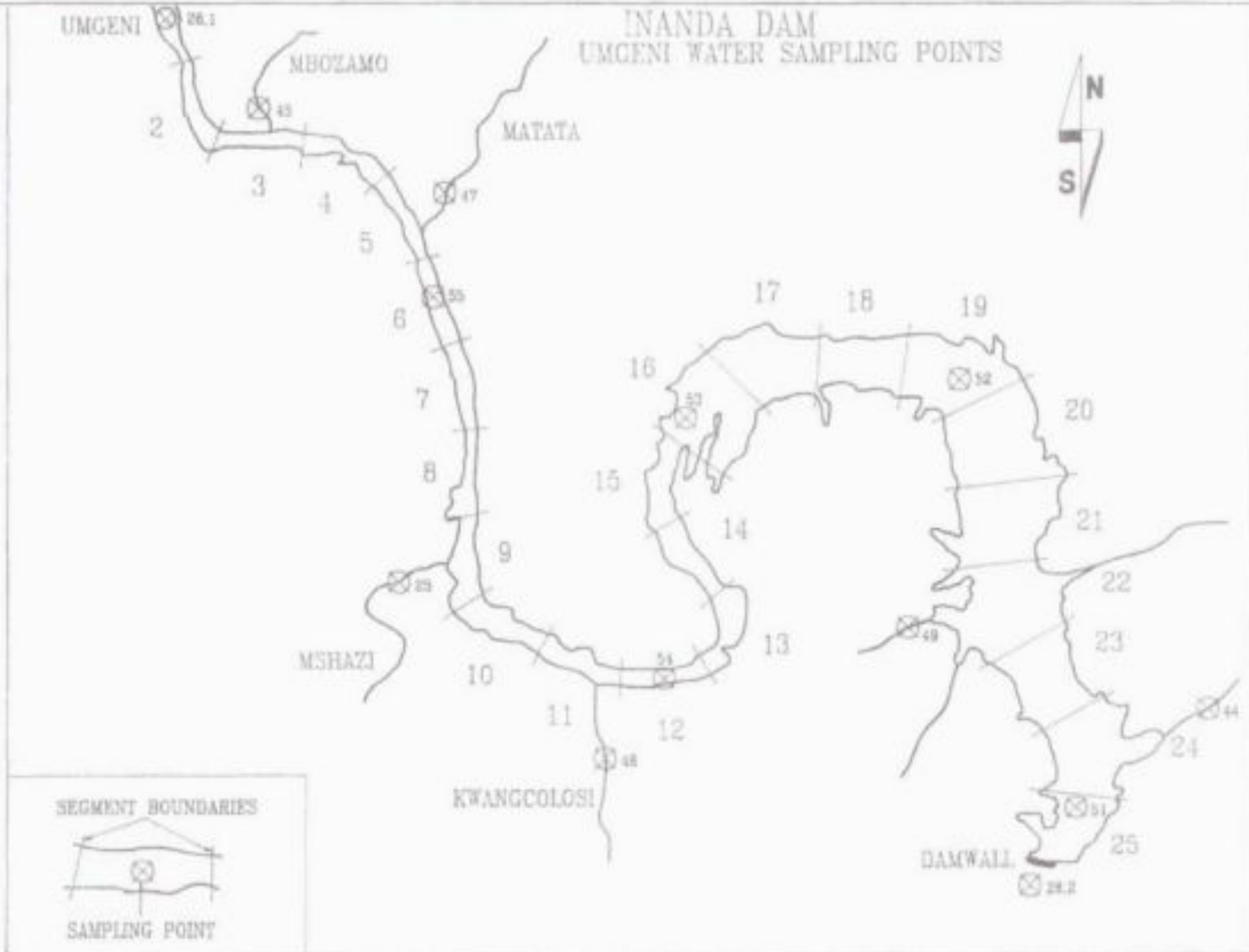
- Figure 4.9 shows the full supply level of Inanda Dam with the segment layout and position of the bathymetric cross-sections. Using CAD, the orientation of each segment was determined, see Figure 4.11.

- A spreadsheet was used to input the flow cross-sectional widths for each cell in the 24 segments. Linear interpolation was used in cells where no cross-sectional width data were available. Figure 4.12 shows the format of the spreadsheet used to compute the volume of the reservoir for different stage levels. In Figure 4.12, grid "A" shows the lateral widths of each cell, and grid "B" the computed volumes for each cell.

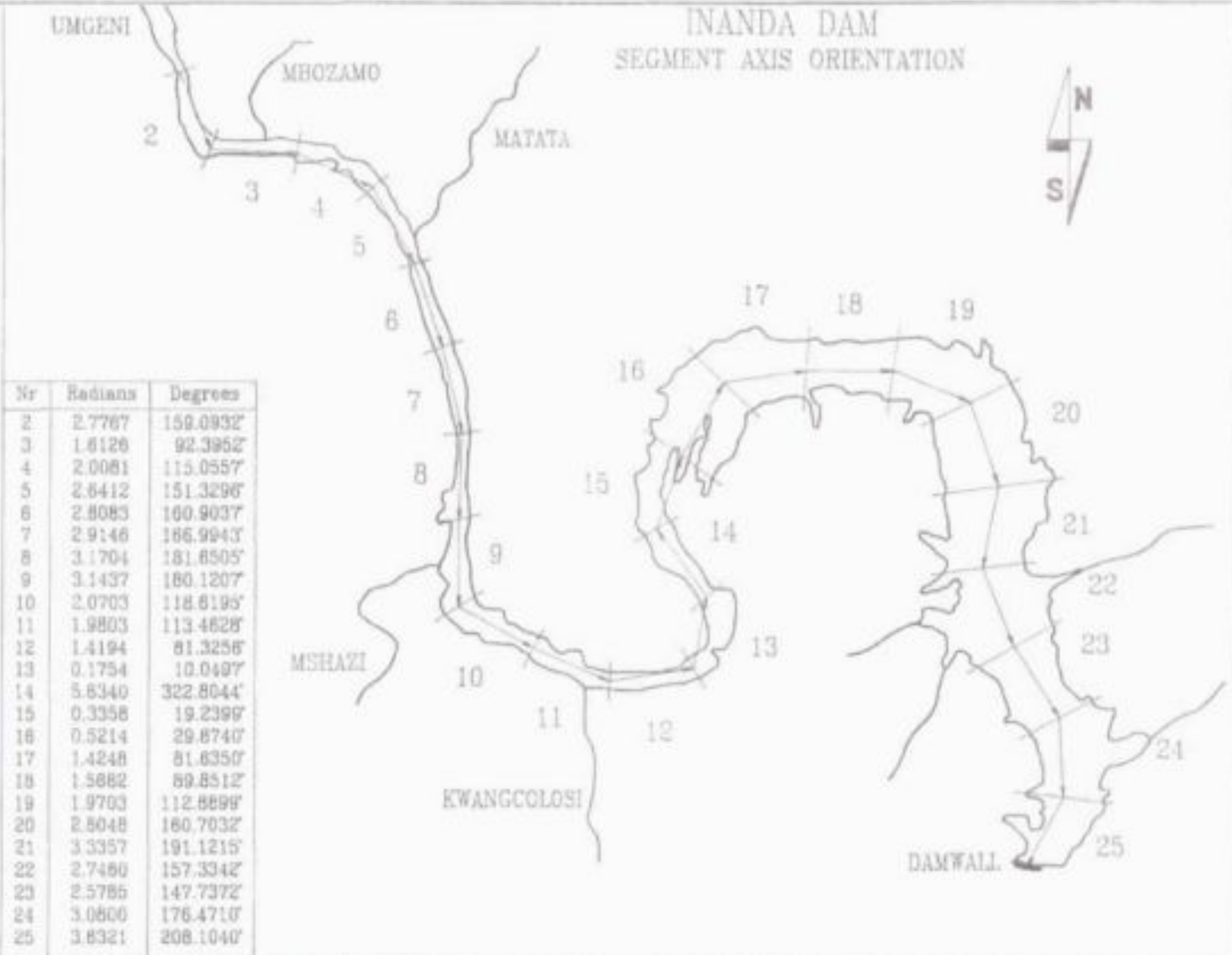
- Figure 4.13 shows the preliminary stage/reservoir volume relationship. The CE—QUAL—W2 preprocessor was used to optimize the bathymetric data and provided a near perfect correspondence between simulated and measured reservoir volumes. Figure 4.13 shows the adjustment of the data to minimize the difference between simulated and measured stage data.

Initial conditions The water quality boundary conditions are specified in the longitudinal and vertical profile files as well as in the control file, see Appendix A4.3. The initial conditions include:

- The starting and ending dates of the simulation period. A simulation period of 200 days spanning the period 1 January to 19 July 1990 was chosen as the calibration period for the Inanda Dam simulation.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Inanda Dam: Location of water quality monitoring points used by Umgeni Water and segment layout used in reservoir configuration.	FIGURE 3.10



Nr	Radians	Degrees
2	2.7767	159.0932'
3	1.6126	92.3952'
4	2.0081	115.0557'
5	2.6412	151.3296'
6	2.8083	160.9037'
7	2.9146	166.9943'
8	3.1704	181.6505'
9	3.1437	180.1207'
10	2.0703	118.6195'
11	1.9803	113.4628'
12	1.4194	81.3256'
13	0.1754	10.0497'
14	5.6340	322.8044'
15	0.3358	19.2399'
16	0.5214	29.8740'
17	1.4248	81.6350'
18	1.5682	89.8512'
19	1.9703	112.8899'
20	2.8048	160.7032'
21	3.3357	191.1215'
22	2.7460	157.3342'
23	2.5785	147.7372'
24	3.0800	176.4710'
25	3.6321	208.1040'

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Inanda Dam: application of CAD package to determine the orientation of the segments used in the CE-QUAL-W2 simulation.

FIGURE 4.11

A

B

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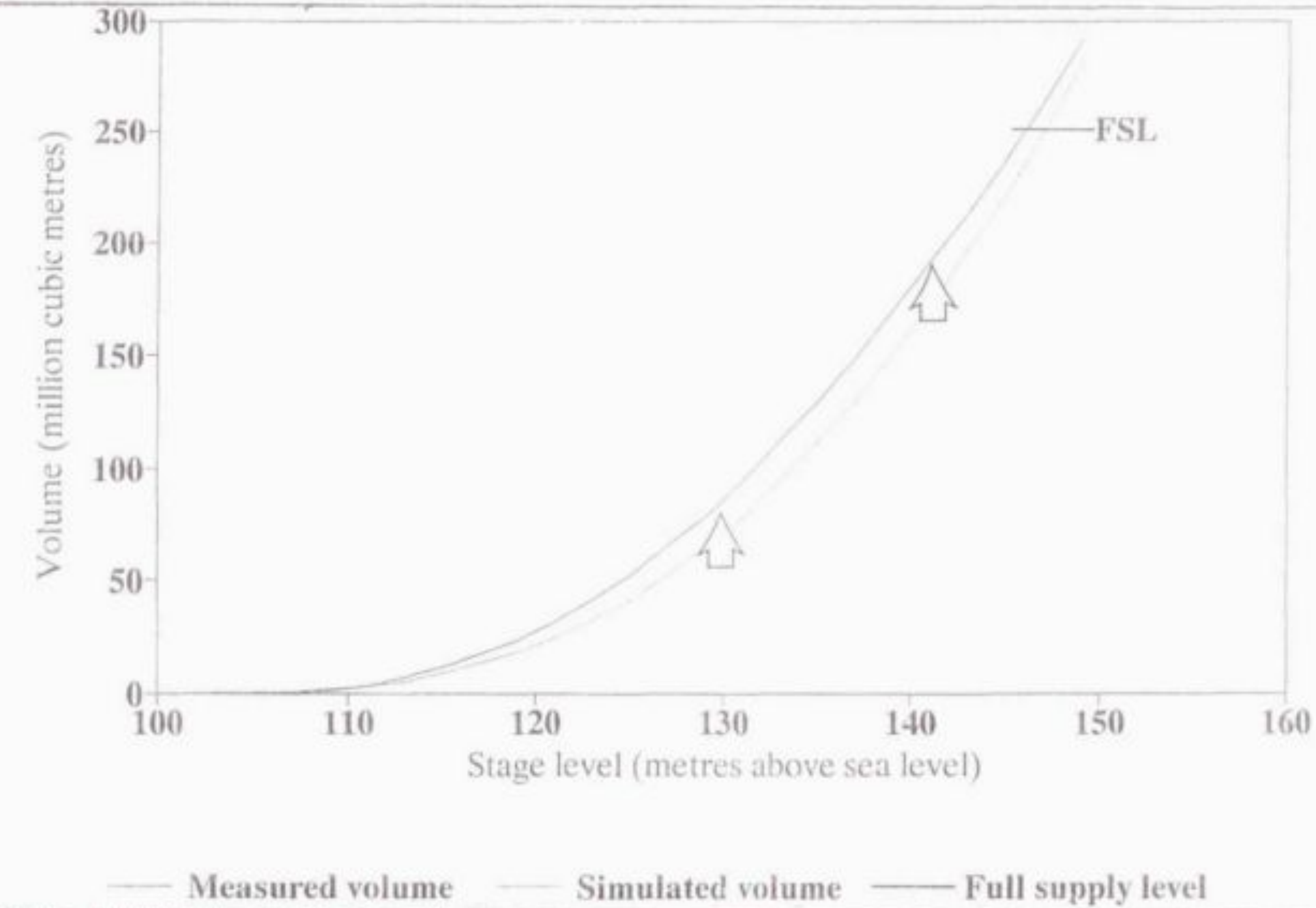
Spreadsheet used in the formulation of the bathymetric data file for Inanda Dam. Grid "A" shows the values of the lateral widths for each cell, and grid "B" shows the volumes of each cell used in data verification.

FIGURE

4.12



UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Preliminary estimates of the simulated volume of Inanda Dam. Optimization of the simulated data resulted in the convergence on the measured data, as depicted by the arrows.	FIGURE 4.13

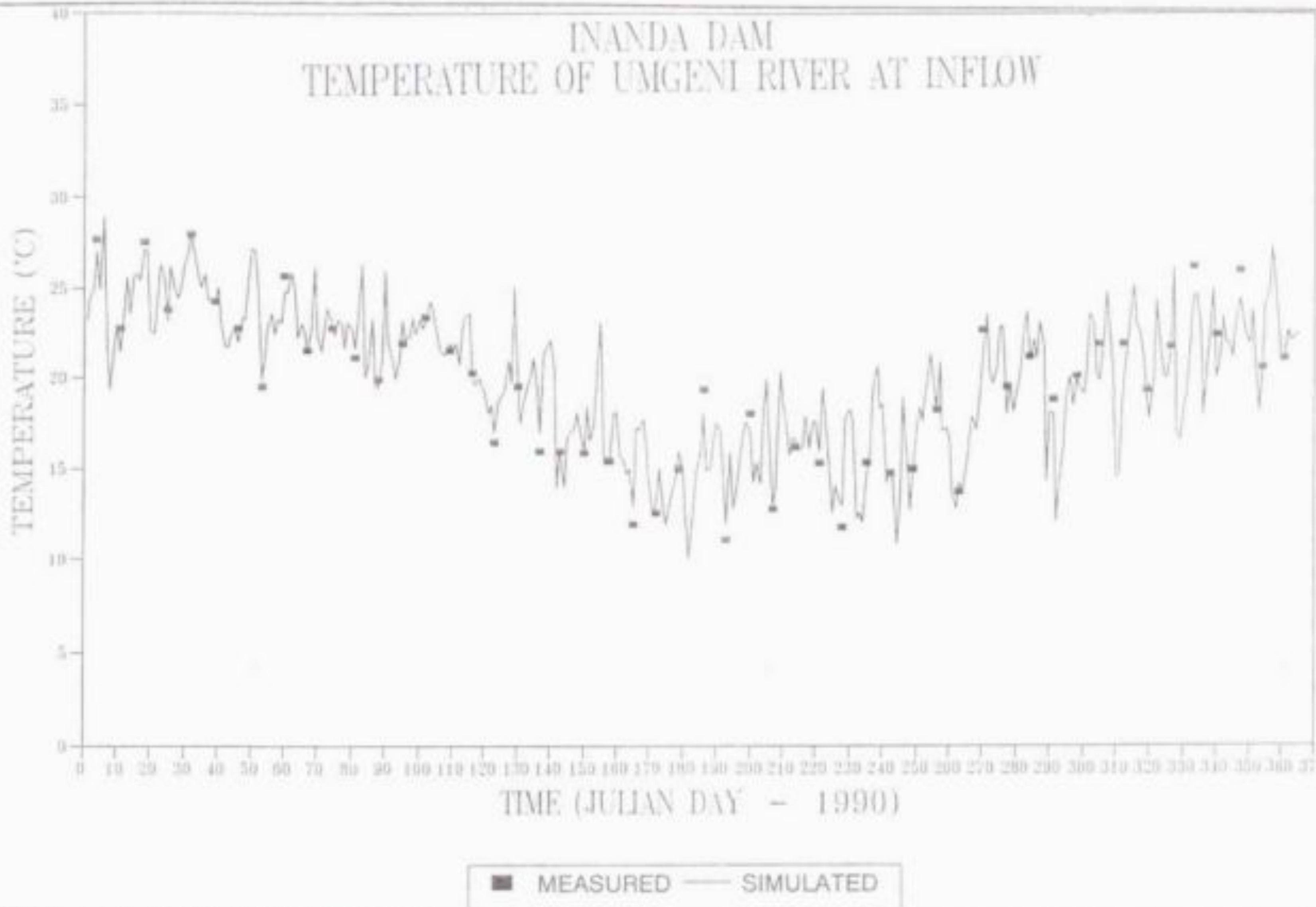
- Location of the surface layer of water. This was determined from reservoir water level data provided by Umgeni Water.

- Initial temperature and water quality concentrations. The model uses either (1) a single value for the entire reservoir, (2) a single vertical profile applicable to all segments, or (3) longitudinally and vertically varying initial conditions where a concentration is defined for each computational cell. As stated earlier, the model was initially configured with single vertical profile water quality data. In later calibration runs, a longitudinal profile file is used in setting the boundary conditions. Temperature and water quality concentrations were derived from the data base provided by Umgeni Water.

- The location and number of inflows and outflows is specified. Initial simulations used a single inflow at the Umgeni River. In later simulations, three inflows were used to account for the Umgeni River as well as small tributary inflows from the Matata and Mshazi Spruits, see Figure 4.11.

Boundary conditions The boundary conditions include, inflows to the reservoir and outflows. For each inflow, the temperature, discharge and chemical constituents are specified. The model accepts data at time increments of daily, or greater. Initially, it was assumed that the main inflow to Inanda Dam was the Umgeni River and the lateral inflows contributed negligible inflow to the reservoir. In later simulations, the lateral inflows were incorporated into the simulation. Water quality and flow data were available for the inflow to Inanda Dam. The inflow data were obtained from Umgeni Water who calculated the inflow rate from a volumetric balance of Inanda Dam - no gauging facility was located near the point of inflow to the reservoir. Tributary discharge data were also not available because of the lack of flow gauging weirs. Water quality data were available for the tributaries and main channel with samples collected at the points shown on Figure 4.10. Data on the outflow releases from Inanda Dam were provided by Umgeni Water. Where necessary, additional water quality data were obtained from the Hydrological Information System of DWA&F.

For effective calibration, the model requires daily values for chemical constituents listed in Section 4.2. The following methods were used to in-fill the data from weekly values to daily. The methods used provided the most convenient and rapid in-filling technique and may not be the most statistically valid method.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Simulated and measured water temperature of the Umgeni River flowing into Inanda Dam.	FIGURE 4.14

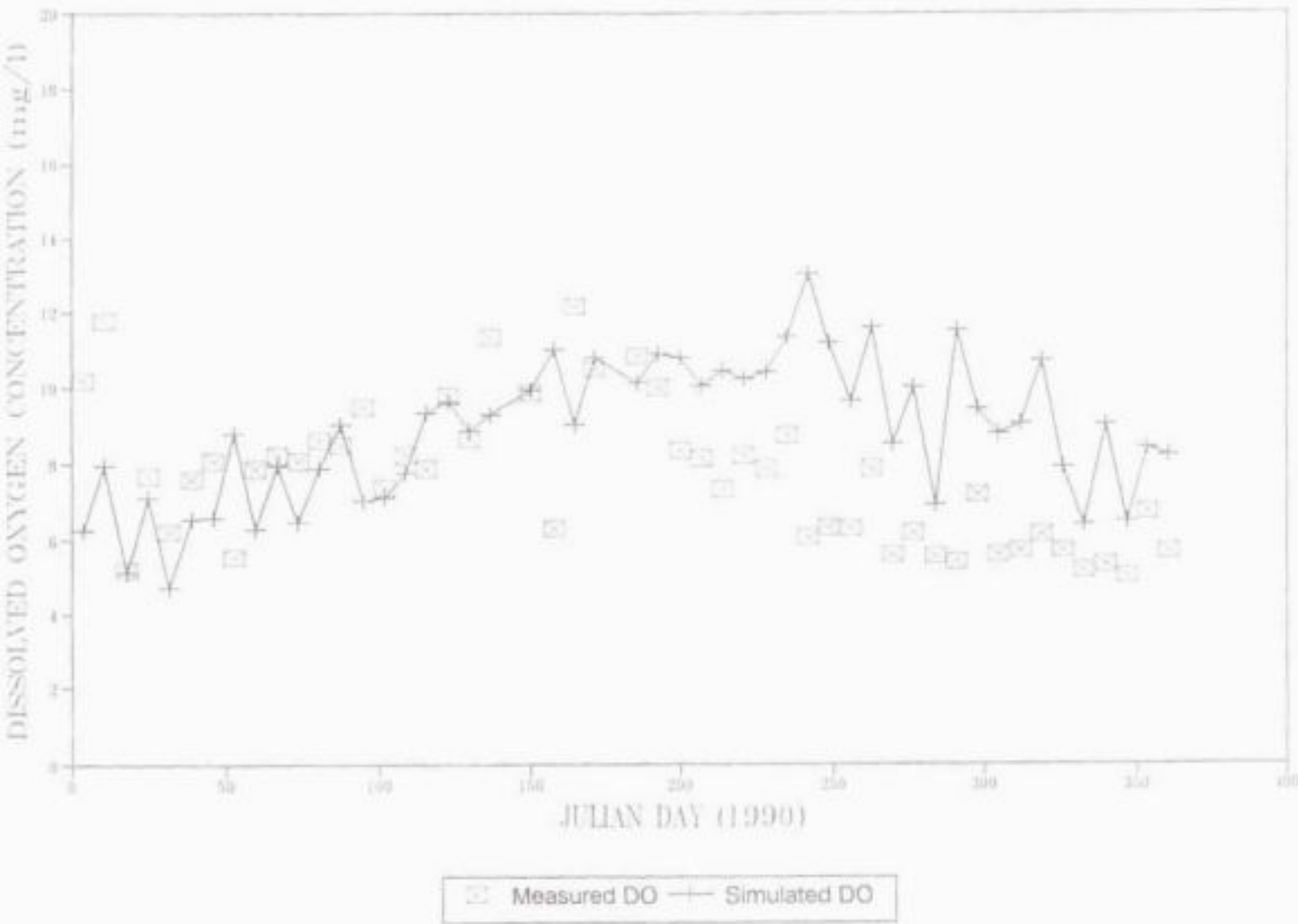
Temperature: The inflowing Umgeni River is monitored at Point 26.1, see Figure 4.10. The weekly data records were in-filled to produce a daily record using a regression relationship between air and water temperature. A linear equation was derived to in-fill the data set. Table 4.1 shows the equation used to in-fill the data. Figure 4.14 shows the good agreement between the simulated and measured data.

Total dissolved salts (TDS): The TDS of Umgeni River was derived using a curvi-linear regression on river discharge, see Table 4.1.

Dissolved Oxygen (DO): The available data set contained weekly values of DO measured at Point 26.1. The data were in-filled using the equation shown in Table 4.1. Figure 4.15 shows the simulated and measured dissolved oxygen data for the Umgeni River at the point of inflow to Inanda Dam.

Suspended solids: Analysis of the suspended solids and river flow data showed that the highest suspended solids values were measured on the rising stage of the flood hydrograph, see Figure 4.16. Similar response has been observed in other river basins in South Africa and has been described using a hysteresis or looped concentration response with river discharge (Zingales *et al.*, 1984; Bath, 1989). The data were in-filled using a multiple regression technique. The regression uses the flow and rate of change of flow to provide a looped effect with changes in the hydrograph (Bath, 1989). Figure 4.16 shows the simulated data derived from the multiple regression equation as well as the measured suspended solids data.

Phosphate: No direct relationship between the river discharge and phosphate concentration was evident. Therefore, a similar approach was used as described above for suspended solids. A multiple regression equation was eventually derived which used both the instantaneous flow as well the antecedent flow. A similar approach has been used in other basins in South Africa and found to give representative results of the time varying concentration (Bath, 1989). The antecedent flow was found to improve the simulation by giving higher phosphate concentrations on the rising limb of the flood hydrograph, see Figure 4.17. To improve the daily time series, the measured data were then patched back into the time series. Table 4.1 shows the values of the constants used in the regression equation.



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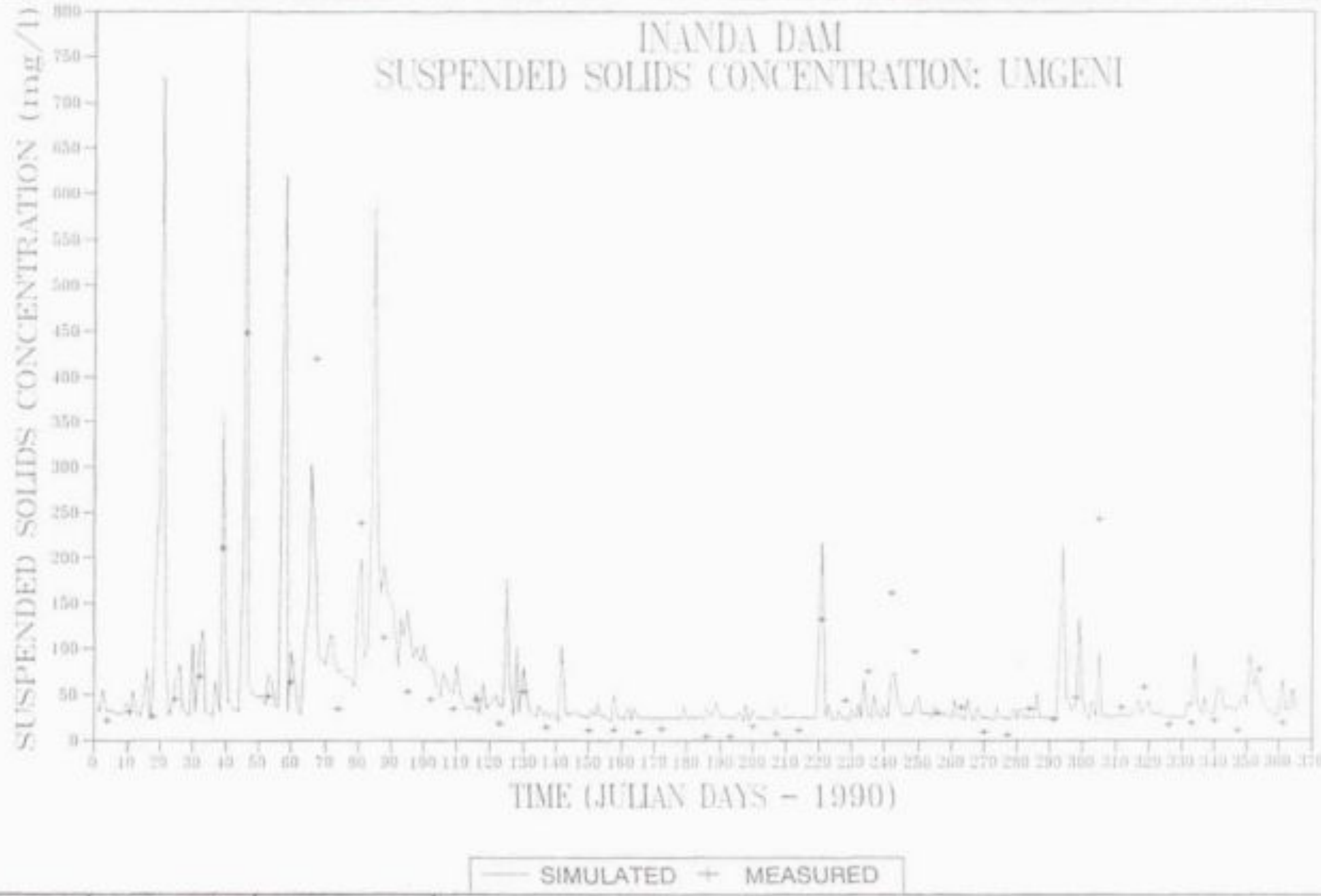
Simulated and measured dissolved oxygen concentration of the Umgeni River flowing into Inanda Dam.

FIGURE 4.15



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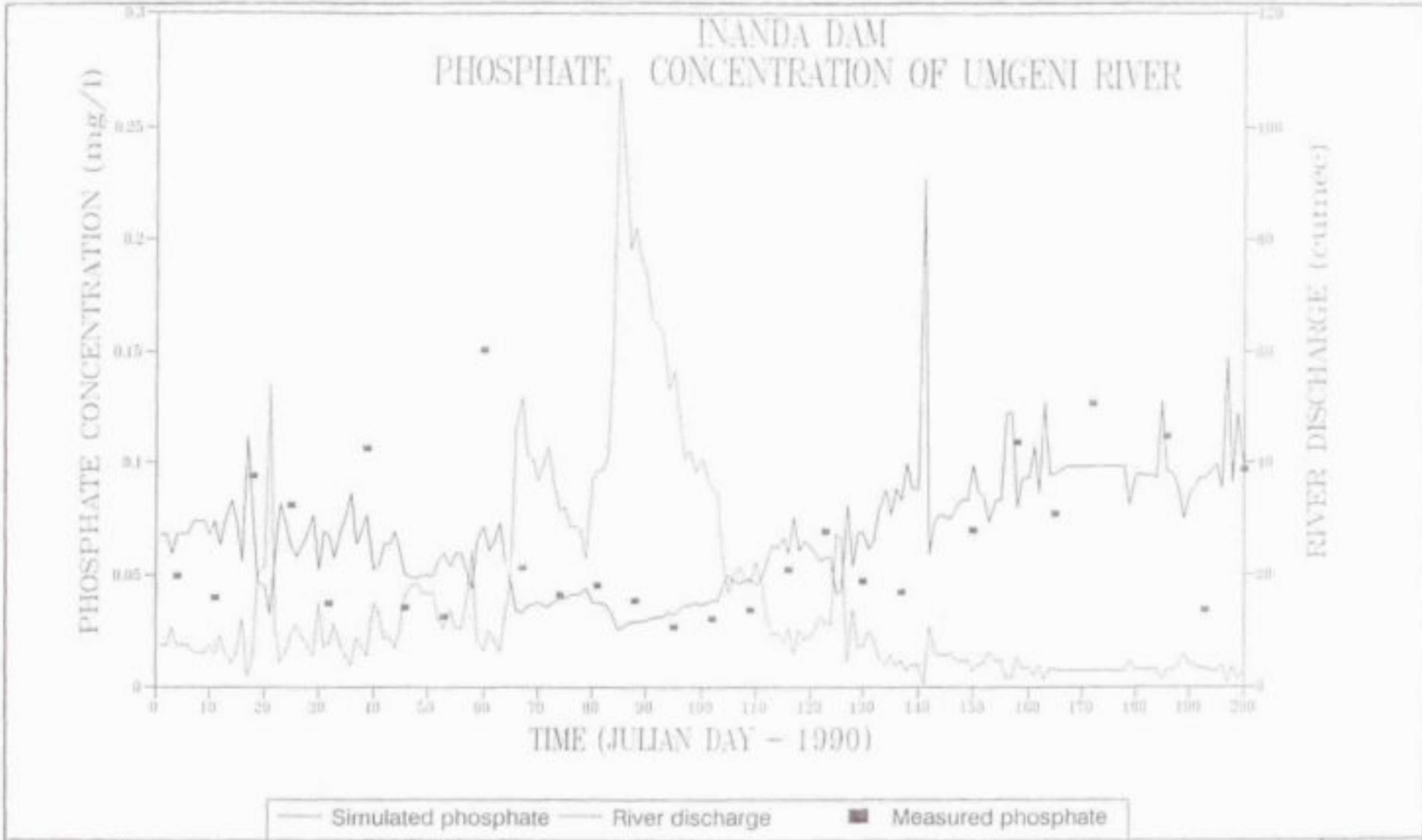
Simulated and measured suspended solids concentration data for the Umgeni River at the point of inflow to Inanda Dam.

FIGURE 4.16



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Measured and simulated phosphate concentration of the Umgeni River at the point of inflow to Inanda Dam. The discharge hydrograph for the Umgeni River is shown.

FIGURE 4.17

Algae: CE-QUAL-W2 expresses the algal concentration as dry weight of algae per unit volume. To convert the chlorophyll-a concentration data to mass dry weight per unit volume, the following conversion was used

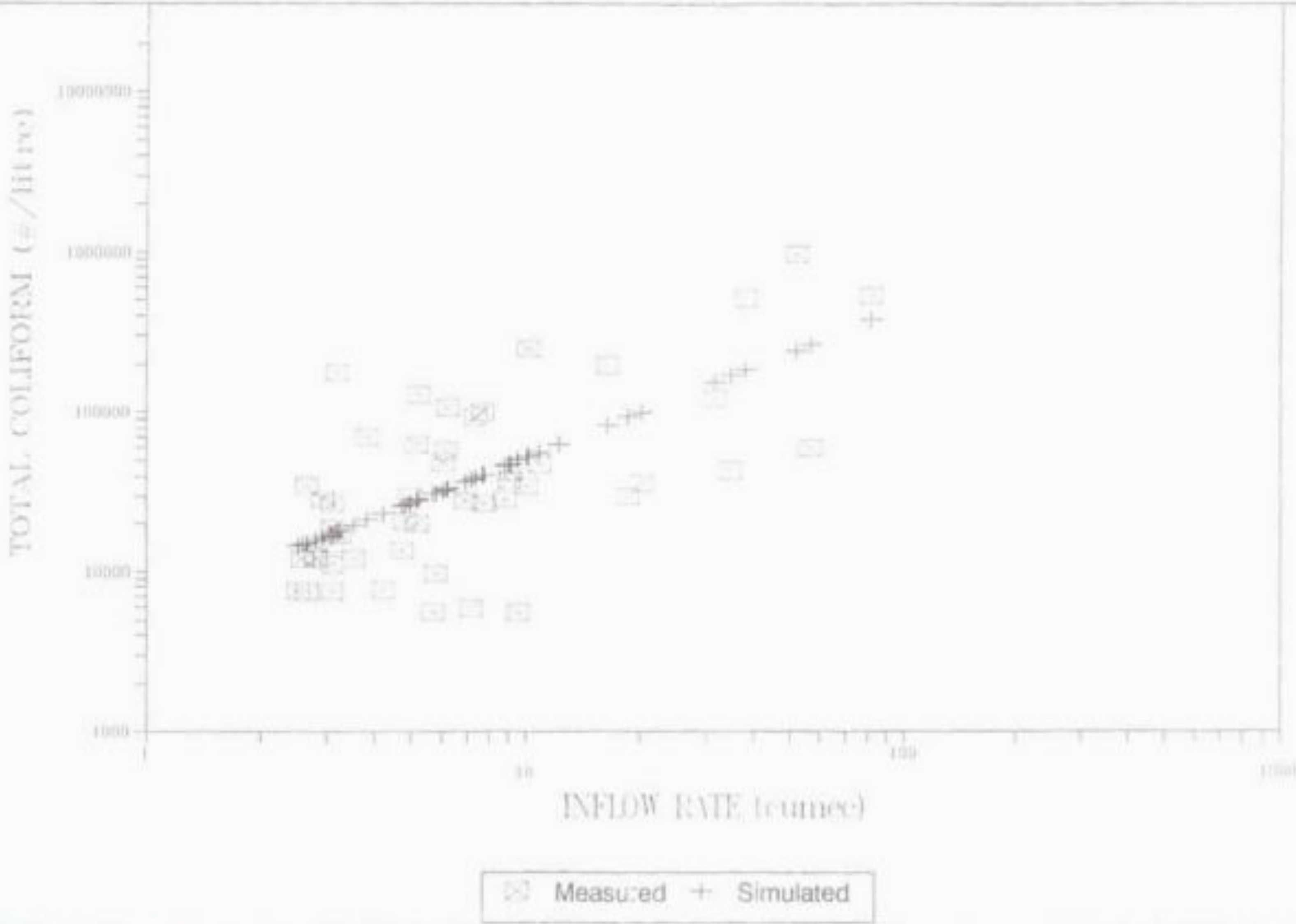
$$\text{Algal Dry Weight per litre} = [\text{Chlorophyll-a}] * 67 \qquad \ldots\ldots (4.1)$$

The factor of 67 was calculated by Umgeni Water (Richards, 1992). The weekly data were used to in-fill daily values using linear interpolation.

Ammonia: The ammonia concentration was found to be weakly linked with the discharge rate of the Umgeni River. Linear interpolation was used to in-fill the ammonia concentration to give estimates of the daily values.

Nitrate: The nitrate concentration was found to decrease with increasing river discharge and a regression equation was derived to in-fill the weekly time series of data. Table 4.1 shows the constants used in the regression equation.

Coliform: In the Umgeni River, the variation in coliform counts was found to be linked to the discharge rate. High discharges corresponded with high coliform values, see Figure 4.18. A simple relationship between the discharge and coliform mass concentration was used to generate a daily time series. Figure 4.18 shows the simulated and measured data and Table 4.1 shows the values used in the regression.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured and simulated coliform bacteria in the Umgeni River at the point of inflow to Inanda Dam.	FIGURE 4.18

TABLE 4.1 TECHNIQUES USED TO IN-FILL WATER QUALITY DATA RECORDS

Variable: (units)	Source of data:	Method:	Independent variable:	Form of Equation:
Water temperature (°C)	Umgeni Water	Linear regression	Air temperature (T)	(T*1.29)-6.39
TDS (mg/l)	Umgeni Water and DWA&F	Nonlinear regression	Flow (Q)	(log(Q)*-57)+181
DO (mg/l)	Umgeni Water	Linear regression	Water temperature (T)	(T*-0.5)+18.7
SS (mg/l)	Umgeni Water	Multiple regression	Flow (Q) and antecedent flow (q)	(Q*1.10)+((Q-q)*4.03)+15.02 when Q>q (Q*1.10)+15.02 when Q≤q
Phosphate (mg/l)	Umgeni Water	Nonlinear regression	Flow (Q) and antecedent flow (q)	(Q*0.002)+((Q-q)*0.005)+0.017 when Q>q (Q*0.002)+0.0017 when Q≤q
Nitrate (mg/l)	Umgeni Water	Nonlinear regression	Flow (Q)	(log(Q)*-0.147)+0.401 when Q<300 cumec
Ammonia (mg/l)	Umgeni Water			linear interpolation used to in-fill data between measured data points
E.Coli (mg/l)	Umgeni Water	Nonlinear regression	Flow (Q)	(Q*0.001)+0.02

Surface boundary conditions The model requires a number of boundary conditions to be specified in the meteorological data file, these include:

Surface heat exchange
Dew point temperature
Coefficient of surface heat exchange
Solar radiation adsorption
Wind speed and direction

The Weather Bureau at Mount Edgecomb provided data on the dew point temperature, wind speed and wind direction for 1990. Mount Edgecomb is the most closely situated weather station, 10 km from Inanda Dam. The most closely situated data collection point for solar radiation was Durban Airport, located 30 km from Inanda Dam. Appendix A4.2 describes the use of the program METDATA to pre-screen the meteorological data. METDATA showed that a discrepancy existed between the simulated and measured heat exchange of Inanda Dam. At the end of the summer, CE-QUAL-W2 predicted the reservoir was vertically mixed 30 to 40 days prematurely. Detailed analysis of the meteorological data using METDATA showed that the solar radiation data measured at Durban Airport may not be representative of the solar radiation at Inanda Dam, 30 km away. Such differences have not been explained, but may be caused by climatic differences between Durban and Inanda. Appendix A4.2 explains the methods used to in-fill and patch a time series of solar radiation data using the measured mixing depth and surface water temperature of Inanda Dam.

The adjustments to the meteorological data had major impacts on the water quality and hydrodynamic simulations of CE-QUAL-W2. The adjusted meteorological data resulted in improvements in the simulation of the thermal dynamics of the reservoir which delayed the date of vertical mixing which in turn caused the algae to have a secondary bloom during the end of the summer period. Such information shows the importance of meteorological variables being measured at the reservoir site.

Hydraulic parameters The model uses the dispersion coefficients and Chezy coefficient which must be specified at the start of the simulation. The vertical dispersion coefficients are determined by the model during the simulation. The simulation for Inanda Dam used the same values for the coefficients and constants as used in the DeGray Lake simulation.

Kinetic parameters The kinetic parameters include the 60 coefficients which influence the constituent kinetics, the main coefficients are shown in Figures 4.2 to 4.5. These coefficients are specified in the control file, see Appendix A4.3 and Table 4.2. In the preliminary calibration runs, the values used for the kinetic parameters were taken from the control file for the DeGray Lake simulation and user documentation.

Data input files These files were produced on spreadsheet and edited using a full screen editing package. In summary, the input files used by CE-QUAL-W2 are listed in Appendix A4.3 which gives examples of each of the files.

Calibration and verification data The effective application of CE-QUAL-W2 requires at least two sets of measured in-dam profile data along with the corresponding time-varying input data. One set is used to calibrate the model whereby the coefficients of the model are adjusted until the simulated data adequately reproduces the measured data. The calibrated model is then run using the second set of data. Should the model simulate the measured data for the second period and on condition that the data periods are representative enough, then the model may be considered verified (Cole, 1991). In terms of the data set for Inanda Dam, the model was calibrated using a period of 200 days.

Model preparation The FORTRAN "Include file" is used to compile and link with the model source code, see Figure 4.6. The file gives specifications for the control and bathymetric file names as well as parameter statements for the layout and configuration of the model simulation. The parameter statement includes the number of layers, segments, tributaries, outlets, branches and withdrawals. Every time the constants in the parameter statement are changed the model code must be recompiled, linked and bound.

Calibration runs Calibration is an iterative process whereby model coefficients are adjusted until an adequate fit of measured and simulated data is obtained. Cole (1991) recommends that the calibration sequence should start with the water budget, then the temperature and finally the water quality constituents. Figure 4.19 shows the order and sequence used in the calibration of CE-QUAL-W2 for Inanda Dam.

4.4.3 Results of simulation: Inanda Dam

Water budget The water budget is evaluated by comparing the simulated and measured water levels of the reservoir. Cole (1991) states that errors in the water budget may be caused by

- Incorrect bathymetric data.
- Incorrect flow data during storm events.

START

⇩

1. Water and stage level

2. Temperature

3. TDS

4. Suspended solids

5. Hypolimnetic phosphorus

6. Surface phosphorus

7. Algal biomass

8. Oxygen

9. Nitrogen compounds

10. Coliforms

(Items 5–9: Iterative)

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FIGURE 4.19: Calibration procedure used for the CE-QUAL-W2 water quality simulation of Inanda Dam.

- Evaporative losses: The model may be used with evaporation switched on, or off.
- Seepage: The model does not include the effect of seepage losses. These may be positive in the form of groundwater return flows, or negative in the form of ground water losses from the reservoir. These may have to be accounted for empirically if it is suspected they have an influence on the water budget.

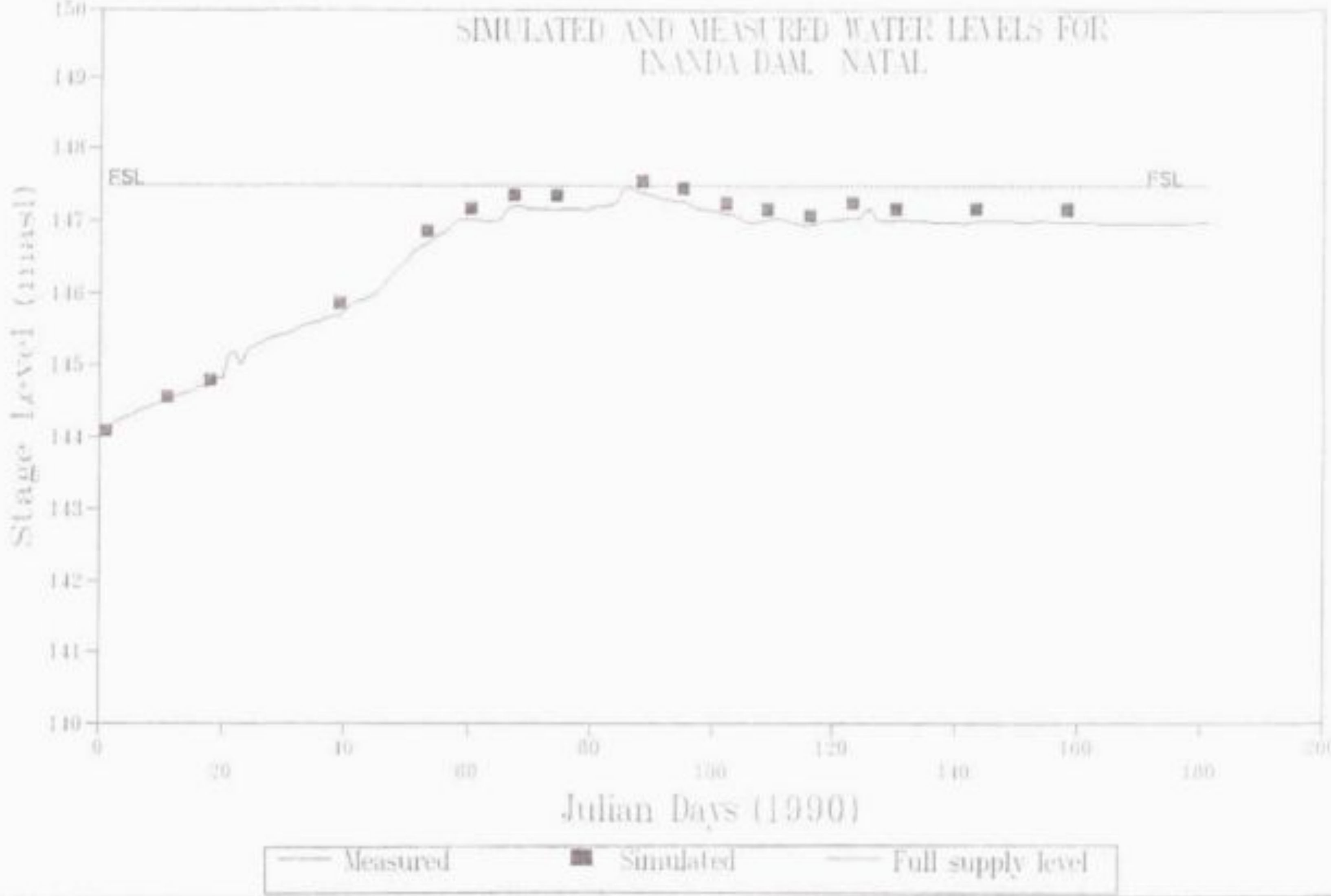
Figure 4.20 shows the measured and simulated water levels for Inanda Dam for the first 200 days of 1990 which shows good agreement. Figure 4.21 shows the inflow hydrograph for the Umgeni River which discharges into Inanda Dam. The results required no calibration or adjustment of the input data because the discharge data for the Umgeni River were derived using a volumetric balance for Inanda Dam. However, should the bathymetric data have been in error there would have been discrepancies between measured and simulated data.

Hydrodynamics and temperature The coefficients used to calibrate the hydrodynamics and temperature are the following:

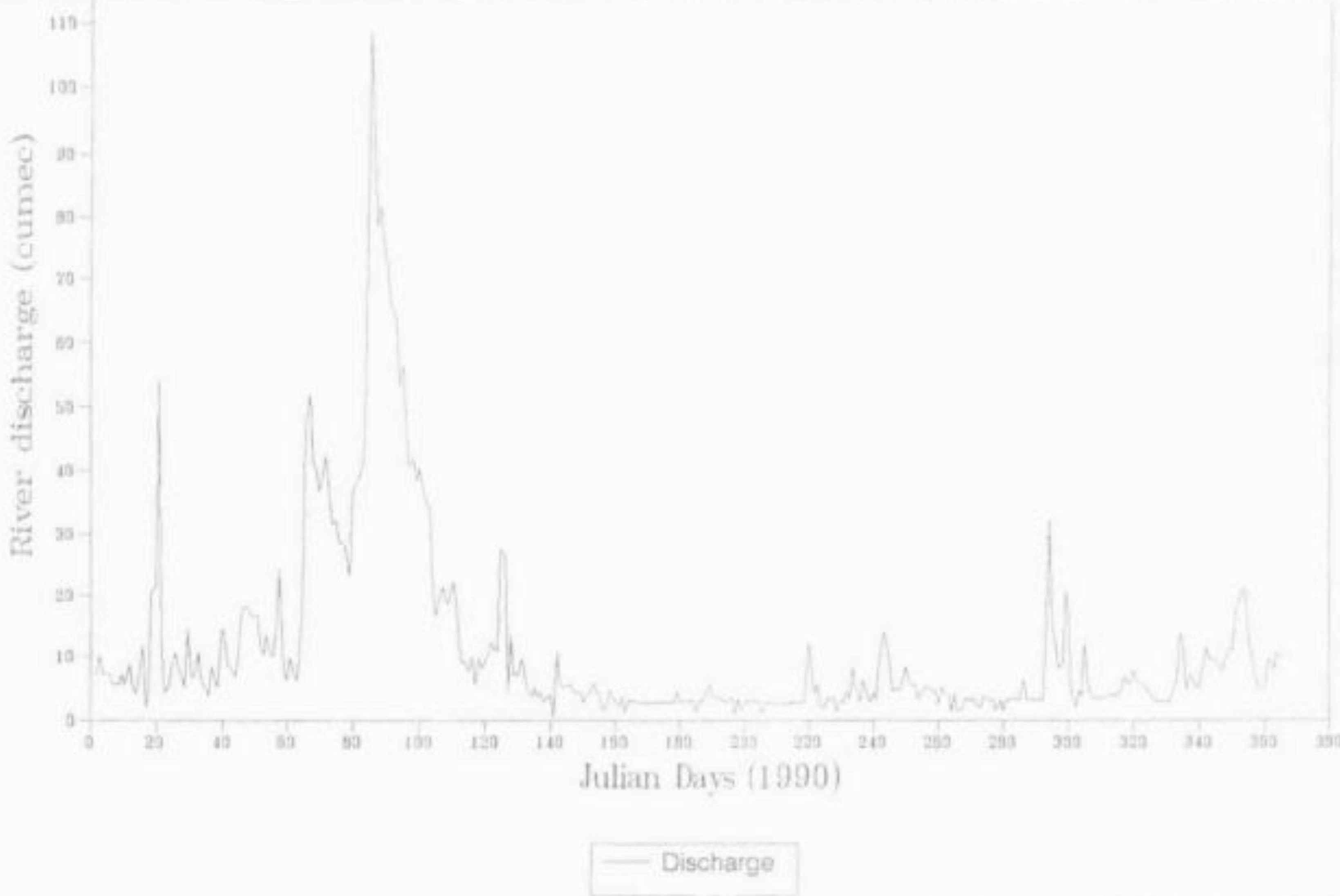
- Longitudinal eddy viscosity
- Longitudinal eddy diffusivity
- Chezy friction coefficient
- Wind sheltering coefficient
- Solar radiation absorbed in surface layer
- Extinction coefficient for pure water
- Extinction coefficient for inorganic solids
- Extinction coefficient for organic solids (POM and algae)

The longitudinal eddy viscosity, Chezy coefficient, and the wind sheltering coefficient directly influence the hydrodynamics and the transport of heat energy. The remaining coefficients directly affect water temperature which influences the hydrodynamics of the reservoir, see Figure 4.22. The values of these coefficients was taken from the user documentation.

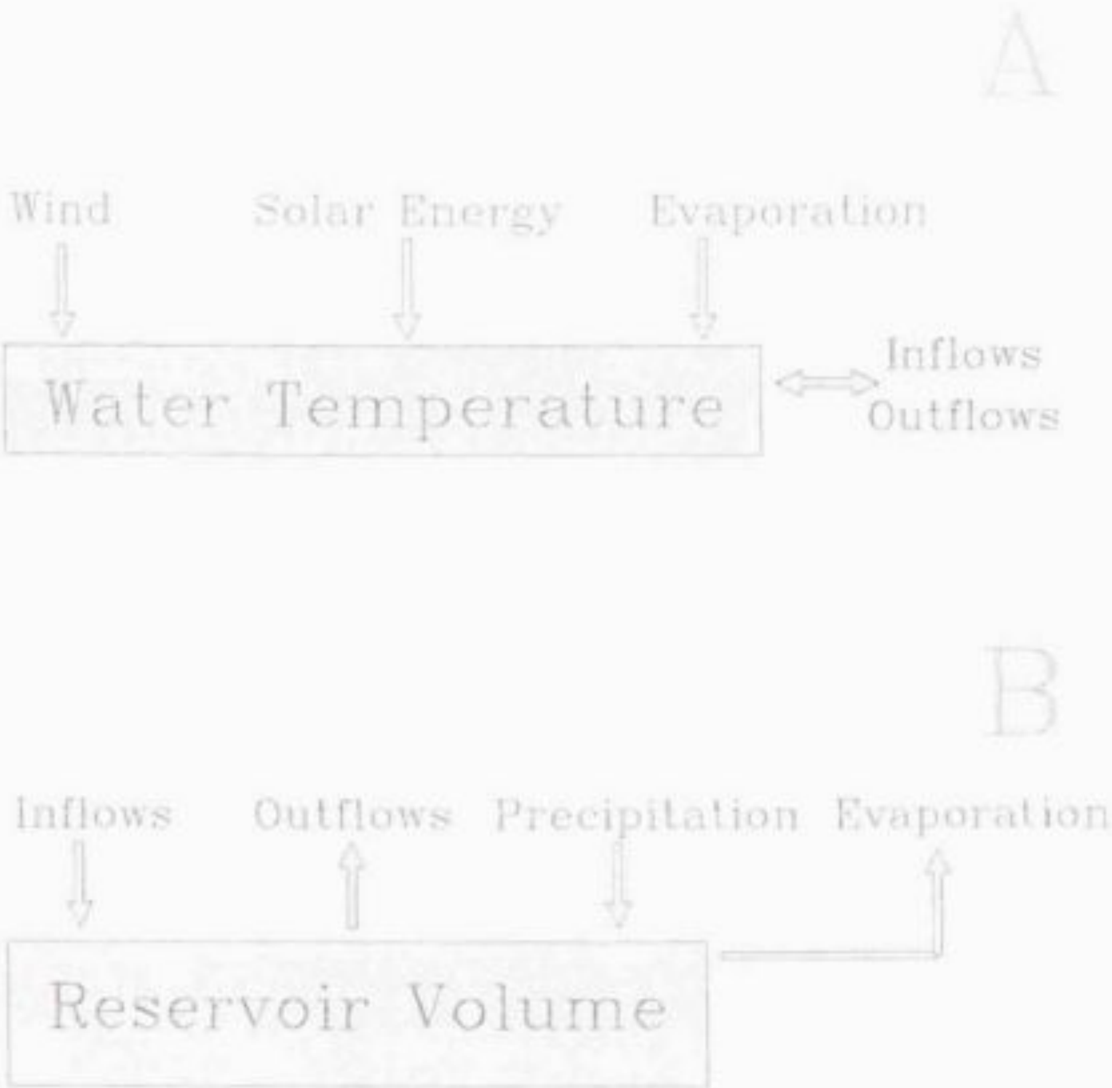
Figure 4.23 shows the temperature profile plots of the simulated and measured data at the dam wall. Figure 4.24 shows a time series plot of simulated and measured surface water temperature, which shows reasonable correspondence between simulated and measured data. In Appendix A4.5 the simulated and measured data are compared using both two-dimensional and profile plots.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured and simulated stage level of Inanda Dam - 1990. The full supply level (FSL) of the reservoir is shown.	FIGURE 4.20



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured river discharge hydrograph for the Umgeni River at the point of inflow to the Inanda Dam.	FIGURE 4.21



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Input variables used for the calibration of water temperature (A) and reservoir volume (B).

FIGURE 4.22

Figure 4.23

Profile plots showing the simulated and measured water temperature in Inanda Dam at Segment 25, located at the dam wall.

DAY NUMBERS:
4 to 25

KEY:
Measured: --
Simulated: ⊙

Variable: Temperature

Units: Degree C

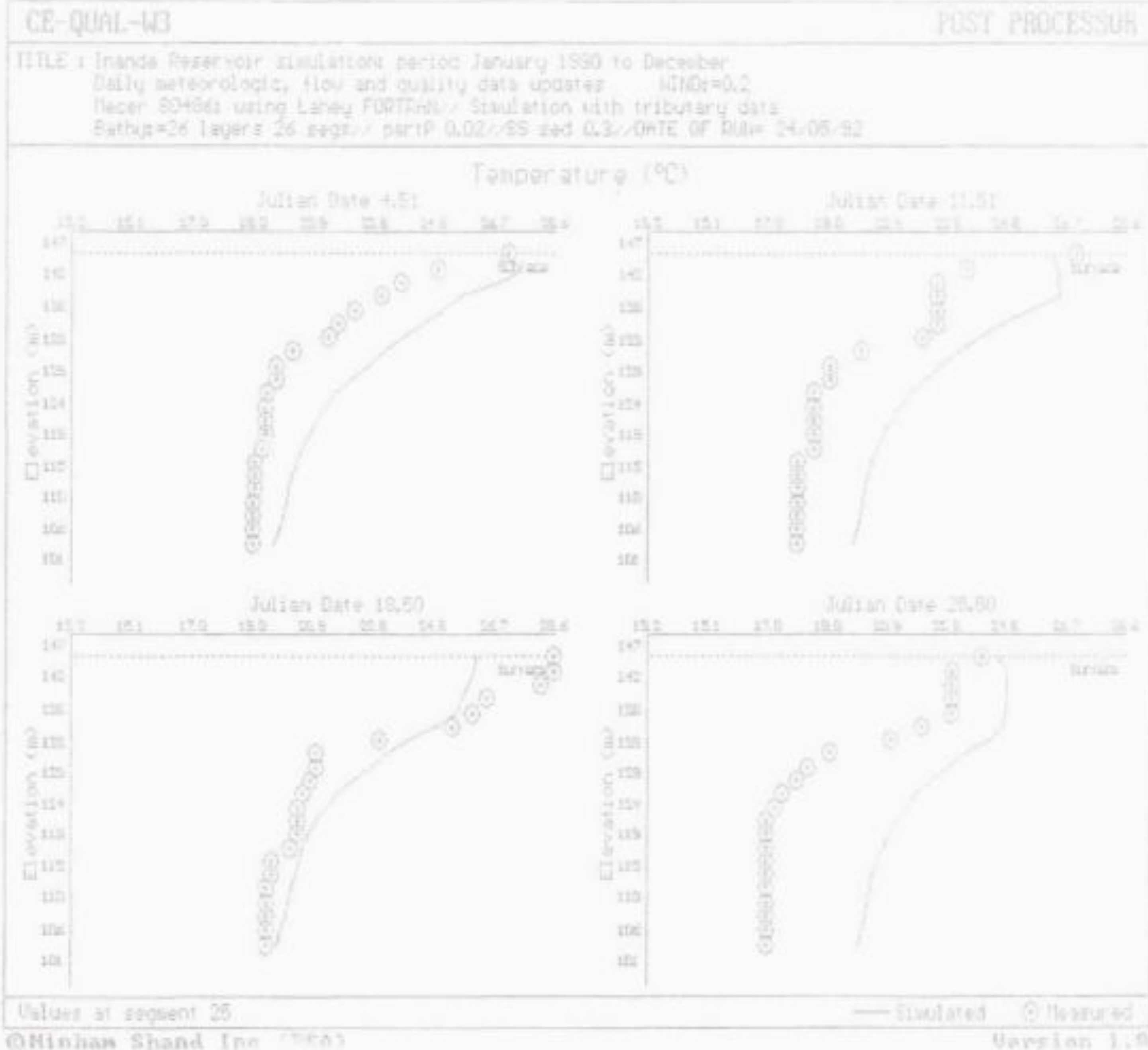


Figure 4.24

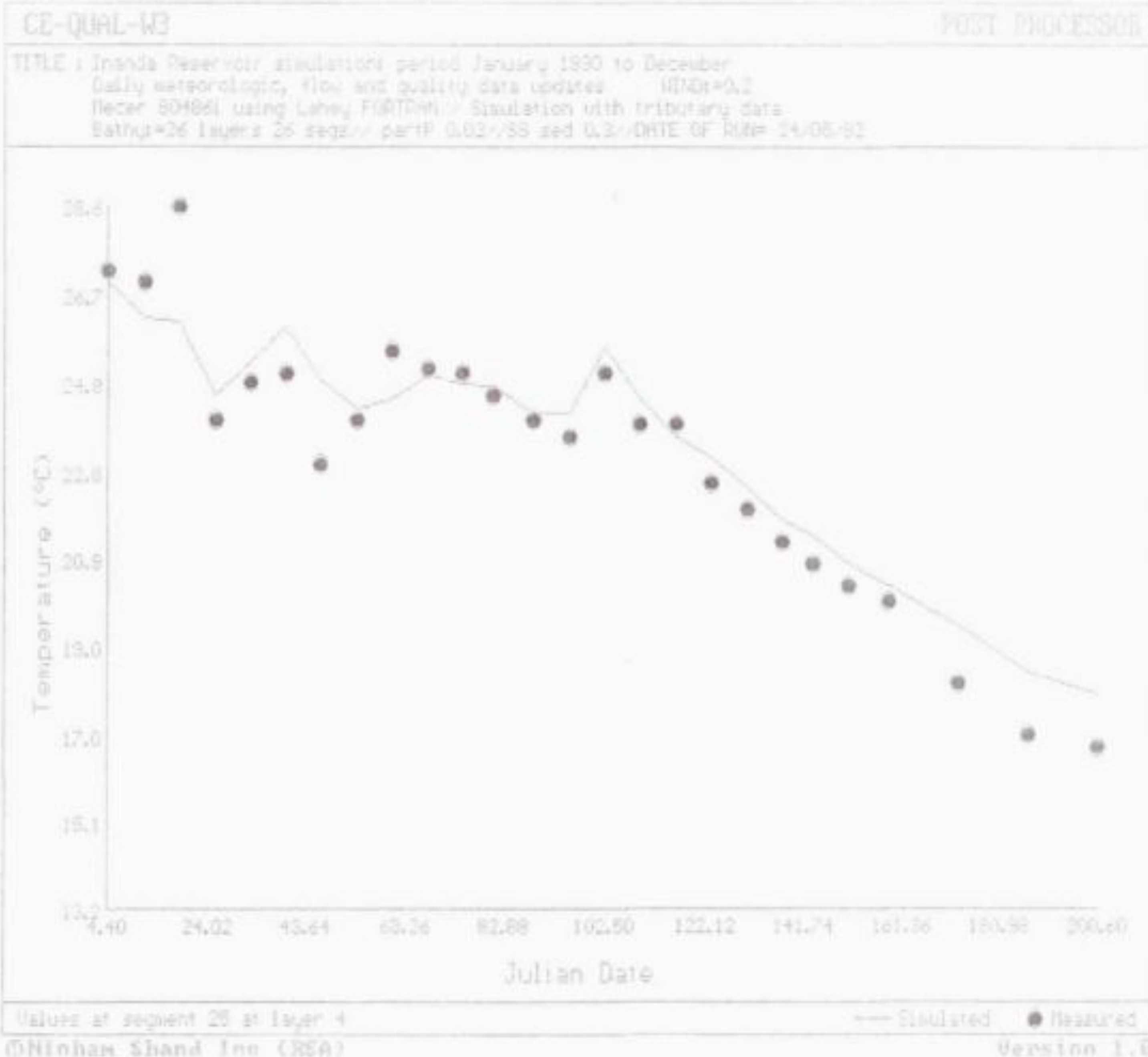
Time series plot showing the simulated and measured water temperature in Inanda Dam at Segment 25, located at the dam wall.

SURFACE LAYER

KEY:
Measured: ●
Simulated: ---

Variable: Temperature

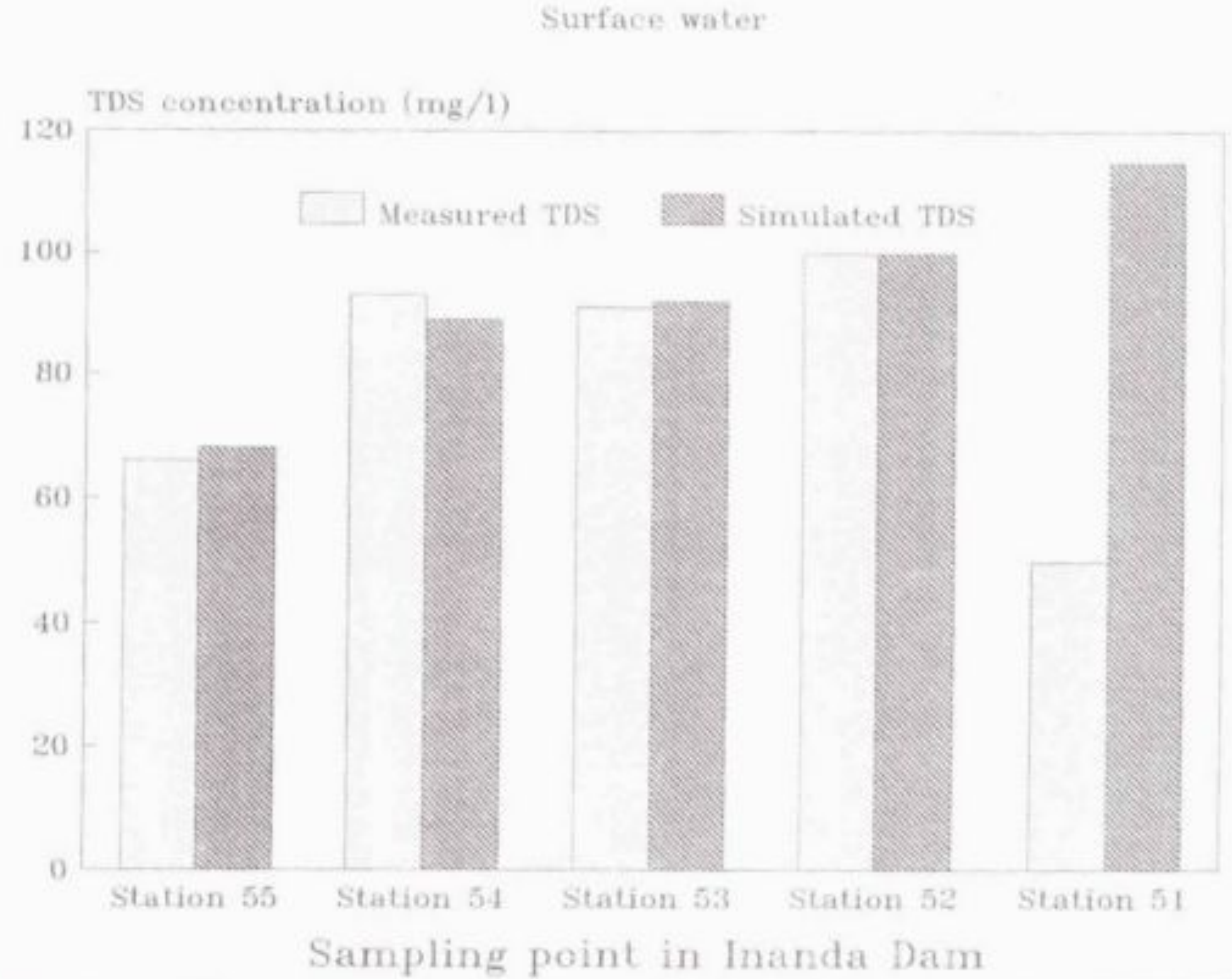
Units: Degree C



Biological and chemical simulations The water quality constituents are strongly coupled so that calibration of one component will influence another component thereby making calibration difficult. Cole (1991) states that an understanding of the processes taking place as well as a knowledge of the system being simulated is an absolutely essential prerequisite to effective calibration of the model. The manual provides a description of the coefficients and variables used in the calibration of the water quality components but provides little information on the calibration approach to be used. Figure 4.19 shows the calibration method used for Inanda Dam based on the method described by Riley (1988).

Total dissolved salts The first "level" of constituents include tracer, TDS and coliform bacteria. The tracer and TDS are conservative constituents while coliform bacteria is non-conservative because the coliform concentration decreases with time as a function of the water temperature and decay rate. The model was calibrated using TDS as a conservative chemical constituent. Figure 4.25 shows the simulated and measured TDS concentration at day number 74 of the 200 day calibration period. Unfortunately, measured TDS data were available at relatively infrequent intervals during the calibration period. Figure 4.25 shows a general correspondence between the simulated and measured TDS data, except for Station 51 at the dam wall. Here, the discrepancy between measured and simulated data may be caused by lateral tributary inflows. Scrutiny of the water quality data for the tributaries inflowing into Inanda Dam shows the tributaries have TDS concentrations ranging from 60 to 1000 mg/l. The model shows that depending on density, high TDS water flows into the bottom layers, and low TDS water flows onto the surface of the reservoir.

Suspended solids The second "level" of constituents include suspended solids. Sufficient data were available to define the boundary conditions and describe the time varying concentration changes in the Umgeni River. The model uses a term (SSETL) to control the settling of suspended solids, see Figure 4.3. In the DeGray Lake simulation SSETL was set at a value of 1.2, but for Inanda Dam, SSETL was found to require a value of 0.3, see Table 4.2. The lower value of SSETL was found to decrease the settling rate and could be attributed to fine suspended solids derived from erosion processes in the catchment. Figure 4.26 shows the simulated and measured suspended solids data for the dam wall sampling point at Inanda Dam. The model provides a general agreement between simulated and measured data but predicts the peak concentrations slightly prematurely. The reason for the discrepancy in simulated data is not known, but it may be caused by the methods used to synthesize suspended solids data at the inflow.



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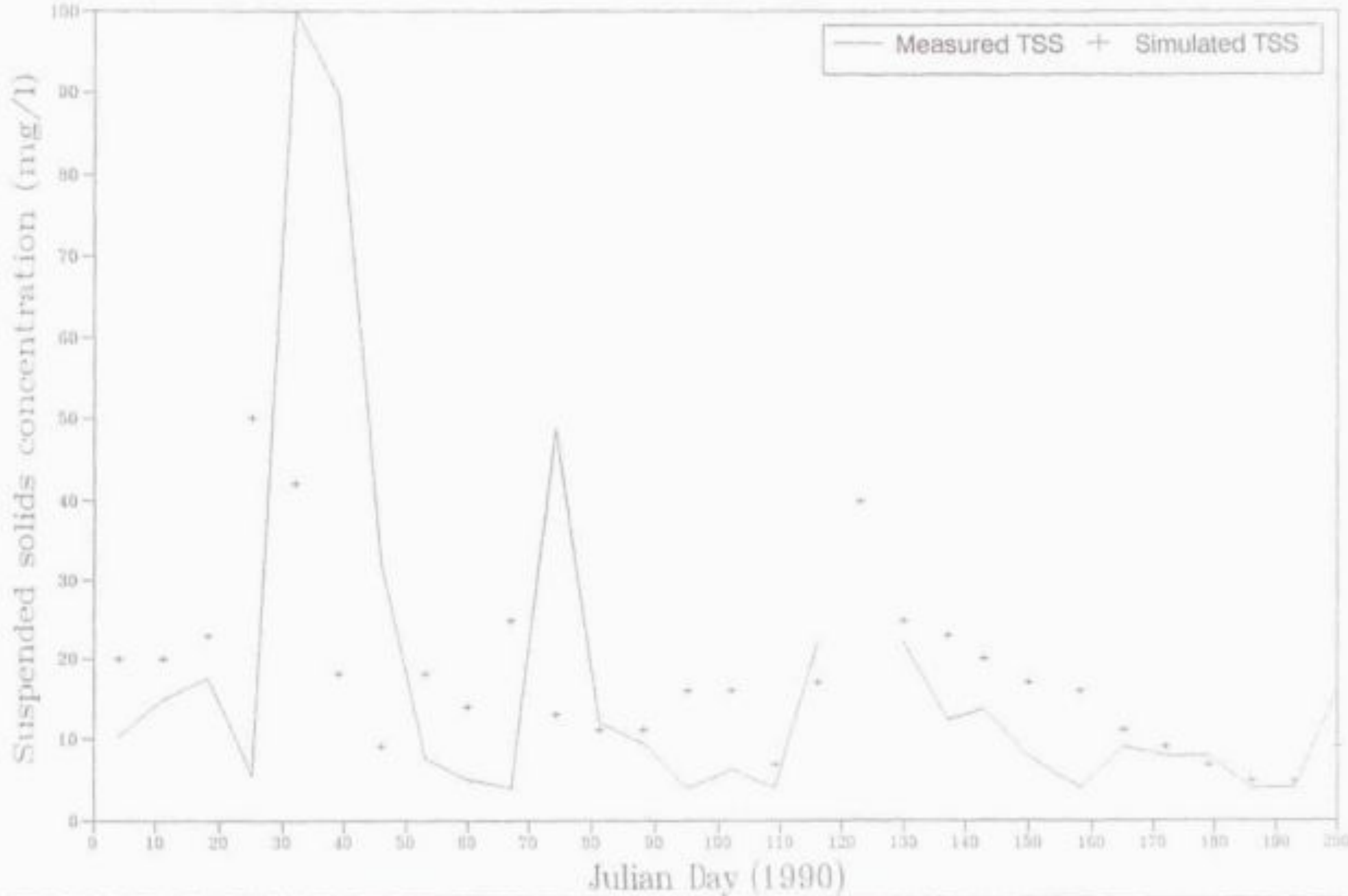
Measured and simulated TDS concentration of Inanda Dam at the water quality monitoring points 51 through to 55, used by Umgeni Water. Simulation date: Julian Day 74.

FIGURE 4.25



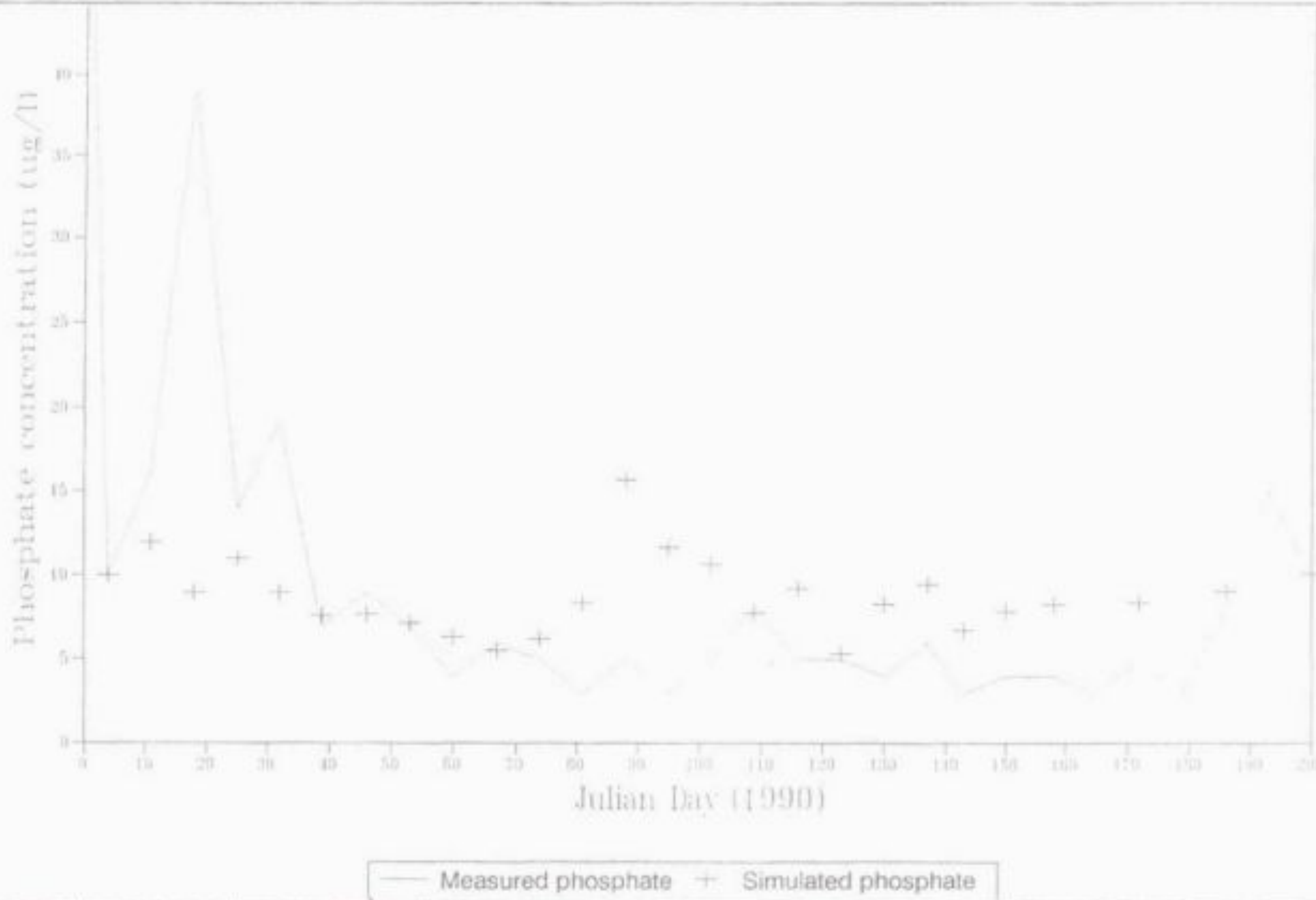
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured and simulated suspended solids concentration for Inanda Dam at the dam wall (point 51). Simulation period: January to July 1990.	FIGURE 4.26

Hypolimnetic phosphorus Figure 4.5 shows the inter-relationship between phosphorus and other constituents. The first coefficient which received attention was the partition coefficient for phosphorus, PARTP. This coefficient accounts for the adsorption of phosphorus onto sediment particles. From the DeGray Lake Simulation, an initial value of 1.2 was used. After numerous calibration runs, it was noted that the high suspended solids concentration causes adsorption of phosphorus from the water column onto the particulate matter, causing a rapid depletion in the phosphorus concentration. To counteract this effect, the PARTP was reduced from 1.2 to 0.12. The phosphate release from the sediments is adjusted by means of the release coefficient, PO4REL, which was adjusted from a value of 0.015 to 0.007. The sediment oxygen demand is adjusted through the term SOD, see Figure 4.5. This term has an important influence on the oxygen of the hypolimnion which in turn influences the phosphorus release from bottom sediments. A value for SOD of 0.3 was adopted from the DeGray Lake simulation. Figure 4.27 shows the phosphorus concentration in the hypolimnion of Inanda Dam. The calibration does not permit an ideal simulation of the initial conditions up to day 30, but thereafter the simulated and measured data are in reasonable agreement. The discrepancy may be caused by incorrect starting conditions.

Surface phosphorus Figures 4.2 and 4.5 show the inter-relationships between phosphorus and the other water quality variables. In the surface waters of the reservoir, the phosphorus is influenced by particulate matter and algal uptake. A considerable number of model runs were performed to obtain a calibration of phosphorus in the surface waters. Figure 4.28 shows the results of the calibration using the constants and coefficients used in Table 4.2.

Algae Figure 4.29 shows the preliminary calibration of the algal biomass at the dam wall. Difficulties were experienced in producing a second peak in the biomass during the middle of the calibration period (day 80 to 120). Once the meteorological data were adjusted using METDATA, the influence of vertical mixing caused an increase in algal biomass in the early winter period, see Figure 4.30. Figure 4.31 shows the simulated data plotted against the corresponding measured data, with the line of perfect agreement. Figure 4.31 shows the model provides a reasonable agreement between the simulated and measured data.

Dissolved Oxygen Figure 4.32 shows the results of the preliminary calibration for dissolved oxygen. The sediment oxygen demand (SOD) controls the oxygen content of the hypolimnion. A number of calibration runs were preformed before a value of SOD of 0.5 was selected. Figure 4.32 shows the simulated and measured dissolved oxygen concentration for the upper layer at the dam wall. Appendix A4.3 shows a selection of plots of the simulated and measured dissolved oxygen concentration.



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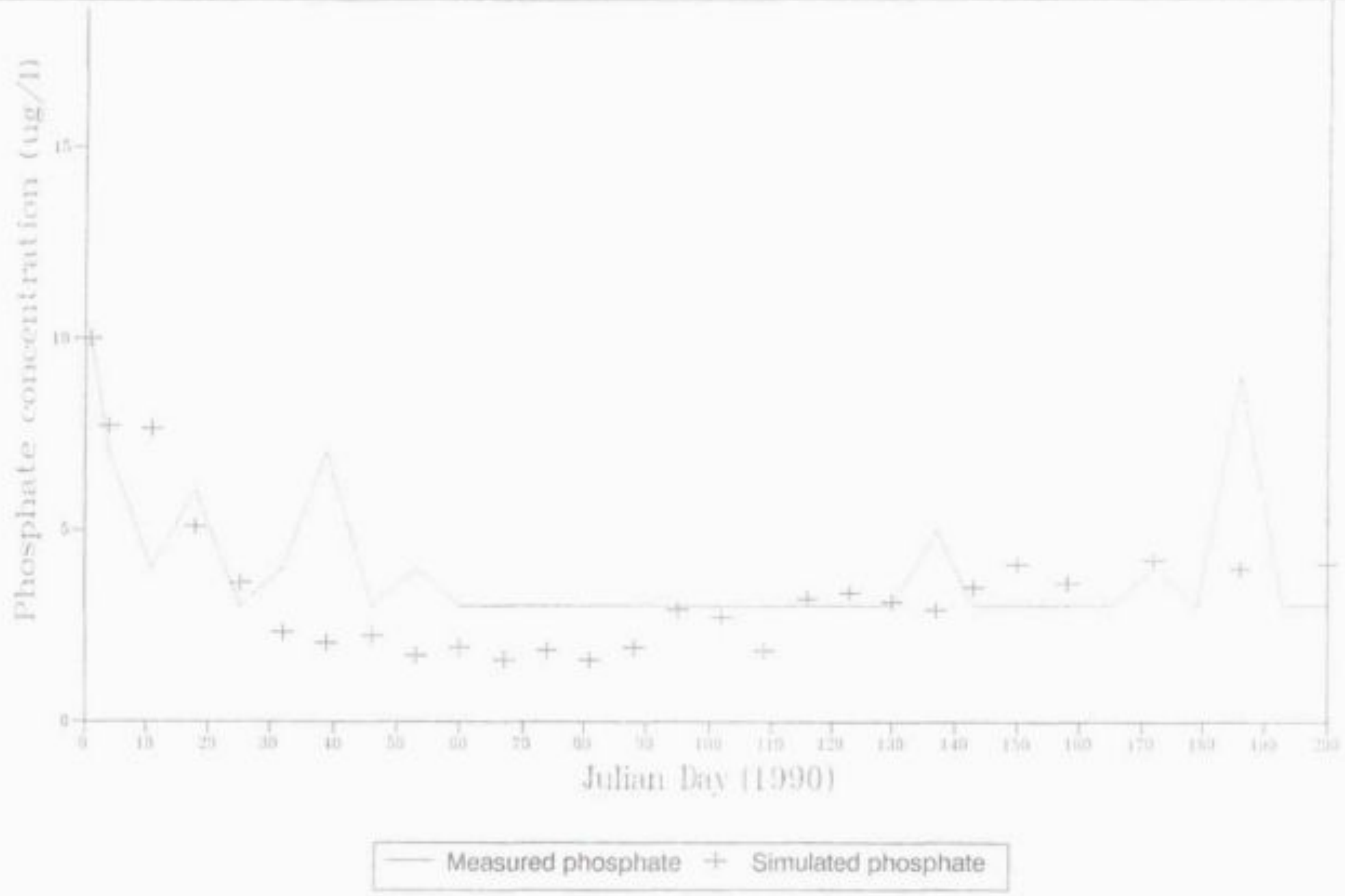
Measured and simulated hypolimnetic phosphorus concentration for Inanda Dam at the dam wall (point 51). Simulation period: January to July 1990.

FIGURE 4.27



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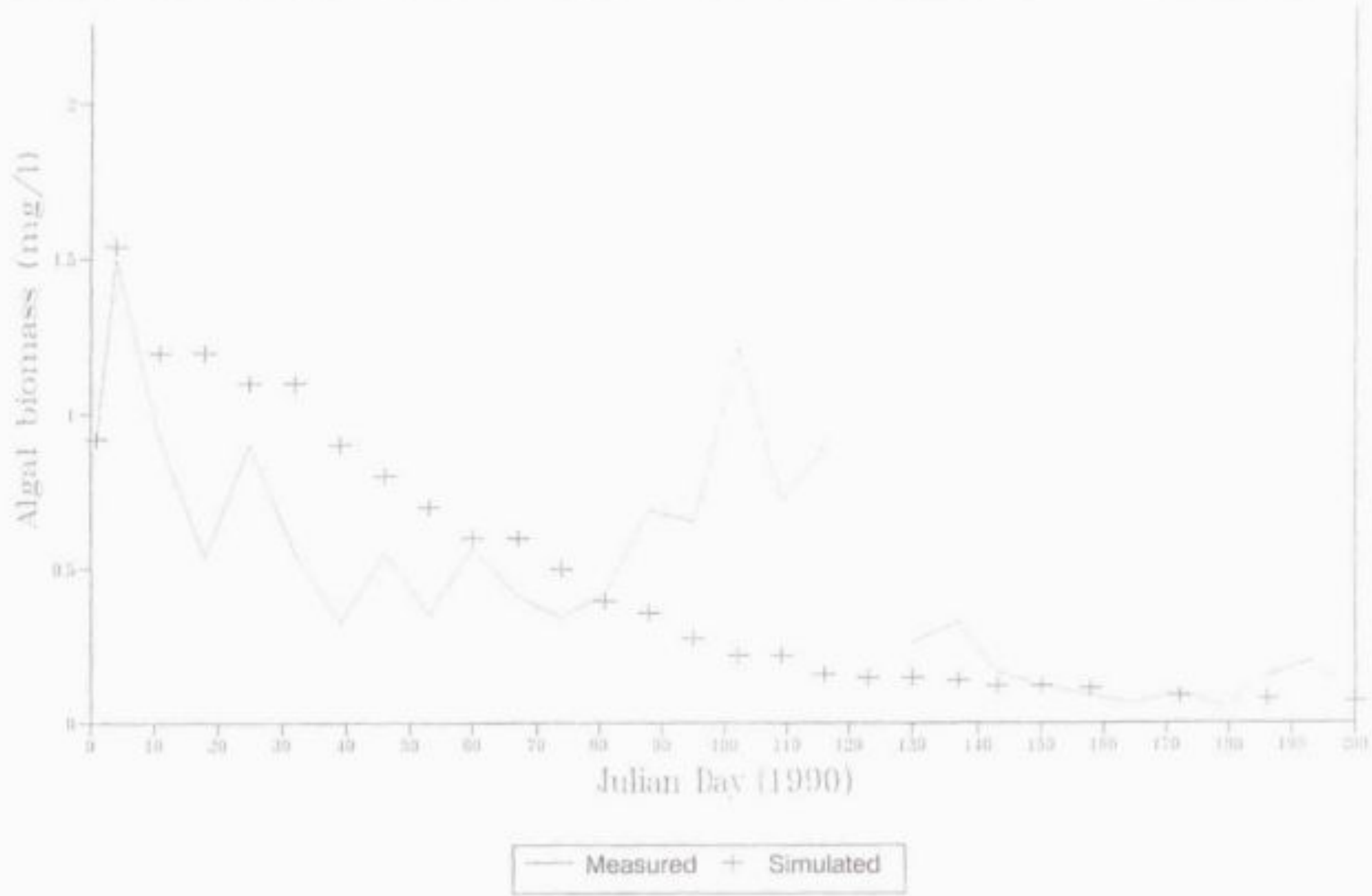
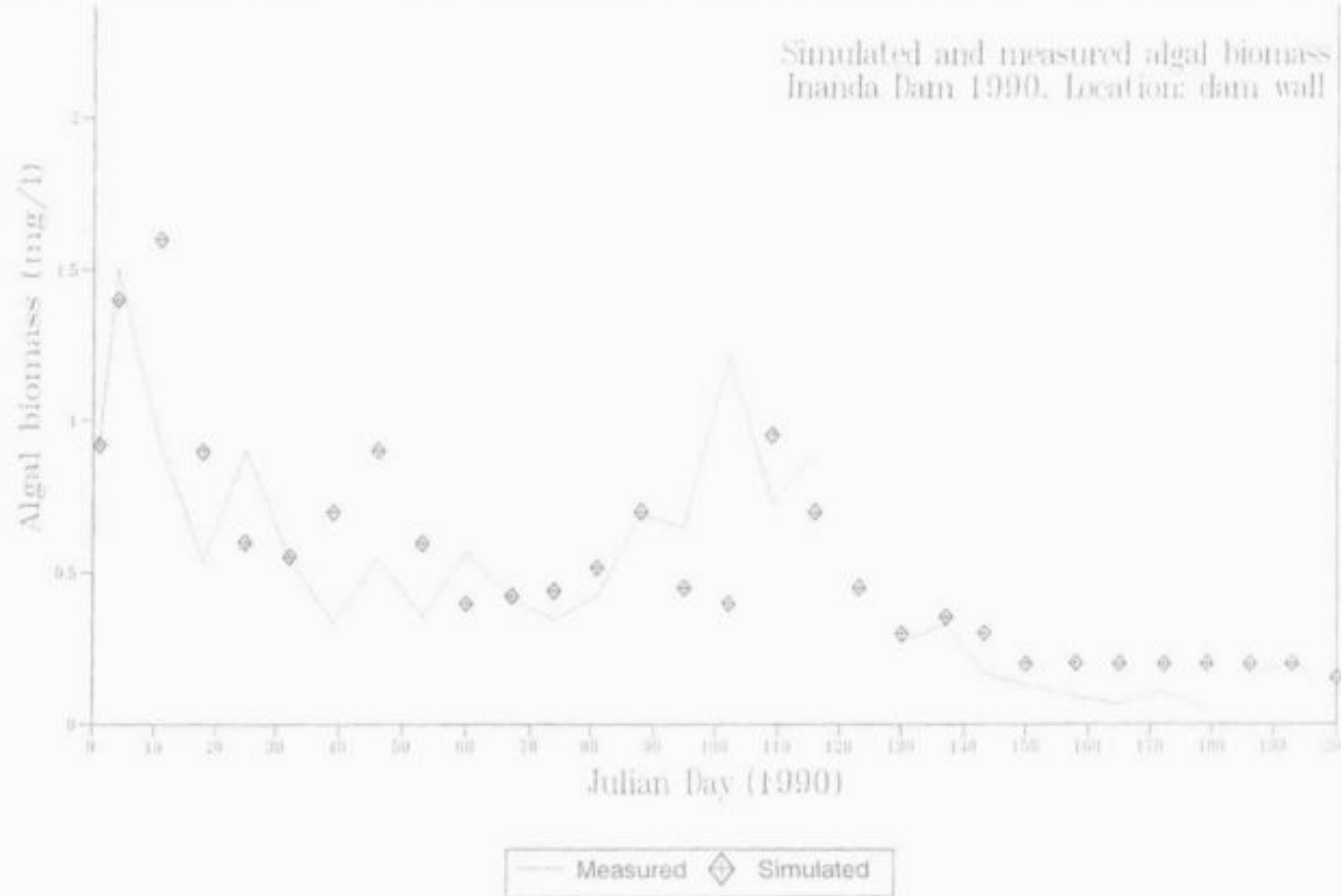
Measured and simulated surface phosphorus concentration for Inanda Dam at the dam wall (point 51). Simulation period: January to July 1990.

FIGURE 4.28



HINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured and simulated algal biomass for Inanda Dam at the dam wall (point 51). The simulation uses original meteorological data.	FIGURE 4.29



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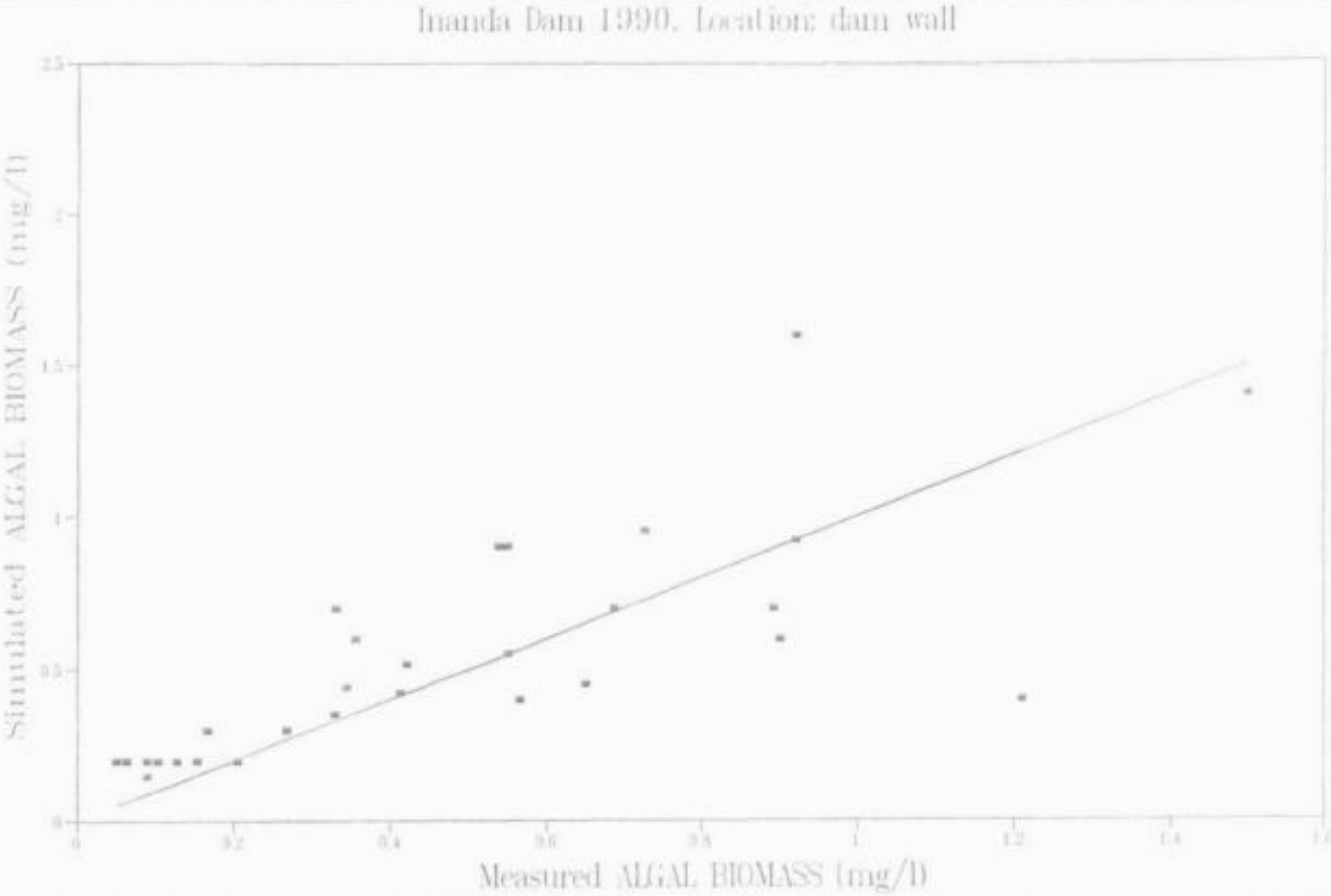
Measured and simulated algal biomass for Inanda Dam at the dam wall (point 51). The simulation uses updated meteorological data.

FIGURE 4.30



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION		FIGURE
			Measured and simulated algal biomass data using the updated meteorological data set.	4.31

Figure 4.32

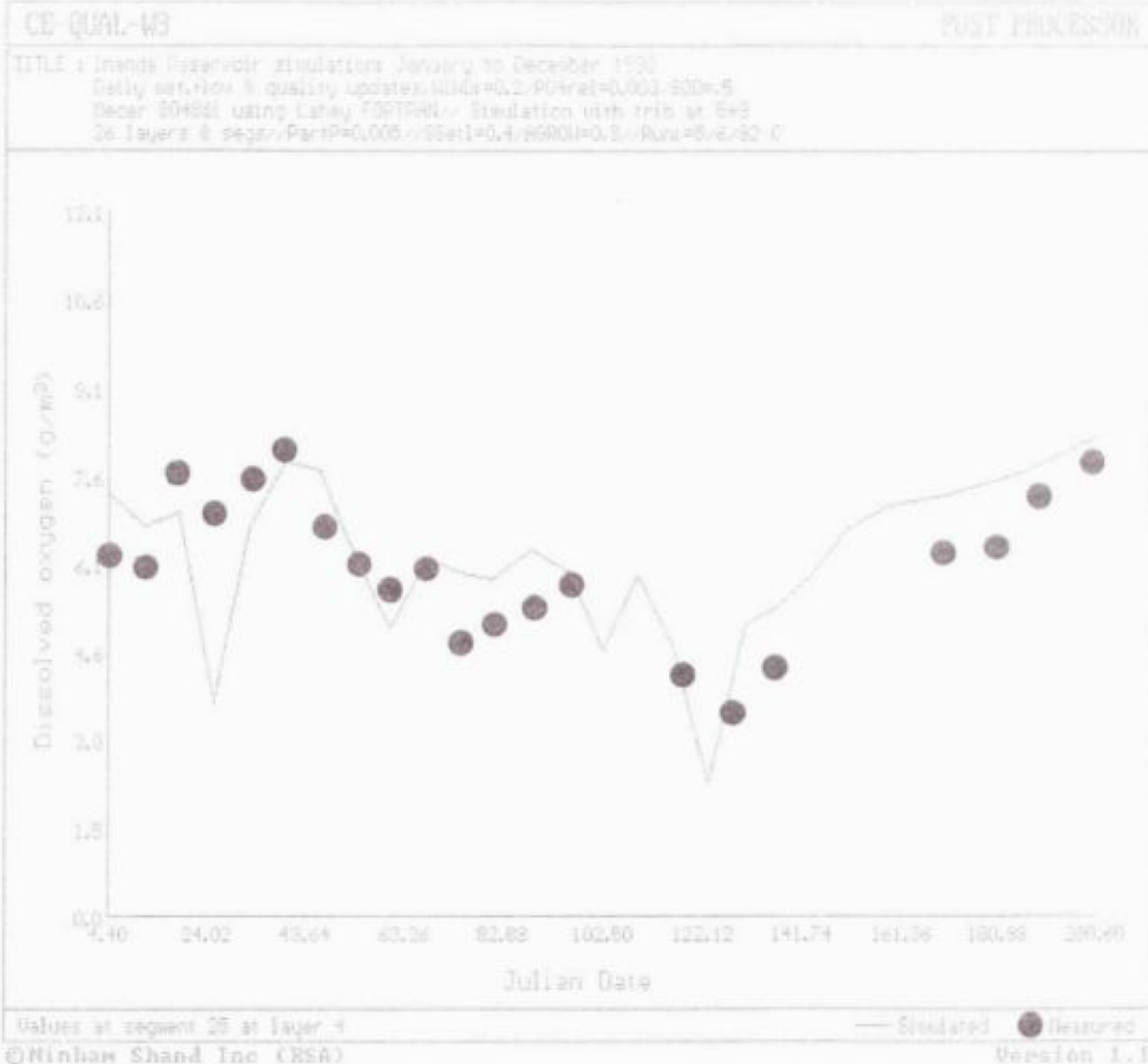
Time series plot showing the simulated and measured dissolved oxygen in Inanda Dam at Segment 25, located at the dam wall.

SURFACE LAYER

KEY:
Measured: ●
Simulated: —

Variable: Dissolved oxygen

Units: mg/l



INANDA DAM - Temperature & DO data Stations 51 TO 55, Date: 28/12/89

TEMPERATURE

	Station:-	51.1	52.1	53.1	54.1	55.1	MEAN:
DEPTH	0M	28.1	29.9	31.0	30.0	30.3	29.9
	2M	27.4	26.8	27.1	28.0	26.1	27.1
	4M	26.3	26.4	26.9	27.4	24.2	26.2
	6M	24.9	26.3	26.6	27.1	24.0	25.8
	8M	23.6	26.0	26.2	26.2	23.9	25.2
	10M	21.9	24.1	25.1	25.0	23.6	23.9
	12M	20.9	23.5	24.4	24.1	23.3	23.2
	14M	20.8	23.2	23.8	22.3	22.6	22.5
	16M	20.5	23.0	22.9	22.2	22.0	22.1
	18M	20.4	22.6	22.8	22.0		22.0
	20M	20.4	21.6	22.6	21.6		21.6
	22M	20.3	21.3	22.3	21.3		21.3
	24M	20.2	21.1	21.9	21.1		21.1
	26M	20.2	20.9	21.5			20.9
	28M	20.2	20.4	21.3			20.6
	30M	20.0	20.4	21.2			20.5
	32M	20.0	20.2				20.1
	34M	20.0	19.9				20.0
	36M	20.0	19.9				20.0
	38M	19.9					19.9
	40M						—

DISSOLVED OXYGEN

	Station:-	51.1	52.1	53.1	54.1	55.1	MEAN:
DEPTH	0M	9.6	11.4	9.9	7.5	7.9	9.3
	2M	6.4	7.8	6.9	5.9	7.4	6.9
	4M	6.0	7.8	6.9	5.2	7.0	6.6
	6M	3.2	4.3	5.9	5.0	6.2	4.9
	8M	0.0	4.0	5.0	4.2	5.7	3.8
	10M	0.0	1.3	3.2	3.8	5.4	2.7
	12M	0.0	0.1	2.0	2.1	3.0	1.4
	14M	0.0	0.1	1.8	2.0	1.9	1.2
	16M	0.0	0.0	1.8	1.9	1.5	1.0
	18M	0.0	0.0	3.4	2.3		1.4
	20M	0.0	0.0	3.4	2.9		1.6
	22M	1.9	0.6	3.0	2.4		2.0
	24M	3.4	2.8	3.3	2.0		2.9
	26M	3.3	3.2	3.2			3.2
	28M	3.4	3.2	3.0			3.2
	30M	3.0	3.2	1.9			2.7
	32M	3.0	2.8				2.9
	34M	1.9	1.4				1.7
	36M	1.6	1.0				1.3
	38M	1.2					1.2
	40M						—

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Temperature and dissolved oxygen data used in the development of a longitudinal data file. Data measured at the five sampling points in Inanda Dam. Date of sample collection: 28-12-1989.

FIGURE 4.33

Advanced reservoir configuration The calibration runs described above used a single branch structure to represent Inanda Dam. The water quality was described using a single initial vertical profile. It was found that improved simulations could be obtained using a vertical profile file for each individual segment. These files are input to the program in the form of a longitudinal profile file. Appendix A4.3 shows examples of the formats used to describe the boundary conditions. Figure 4.33 shows the vertical profile data available from Umgeni Water. These data were interpolated to provide an oxygen and temperature value for each cell. Where a single data value was available for the surface and bottom water, linear interpolation was used to define the initial boundary conditions.

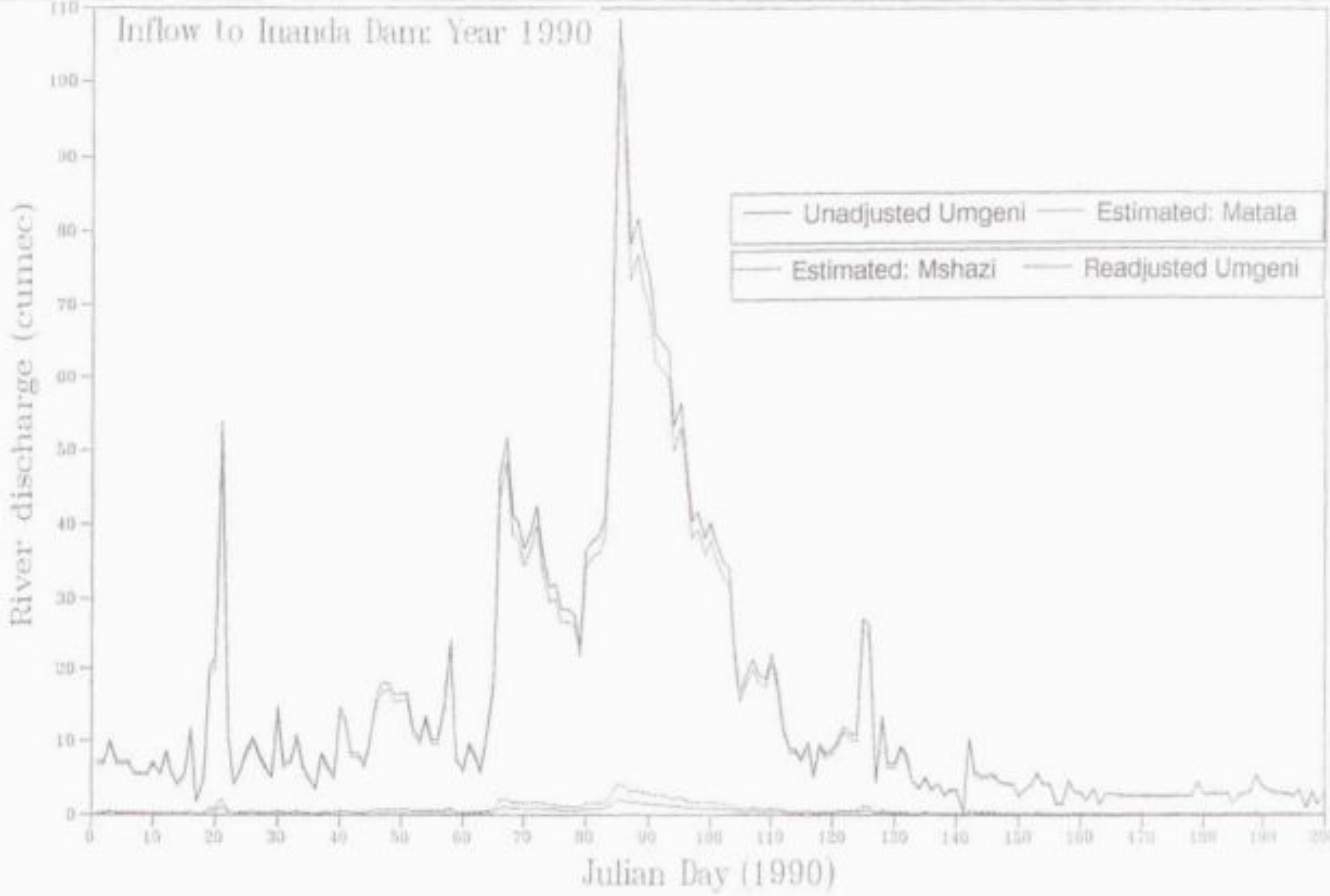
The next stage in the testing of CE-QUAL-W2 required the extension from a one branched to a three branch configuration, see Figure 4.34. The model had to be recompiled, linked and new data files developed to accommodate the different branching structure. The program was found to give a number of coding errors which required a complete review of the FORTRAN code used in the water balance of the model. Considerable time was spent debugging the code and it was found eventually that a 3 branch, sequentially linked configuration could not be used with this version of CE-QUAL-W2. Multiple branches can however be used when a dendritic shape is used.

The branch structure in CE-QUAL-W2 uses a single orientation for each branch. In the case of Inanda Dam, the individual segments within a branch have variable orientations. Therefore when a single branch is used, the model assumes that the whole reservoir is orientated in one direction. The source code was modified so that each segment could have a unique orientation and thereby simulate the meandering pattern evident in many reservoirs. The modified code gave improved performance in terms of temperature, dissolved oxygen, algal biomass, and water dynamics.

Lateral (tributary) inflows to Inanda Dam The simulations carried out above assumed that all inflow to Inanda Dam was delivered via the Umgeni River and no flow was derived from the tributaries. Simulations were performed to determine the influence of the tributary inflows on the water quality of Inanda Dam. No discharge data were available for the tributaries so discharge hydrographs were estimated using the following method:

- Figure 4.35 shows the discharge hydrograph for the Umgeni River (unadjusted), the discharge hydrograph for the Umgeni River with 9 percent of the flow entering the Inanda Dam via the Matata and Mshazi Spruits (readjusted Umgeni), and the two hydrographs for the Matata and Mshazi Spruits. Based on catchment area, the Matata

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Three branch structure used for the water quality simulations for Inanda Dam using CE-QUAL-W2.	FIGURE 4.34



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Hydrograph for the Umgeni River partitioned giving estimated hydrographs for the lateral inflows to Inanda Dam. The Umgeni River hydrograph is reduced by 5 percent for the flow in the Mshazi, and by 2 percent for the flow in the Matata Spruit.

FIGURE 4.35

was given 6 percent and the Matata 3 percent of the Umgeni inflow .

- Water quality input data files were developed for both tributaries using linear interpolation to in-fill the data series.
- Water temperature data were not available and the time series developed from the water temperature of the Umgeni River.

CE-QUAL-W2 was run using additional inflow via the tributary inflows entering Inanda Dam at Segment 5 and 9. Analysis of the simulated data showed that the tributaries had little influence on the surface water quality of Inanda Dam. In many instances, the tributaries discharged into the lower layers of Inanda Dam. Such an application shows the use of the model to investigate the influence of inflows and discharges on the water quality of a reservoir.

4.4.4 Conclusions from the Inanda Dam simulation

CE-QUAL-W2 provided acceptable simulation of the water quality, thermal dynamics and hydrodynamics of Inanda Dam. Only minor changes were made to the source code to account for the meandering shape of Inanda Dam. The simulation provided valuable insight into the dynamics of Inanda Dam, and shows:

- The water quality of Inanda Dam is governed by the main inflow - the Umgeni River which has high turbidity, phosphorus and coliform content.

- Analysis of the two-dimensional plots for TDS and phosphorus show the tributaries flow into the lower layers of Inanda Dam having little influence on surface water quality.

- During periods of high inflow, the flood waters of the Umgeni River plunge into the lower layers of Inanda Dam. The influence of the flood waters on the water quality of the surface layers is limited by the degree of vertical mixing. Such vertical mixing is brought about by wind and advective currents.

- The phosphorus content of the Umgeni River causes high algal growth at the point of inflow to Inanda Dam. As the water passes the length of the reservoir, the combined influence of adsorption onto suspended solids and uptake by algae cause a diminishment in phosphorus concentration bringing about longitudinal gradients in water quality.

- The high suspended solids content of Inanda Dam influences (1) algal biomass through light limitation, (2) in-lake nutrient concentrations through adsorption onto suspended particles, and (3) water temperature through heating of the surface layers.

- Heat exchange processes during the summer cause pronounced thermal stratification lasting up to nine months per year. In early winter, the combination of wind action and reduced solar radiation causes turn-over and vertical mixing of the reservoir. Vertical mixing increases the phosphate concentrations in the upper layers which in turn causes an increase in the algal biomass.

- The hypolimnion of Inanda Dam becomes deoxygenated for up to eight months during the summer. Flood events pass into the deeper layers and increase the oxygen content of the hypolimnion leaving a section of the metalimnion with low oxygen content. This effect is short lived as the oxygen demand of the lake sediments causes rapid deoxygenation of the hypolimnion.

- In terms of water quality management of Inanda Dam, CE--QUAL—W2 could be used to investigate the influence of (1) changes in the external loading of phosphorus to Inanda Dam and (2) the release of water from the hypolimnion during floods to scour nutrient laden water out of Inanda Dam.

- In terms of the operational design of Inanda Dam, CE—QUAL—W2 could be used to optimize the location of abstraction points and develop an operating rule for selection of withdrawal level. Simulations show the longitudinal gradients between the inflow and dam wall result in "improved" qualities at the dam wall. The vertical gradients in water quality are complex and the selection of a withdrawal level must take account of daily variations in water quality brought about by (1) high algal biomass in the upper layers, (2) high nutrients and low oxygen content of the water in the metalimnion and hypolimnion, and (3) vertical mixing during periods of destratification.

TABLE 4.2
Coefficients and constants used in Inanda Dam application of CE-QUAL-W2

Coefficient (1)	Unit (2)	Value (3)
Hydraulic parameters		
Longitudinal dispersion of momentum	m^2/s^{-1}	10.0
Longitudinal dispersion of heat	m^2/s^{-1}	10.0
Longitudinal dispersion of constituents	m^2/s^{-1}	1.0
Chezy coefficient	$m^{1/2}/s^{-1}$	70.0
Radiation absorbed in surface layer	-	0.45
Light attenuation coefficient	m^{-1}	0.40
Attenuation coefficient for inorganic suspended solids	m^2/g^{-1}	0.15
Attenuation coefficient for organic suspended solids	m^2/g^{-1}	0.3
Suspended solids settling rate	m/day^{-1}	0.4
Phytoplankton		
Maximum growth rate	day^{-1}	0.3
Settling rate	m/day^{-1}	0.0
Phosphorus half-saturation constant	mg/L^{-1}	0.006
Nitrogen half-saturation constant	mg/L^{-1}	0.08
Saturation light intensity	W/m^{-2}	150.0
Dark respiration rate	day^{-1}	0.017
Photorespiration rate	day^{-1}	0.02
Mortality rate	day^{-1}	0.001
Nitrogen		
Ammonia decay (nitrification) rate	day^{-1}	0.05
Nitrate reduction rate	day^{-1}	0.25
Sediment release rate	$g/m^{-2}/day^{-1}$	0.02
Partition coefficient	m^3/h^{-1}	0.05
Phosphorus		
Sediment release rate	$g/m^{-2}/day^{-1}$	0.007
Partition coefficient	m^3/g^{-1}	0.005
Dissolved oxygen		
Sediment oxygen demand	$g/m^{-2}/day^{-1}$	0.5

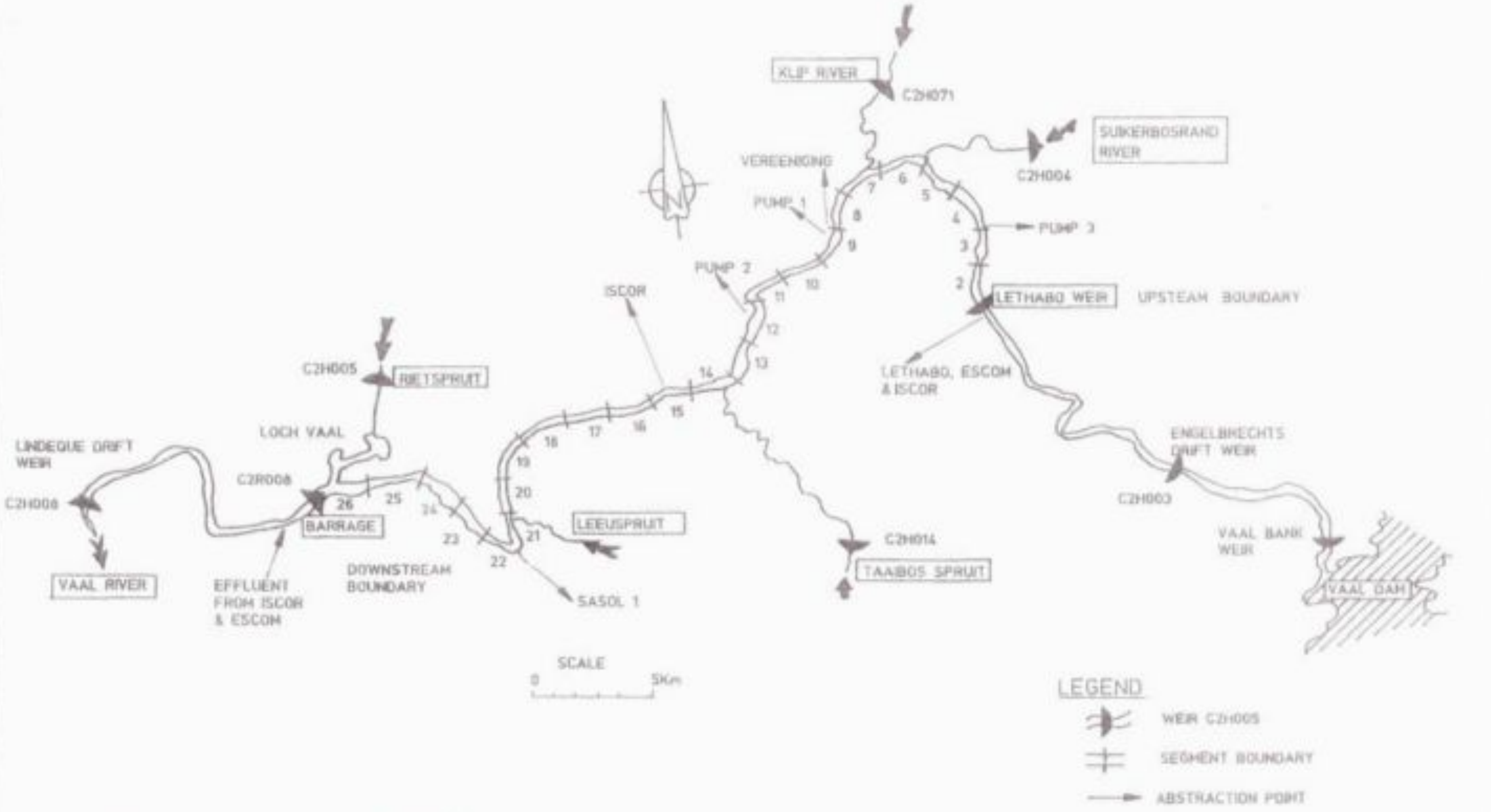
4.5 CE-QUAL-W2 APPLICATION: VAAL BARRAGE

4.5.1 Reservoir characteristics

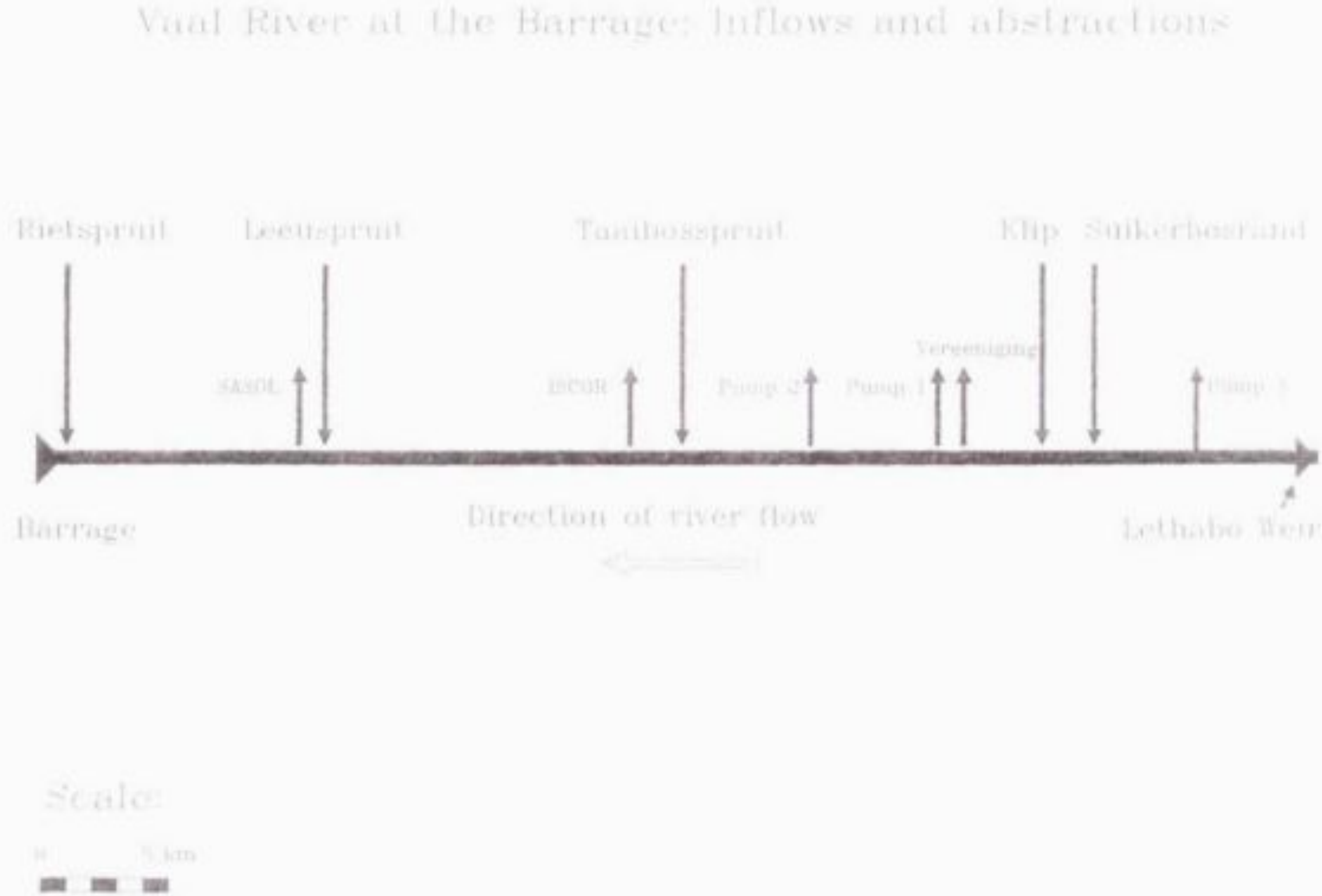
The Vaal River has been impounded forming a riverine lake approximately 50 km long, ±150 metre wide, and ±6 metre deep. Figure 4.36 shows a location map of the Vaal Barrage. At the upstream end of the Barrage (at Lethabo weir), releases are made from the Vaal Dam. The Vaal Dam receives drainage from a catchment area of around 38 500 km² comprising agricultural land interspersed with urban and industrial areas. Water is abstracted from the Vaal Barrage by the (1) Rand Water Board (RWB), (2) Vereeniging Municipality, (3) ISCOR, and (4) SASOL. The points of abstraction are shown on Figures 4.36 and 4.37. Upstream of Lethabo Weir, water is abstracted by ESKOM, ISCOR and SASOL. At the upstream end of the Barrage, a weir has been constructed at Lethabo, see Figure 4.37. Lethabo weir was built to separate the high TDS water of the Barrage from the low TDS water released from the Vaal Dam. Before the Lethabo Weir was built, abstraction by ESKOM, and RWB caused reversed flow in the river resulting in the abstraction of water high TDS water derived from the Barrage. Since Lethabo Weir was built, the upstream water has been separated from the Barrage preventing the ingress of high TDS water towards the abstraction points of ESKOM, ISCOR, and SASOL.

The Rand Water Board supply a large portion of the Pretoria Witswatersrand Vereeniging (PWV) area from the Vaal River system with water blended from both the Barrage and the Vaal Dam to obtain an average TDS concentration of around 300 mg/l (Thirion, 1991). Figure 4.37 shows a schematic of the layout of the Vaal Barrage, with the main tributaries and abstraction points. The Barrage receives tributary flows from the Klip River, Suikerbosrand River, Taaibos Spruit, Leeuspruit and Rietspruit. The Klip River contributes the largest inflow to the Barrage receiving runoff from urban, industrial and mining areas (Jones *et al.* 1988), as well as treated wastewater from treatment works in the south of Johannesburg (Van Vliet and Nel, 1986). Discharges from point and nonpoint sources are also made to the Rietspruit, Leeuspruit and Suikerbosrand River. Funke (1984) and Thirion (1991) report that the tributary inflows deliver a high load of TDS and phosphorus to the Barrage.

To overcome water quality problems caused by high TDS concentrations in the Barrage during the winter low flow period, releases are made from the Vaal Dam. Such releases from Vaal Dam are intended to flush the Barrage using water with low TDS concentration (between 130 to 210 mg/l) from the Vaal Dam (Van Vliet and Nel, 1986). In comparison,



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Location map of the Vaal Barrage showing the main tributaries, abstractions and gauging weirs.	FIGURE 4.36



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Schematic of the Vaal Barrage showing the tributary inflows and abstractions.

FIGURE 4.37

the TDS concentration of the Barrage can exceed 800 mg/l (DWA&F, 1990). A management strategy is used where water is released from Vaal Dam to maintain the Barrage at a TDS concentration of less than 600 mg/l. Such a strategy minimizes water quality problems experienced by users (Thirion, 1991). During July and August 1990, a release was made from the Vaal Dam to reduce the TDS of the Vaal Barrage. The Hydrological Research Institute (DWA&F) undertook a monitoring survey of the Barrage during and after the release period. Thirion (1991) states the objectives of the monitoring exercise were:

- to test the viability of the releases from Vaal Dam to maintain the Barrage at 600 mg/l TDS, and
- to provide data and information on the hydrodynamic behaviour of the Barrage so that mathematical models could be used to assist in the management of the Vaal Barrage.

Monitoring carried out during July to November 1990 showed that releases from Vaal Dam cause a reduction in the TDS concentration of the Barrage. During the release period, the Barrage showed substantial longitudinal and vertical gradients in TDS concentration (Thirion, 1991). The cause of these gradients was not explained and assumed to be caused by differences in the density of the two waters. Based on the information obtained from the survey in 1990, it was decided that the Vaal Barrage would prove to be an excellent case study to test the ability of CE-QUAL-W2 to simulate the two-dimensional water quality characteristics of the water body.

4.5.2 Model application: Vaal Barrage

Choice of simulation period: The simulation period extended over a period of 140 days, beginning 1 July 1990 and ending 15 November 1990. The period was selected to overlap the duration of the release from Vaal Dam, thereby allowing:

- the simulated conditions in the Vaal Barrage to reach an equilibrium condition <u>before</u> the release was made on 21 July 1990, and
- the Vaal Barrage sufficient time to reach a final equilibrium <u>after</u> the release had passed through the water body to determine the duration of the mixing process within the water body.

During the simulation period, water samples were collected from the tributary inflows as well as the Barrage. These data were made available by the Hydrological Research Institute (DWA&F) as well as by the Rand Water Board.

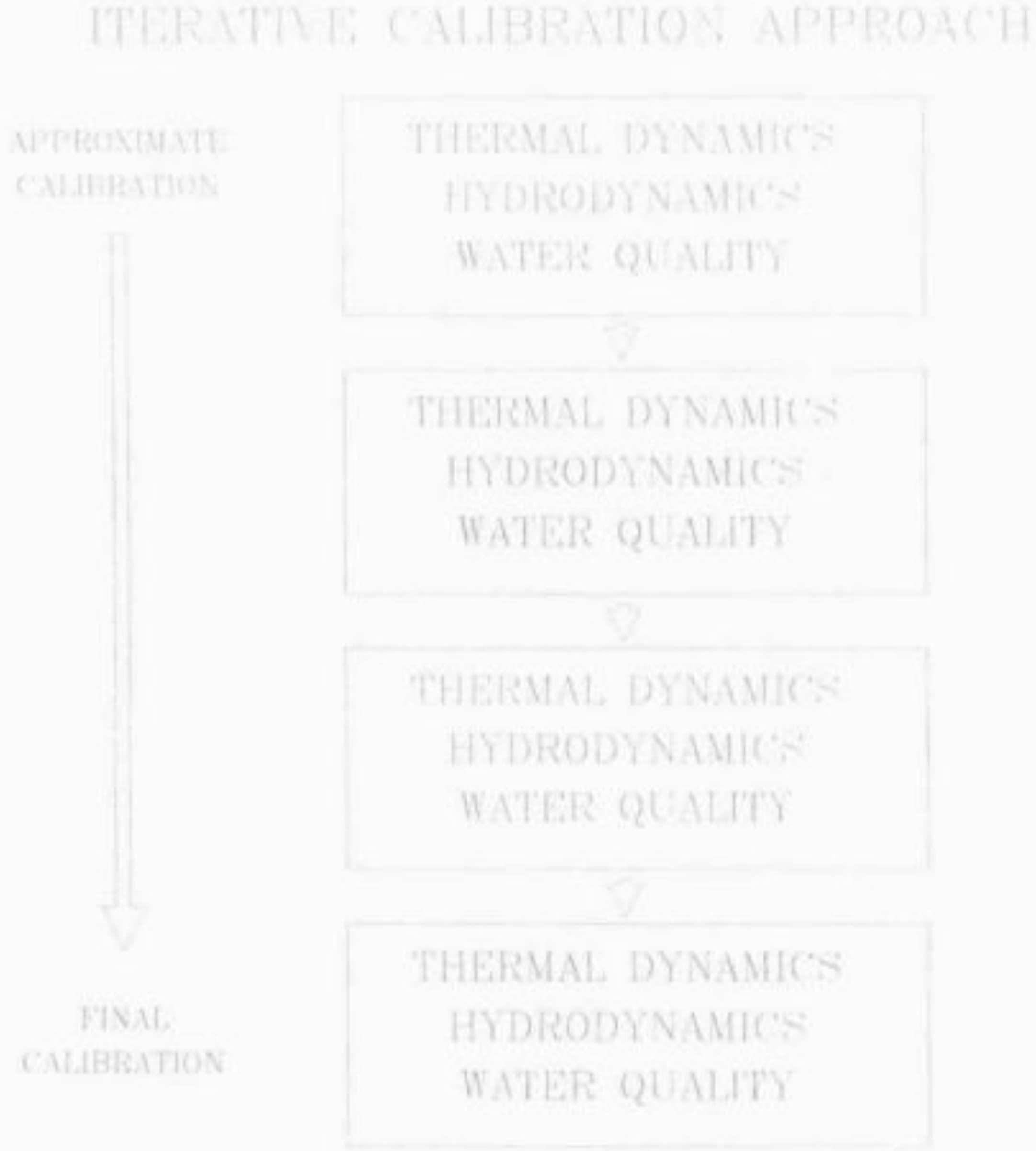
General approach used in model calibration: The calibration procedure for CE-QUAL-W2 comprised three sections: (1) calibration of the thermal dynamics, (2) calibration of the hydrodynamics, and (3) calibration of the water quality components. Figure 4.38 shows the iterative approach used to calibrate CE-QUAL-W2. In the first calibration attempt, the thermal dynamics, hydrodynamics and water quality are calibrated in an approximate fashion. The sequence was repeated until a final calibration achieved. The multiple/sequential calibration approach was used because the processes simulated by the model are coupled, see Figure 4.39. For example, if the thermal dynamics was inadequately calibrated the degree of vertical mixing would be incorrect resulting in errors in the simulation of water quality. When calibrating the model using an iterative approach, these problems were reduced and also allowed a rapid convergence on the final point of calibration. The "final" calibration is generally governed by the information needs of the model user, availability of data for calibration, time constraints, and ability of the model to simulate the governing processes.

CE-QUAL-W2 calibration: thermal dynamics of the Vaal Barrage In the calibration of the thermal dynamics, the following data were used

- wind speed (m/s - verified using the program METDATA),
- wind direction (radians),
- temperature of inflows (degrees C),
- short wave radiation (W/m^2 - calculated using METDATA),
- coefficient of surface heat exchange (W/m^2 - calculated using METDATA),
- dew point temperature (degree C),
- surface water temperature (degree C - used by METDATA to verify the heat exchange of the water body)
- air temperature (degree C), and
- equilibrium temperature (degree C - calculated using METDATA).

The meteorological data were measured by the Weather Bureau at Vanderbijlpark and Vereeniging. The complete data sets were obtained from the Weather Bureau in Pretoria, with the exception of the water temperatures which were obtained from the Rand Water Board. Additional water temperature data for the inflows and Barrage were provided by the Hydrological Research Institute (DWA&F).

The program METDATA was used to screen, verify and adjust the meteorological parameters and produce the input file for CE-QUAL-W2. Appendix A4.1 describes the theoretical background of METDATA and use of the program with the meteorological data



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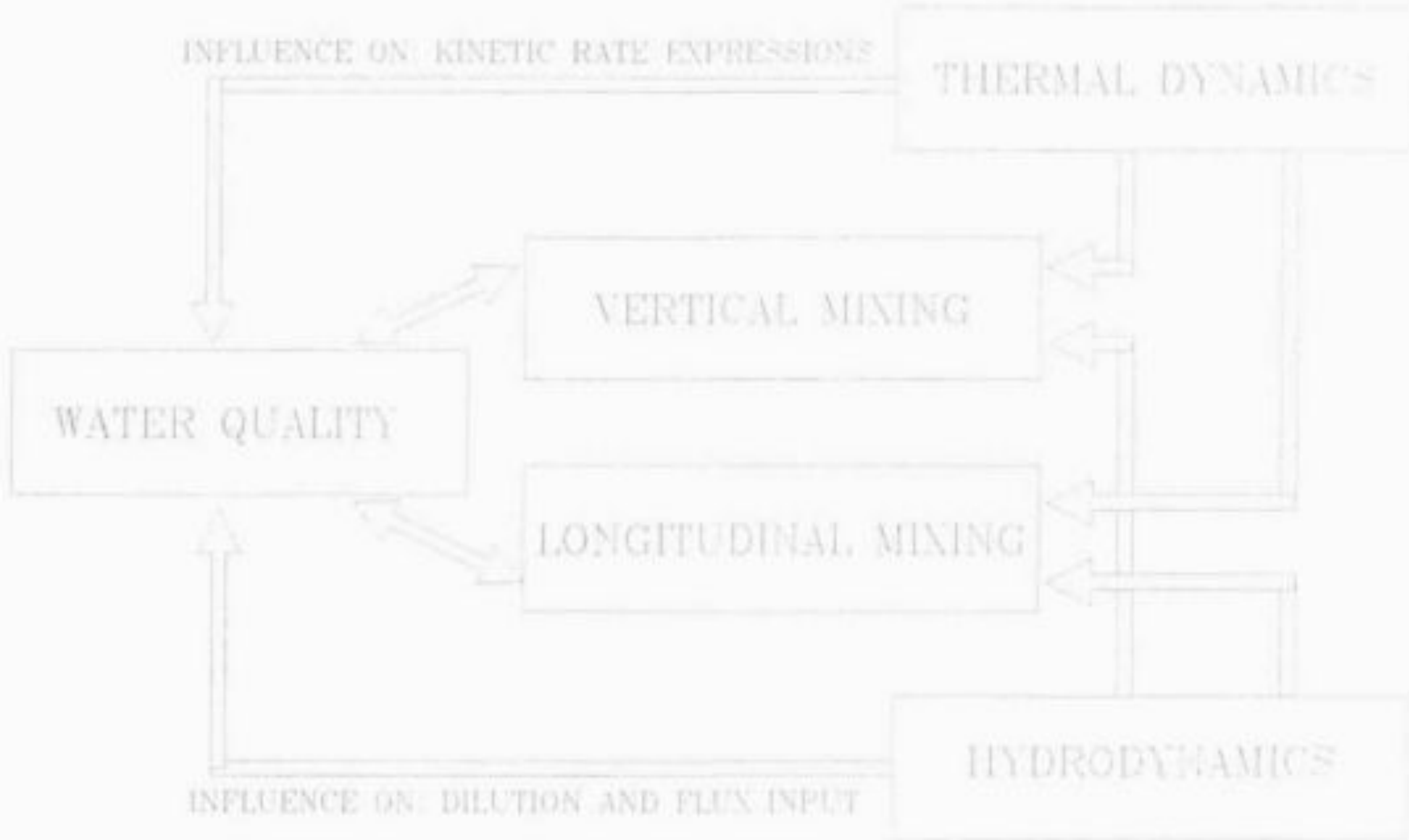
Approach adopted for the calibration of CE-QUAL-W2 for the Vaal Barrage simulation.

FIGURE 4.38



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Interaction of thermal dynamics, hydrodynamics and water quality in relation to longitudinal and vertical mixing processes.

FIGURE 4.10

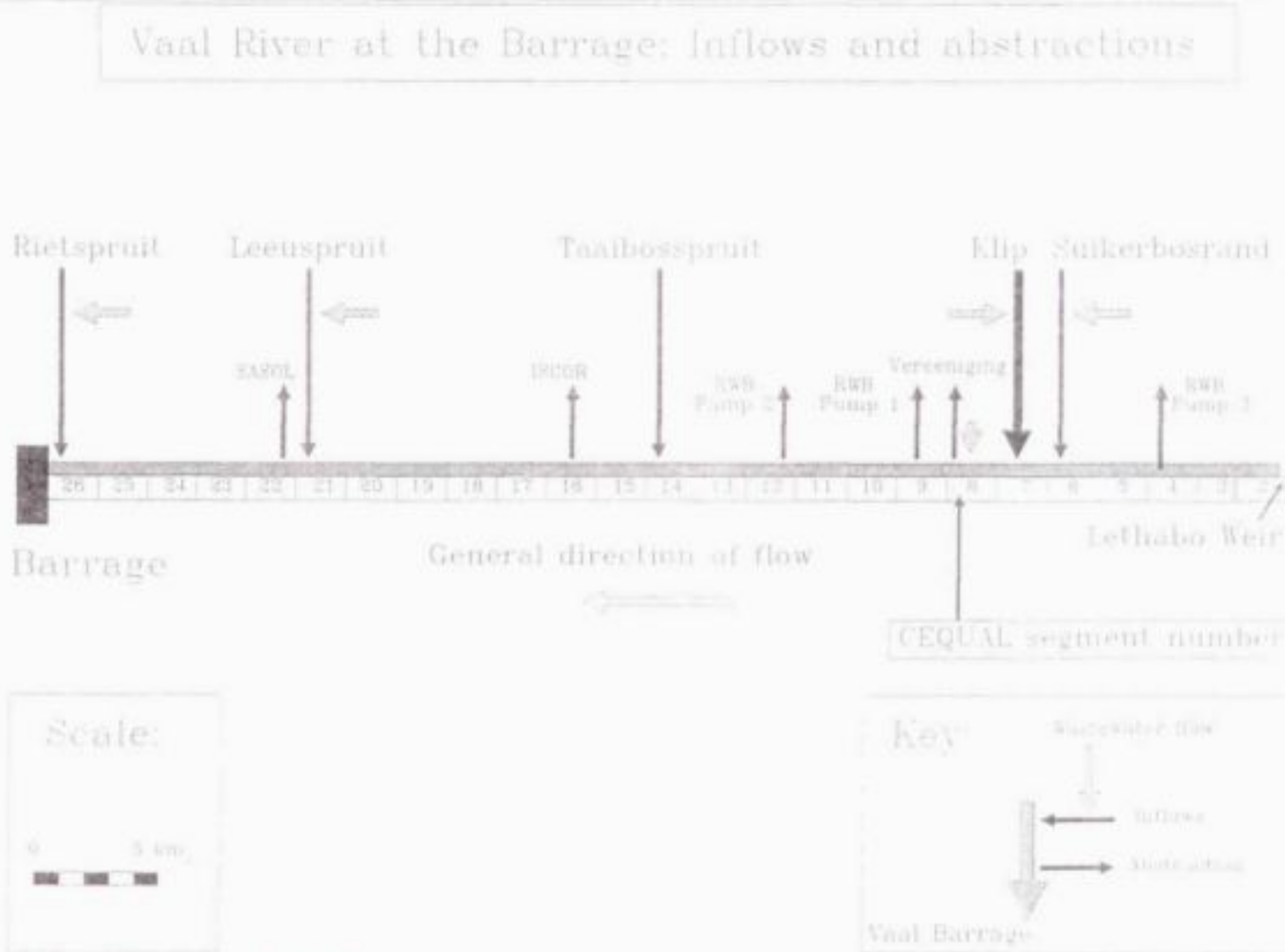

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FIGURE 4.40

Schematic of the Vaal Barrage showing the tributary inflows, wastewater discharge lines and abstraction points. The segment numbers used in the CE-QUAL-W2 simulation are shown.

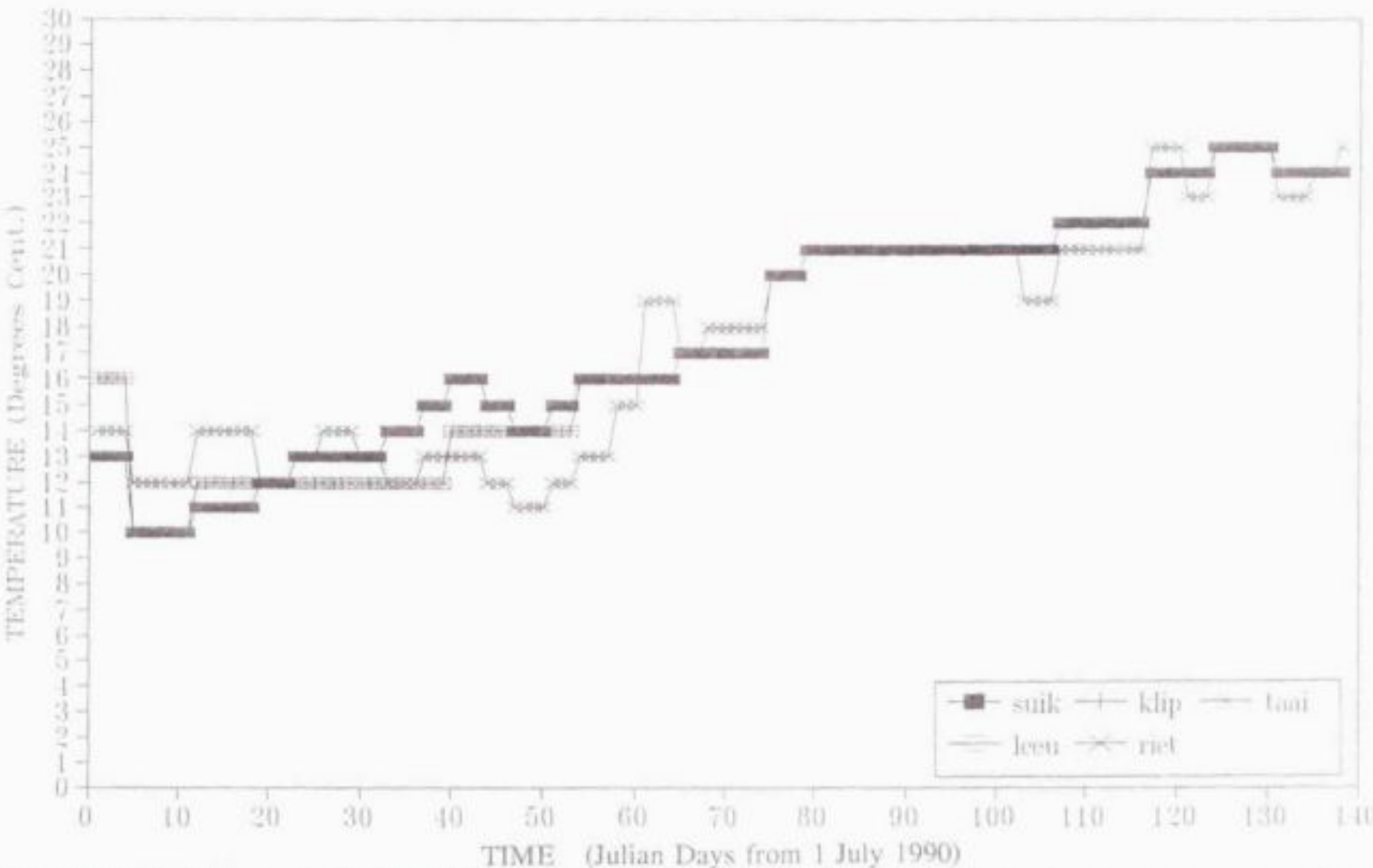
set for the Vaal Barrage. METDATA was used to calculate a number of variables which form input to the model, these include: the equilibrium temperature, coefficient of surface heat exchange and short wave radiation. METDATA may be used to adjust the wind speed to minimize differences between measured and simulated surface water temperatures. It was found that the meteorological data provided excellent results in the simulation of the water temperature of the Barrage and only minor adjustments of the wind speed were required. The compensation for wind may be accounted for by the wind sheltering afforded to the water body by trees, vegetation and buildings along the banks of the Barrage.

The program METDATA enables the pre-screening of the meteorological data, refer to Appendix A4.1 for information on the Vaal Barrage data set. CE-QUAL-W2 uses the heat exchange data from the meteorological data file in addition to the temperature data for each inflow to calculate the heat budget for each cell in the computational grid. Figures A4.6.1 to A4.6.3 (in Appendix A4.6) show measured water temperature of the tributaries flowing into the Barrage, with associated discharge data. In the case of the Leeuspruit, no temperature data were available. The water temperature of the Leeuspruit was estimated from the data for the Taaibos Spruit, assuming that the water temperature would be the same in both streams. This assumption was considered reasonable as both tributaries drain adjacent catchments containing similar land use. Figure 4.41 shows the temperature data for the tributaries of the Barrage during the period of simulation.

Figures 4.42 and A4.6.4 to A4.6.7 show the results of the model run with the measured and simulated temperature of the Barrage during the period, Day 4 to 137. The good agreement between the measured and simulated data for both surface and bottom layers of the Barrage showed (1) the program METDATA was capable of screening the meteorological data, and (2) the model provided an accurate simulation of the temperature regime within the Barrage. Final calibration of the thermal dynamics of the Barrage was only possible once the hydrodynamics and water quality components were calibrated, and described in Section 4.5.3.

CE-QUAL-W2 calibration: hydrodynamics of the Vaal Barrage Figure 4.40 shows the main inflows and withdrawals associated with the Vaal Barrage. As input, CE-QUAL-W2 requires information on the physical configuration of the water body, this includes:

- the number of segments and layers used in the configuration,
- the length of each segment and the depth of the layers,
- the average width of each cell, and
- the inflows and withdrawals associated with each segment.



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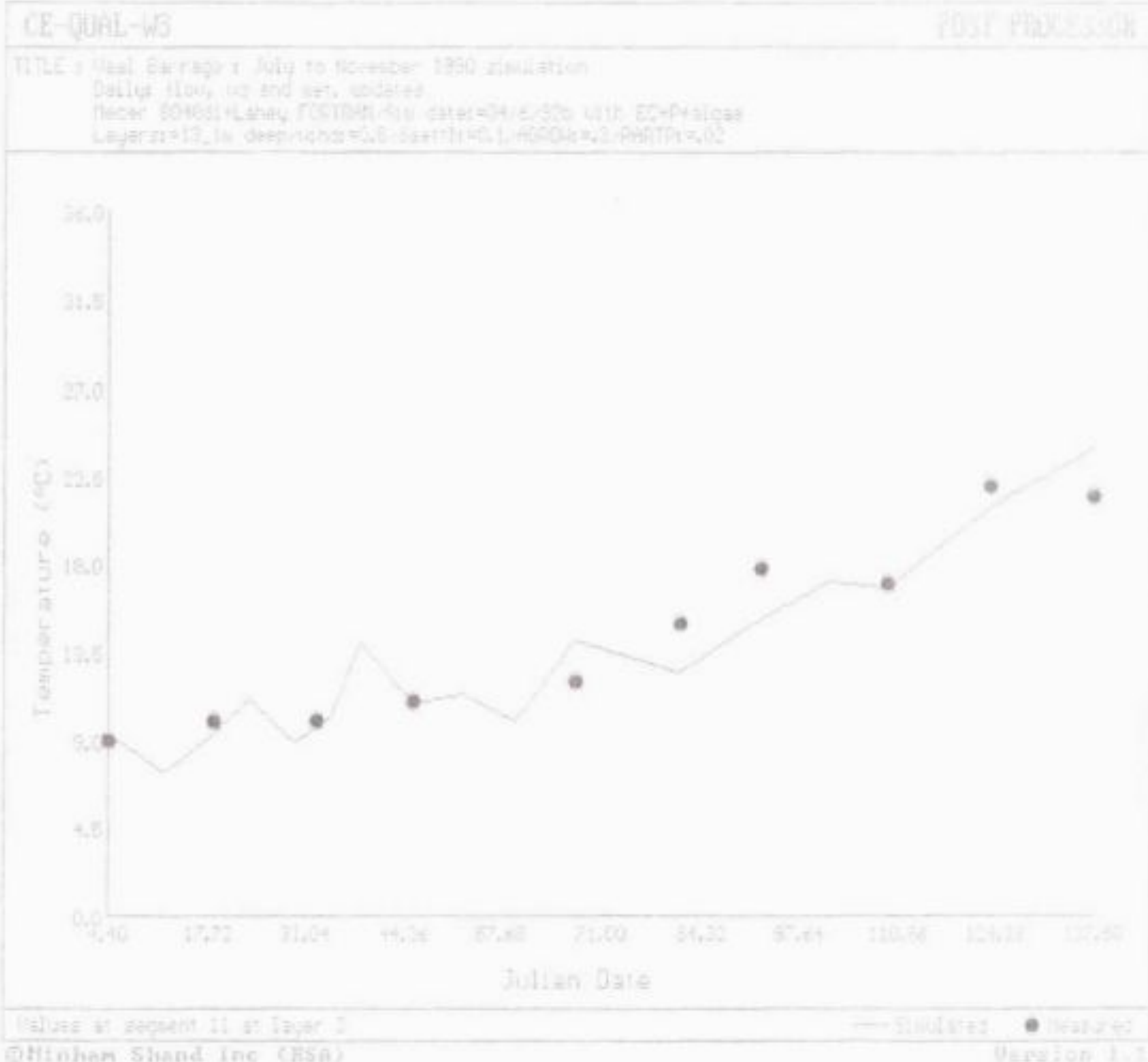
Water temperature of the tributary inflows to the Vaal Barrage.

FIGURE 4.41

Figure 4.42

Simulated and measured temperature of the surface water at Segment 11 in the Vaal Barrage.

Segment 11 is located at Vereeniging.



Segment layout: The distance between Lethabo Weir and the Barrage and was found to be 52 km. To minimize computation time, a maximum limit of 30 segments was set. The 52 km river reach between the upstream (Lethabo Weir) and the downstream boundary (the Barrage) was divided into 2000 metre lengths giving a total of 26 segments. The upstream and downstream boundary of each of the 52 segments was marked on a 1:50 000 scale map. Information provided by the Regional Office of the DWA&F was used to identify each of the main withdrawal points from the Barrage, these points were marked on the 1:50 000 map. Figure 4.40 shows the location of each withdrawal and tributary in relation to the 26 segments.

In 1978, the Department of Water Affairs and Forestry carried out a hydrometric survey of the Barrage. The survey included a series of cross-sections at points along the flow path of the Barrage. Scrutiny of the survey data showed that at the deepest point in the Barrage, the cross-section could be divided at one metre intervals of depth giving a total of thirteen layers. The cross-section data formed the basis for determining the lateral widths for each cell. Unfortunately, only ten out of the total of nineteen cross-sections were carried out between Lethabo Weir and the Barrage and no cross-sections were measured at 16 out of the 26 segments. A spreadsheet package was used to in-fill the cell widths where no segment cross-sectional data were available. The spreadsheet was used also to provide a first estimate of the volume of the Barrage at various stage levels. Figure 4.43 shows the layout of the spreadsheet and the cross-sectional widths for each cell. In Figure 4.43, the zero values represent cells which are "inactive" and form the boundary layers. The spreadsheet was developed so that the bathymetric data could be transferred directly in a format acceptable to CE-QUAL-W2.

Secondary verification of the bathymetric data involved the use of the preprocessor which uses the bathymetric file and calculates the volume/stage (water level) relationship and the water surface area/stage relationship, see example in Appendix A4.4. Unfortunately, no measured volume/stage relationship was available for the Barrage. The only way to verify the bathymetric data was to run CE-QUAL-W2 and compare the simulated and measured water levels. Before the model could be run, input files were required for the tributary inflows, withdrawals, and releases. The formulation of these input files is described below.

Discharge hydrograph data CE-QUAL-W2 calculates the change in volume of the water body as a function of the rate of tributary inflow, rate of withdrawal and rate of release. The discharge data for the Klip River, Suikerbosrand, Taaibos and Rietspruit were obtained from the Directorate of Hydrology (DWA&F) as well as the Rand Water Board. The use of the

Bathymetric data : Vaal Barrage

layer width

Segment numbers

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	layer #	Elevation (m)
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	
0	110	119	128	124	120	115	111	175	168	164	160	165	168	169	179	168	163	159	157	155	213	241	270	328	385	0	2	1421.6
0	109	110	129	117	115	112	109	152	154	154	155	158	159	160	160	158	156	154	153	152	205	231	257	314	370	0	3	1420.6
0	95	104	112	109	106	103	100	137	141	143	145	125	135	140	145	114	113	111	141	140	185	208	230	298	365	0	4	1419.6
0	92	99	106	103	101	98	95	126	128	129	130	115	123	126	130	132	134	136	137	138	162	173	185	271	362	0	5	1418.6
0	87	91	100	98	95	93	90	112	119	122	125	105	115	120	125	126	128	129	129	130	151	162	172	261	350	0	6	1417.6
0	0	0	85	86	86	87	87	101	110	112	115	95	105	110	115	118	120	123	124	125	143	151	160	240	320	0	7	1416.6
0	0	0	0	0	10	10	85	95	101	101	107	90	100	105	110	113	115	118	119	120	135	143	150	218	285	0	8	1415.6
0	0	0	0	0	0	0	0	0	0	20	30	80	90	95	100	101	109	113	115	117	129	134	140	195	250	0	9	1414.6
0	0	0	0	0	0	0	0	0	0	0	0	40	53	59	65	78	88	99	104	110	115	118	120	175	230	0	10	1413.6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	40	49	95	103	106	110	95	80	0	11	1412.6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	90	90	90	10	10	0	12	1411.6
0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	13	1410.6

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Spreadsheet used to calculate the widths of the cells in each of the segments. The cells with zero values refer to inactive cells used as boundaries of the waterbody.

FIGURE 4.43

hydrodynamic model, DYNHYD, in WASP allowed the pre-screening and evaluation of the hydrograph data. Chapter 5 describes the interpretation and manipulation of the hydrograph data used in the Barrage simulation. Discharge data for the Leeuspruit were not measured and had to be estimated using the hydrograph for the adjacent catchment drained by the Taaibos Spruit. Equation (4.2) shows the method used to generate a discharge hydrograph for the Leeuspruit.

$$Q_{Leeu} = Q_{Taai} * (A_{Leeu} / A_{Taai}) \quad \text{.... (4.2)}$$

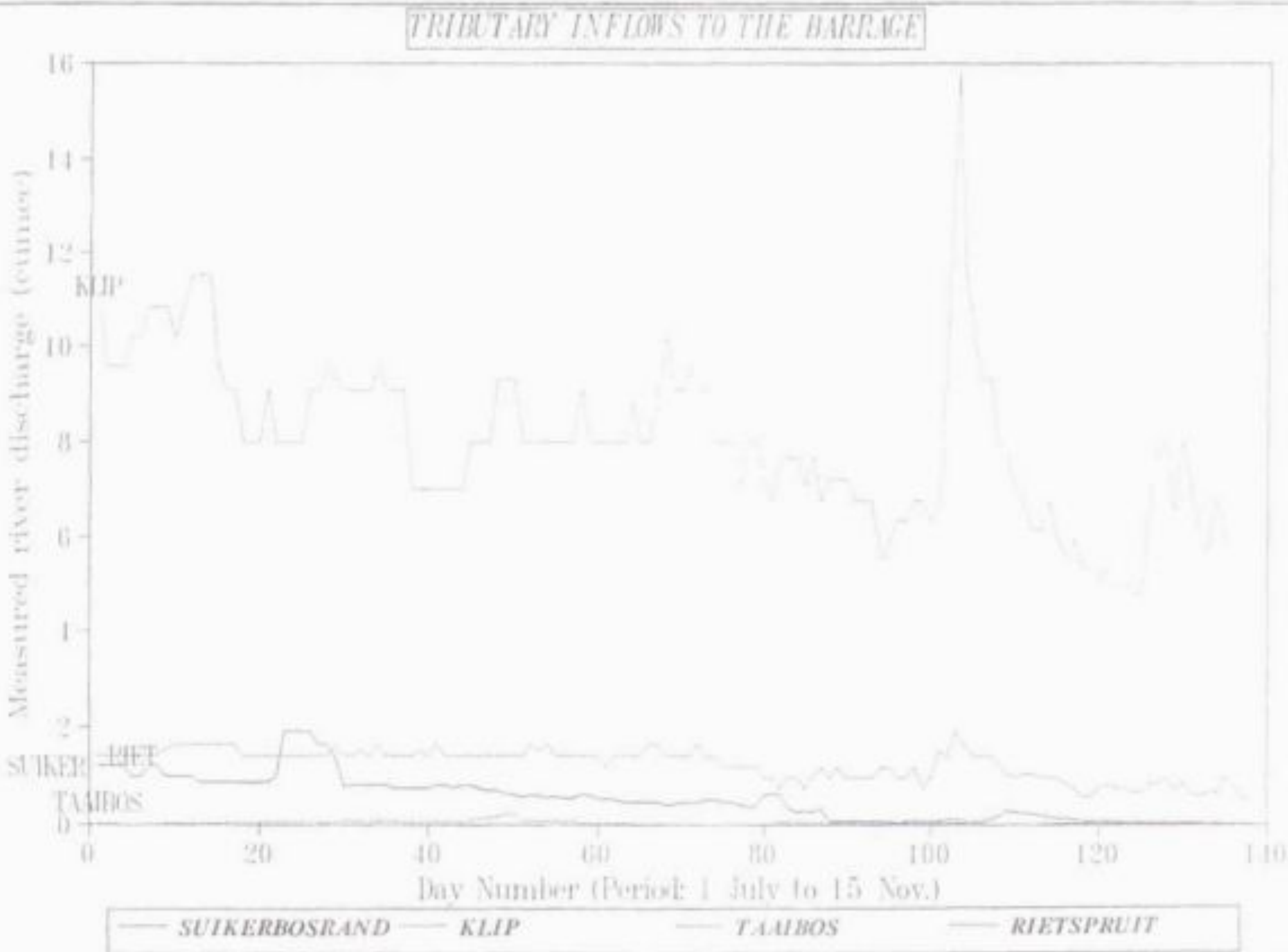
where Q_{Leeu} is the daily average discharge of the Leeuspruit (cumec), Q_{Taai} is the daily average discharge of the Taaibos Spruit (cumec), A_{Leeu} is the catchment area of the Leeuspruit (km^2), and A_{Taai} is the catchment area of the Taaibos Spruit (km^2). The catchment area quotient (A_{Leeu} / A_{Taai}), had a value of 0.3.

Figures A4.6.1 to A4.6.3 (in Appendix A4.6) show the discharge data for the tributary gauged inflows as well as the estimated discharge for the Leeuspruit. Figure 4.44 shows the inflow to the Vaal Barrage at Lethabo Weir and at Vaal Bank Weir. Vaal Bank weir is immediately downstream of the Vaal Dam, see Figure 4.36. The difference between the hydrographs for Vaal Bank and Engelbrechts Drift shows the users upstream of the Lethabo Weir cause a considerable reduction in the flow of the Vaal River and prevented water passing into the Barrage during the first 20 days of the simulation period.

Figure 4.45 shows the discharge hydrographs for the tributary inflows to the Vaal Barrage. Figure 4.46 shows the discharge hydrograph for the water released from the Barrage. Chapter 5 describes the procedures used to derive the discharge hydrograph for the water released from the Barrage. Figure 4.47 shows the rates of withdrawal from the Barrage, with data provided by the operational staff of DWA&F and RWB.

CE-QUAL-W2 was run with inputs of: tributary inflow, withdrawals, and meteorological data. At this stage no water quality constituents were simulated. Figure 4.48 shows the simulated and measured stage data for the first run of the model where the model over-estimates the rate of change in stage level. The over-estimation in the volumetric calculations was not caused by errors in the inflow hydrographs but caused by an under-estimation of the volume of the Barrage. The problem was overcome by increasing the volume of the Barrage by adjusting the bathymetric data. Figure 4.49 shows the results of increasing the full supply volume by ten percent which results in the volume increasing from 43 to 48 million cubic metres.

NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Discharge hydrographs of the Vaal River at Vaal Bank and Lethabo during the simulation period 1 July to 15 November 1990.	FIGURE 4.44



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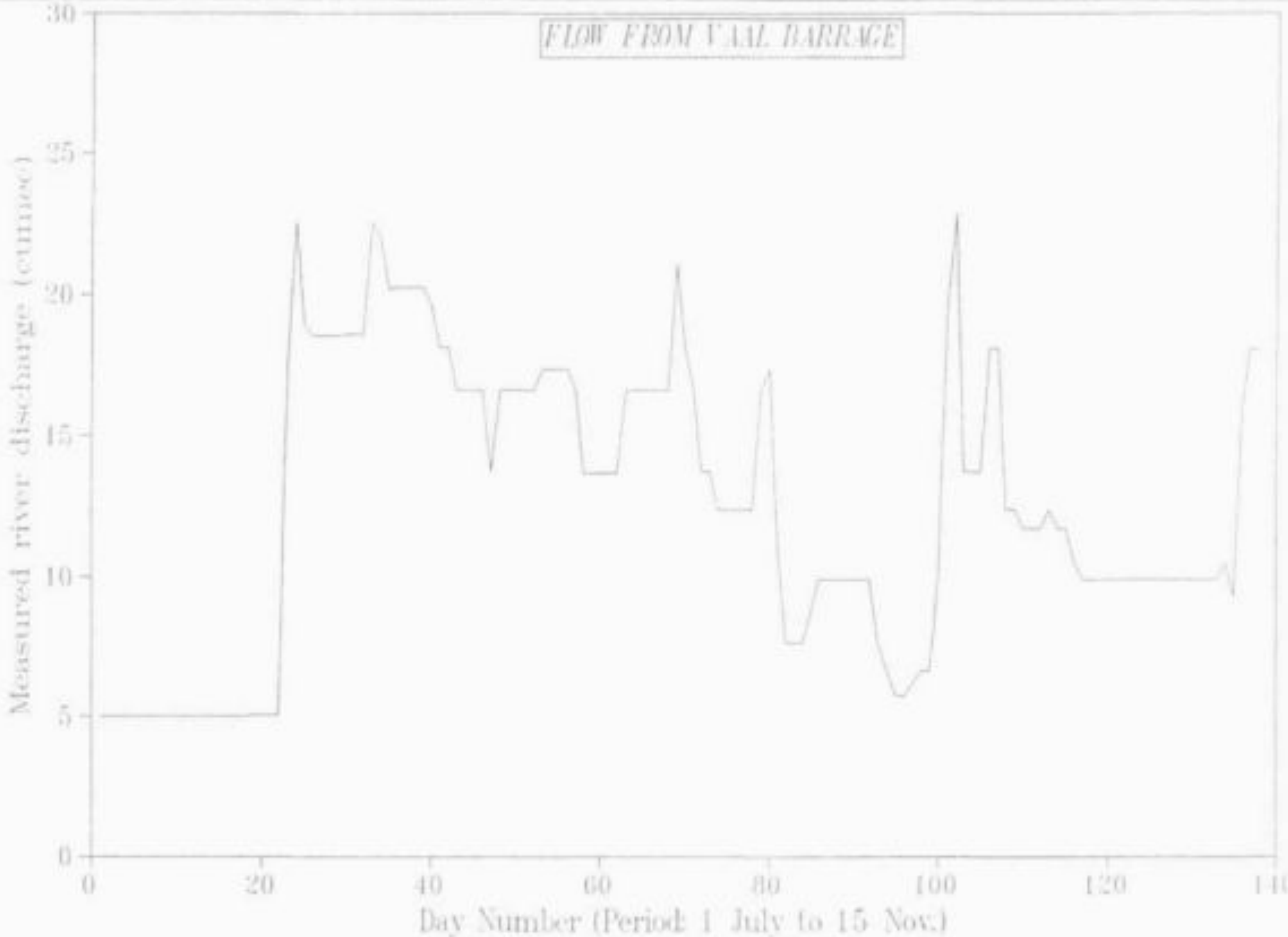
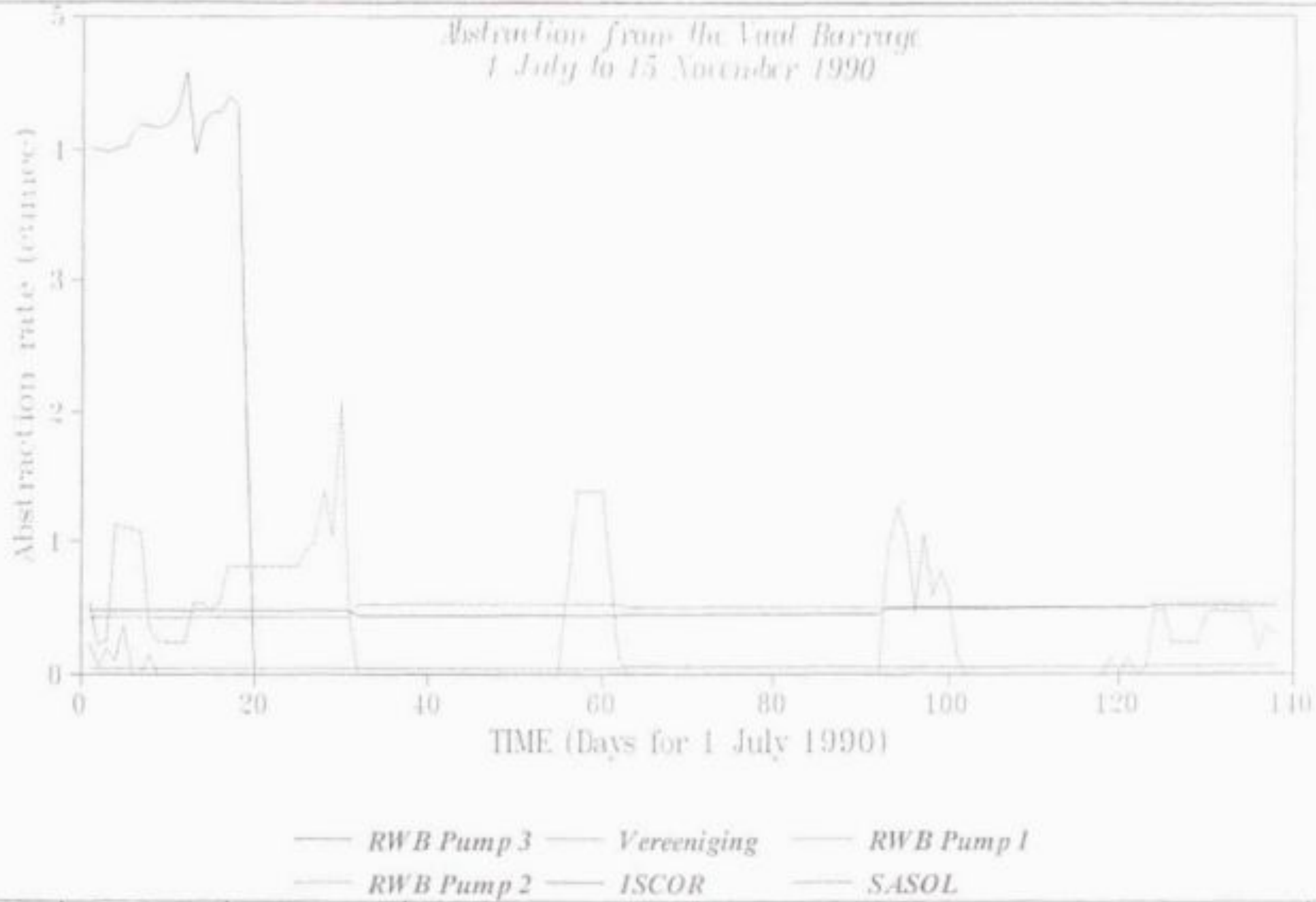
Discharge hydrographs of the tributary inflows to the Vaal Barrage during the simulation period 1 July to 15 November 1990.

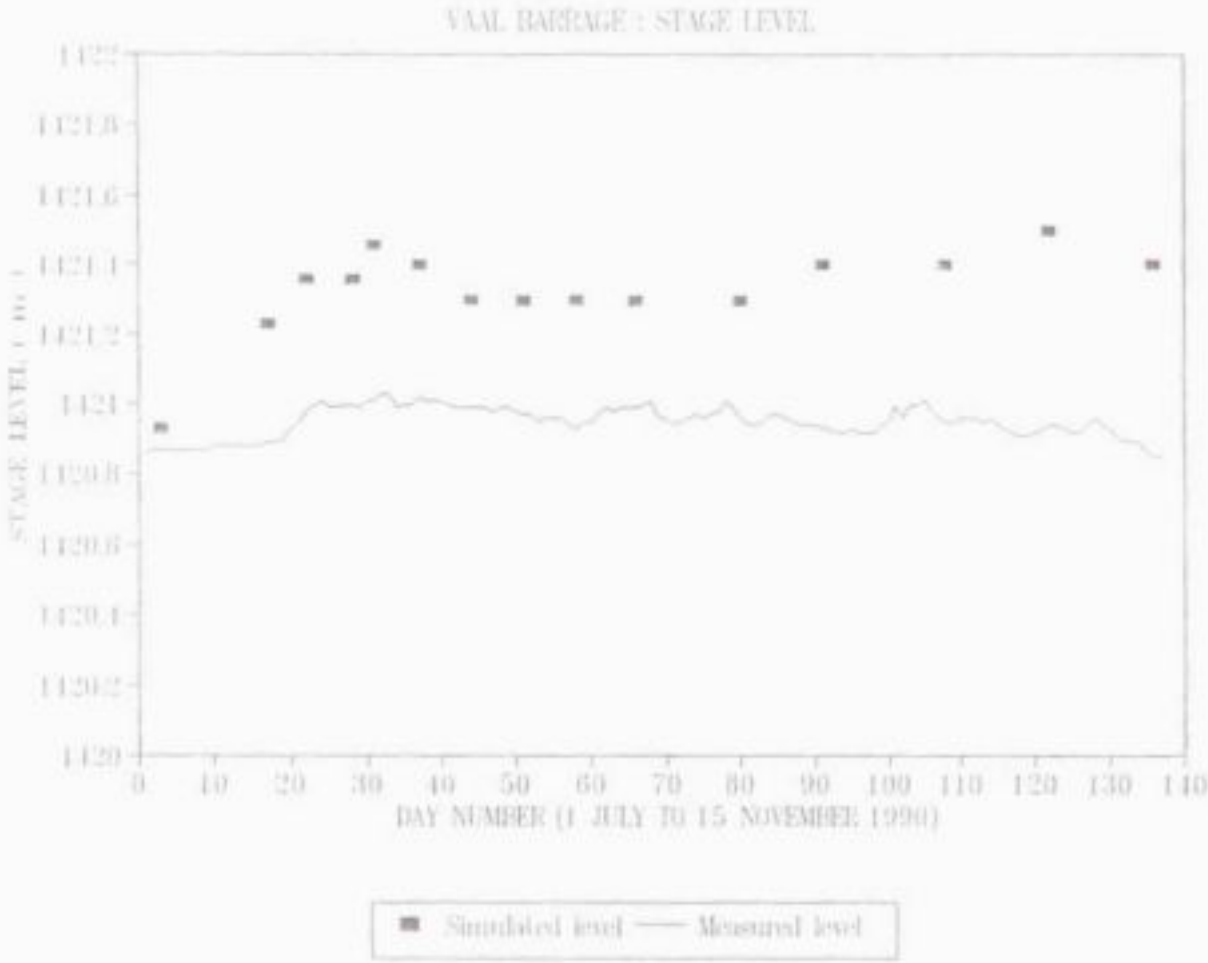
FIGURE 4.15



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION		FIGURE
			Discharge hydrograph of the water released from the Vaal Barrage during the simulation period 1 July to 15 November 1990.	4.46



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Hydrographs showing the rate of abstraction from the Vaal Barrage during the simulation period 1 July to 15 November 1990.	FIGURE 4.47



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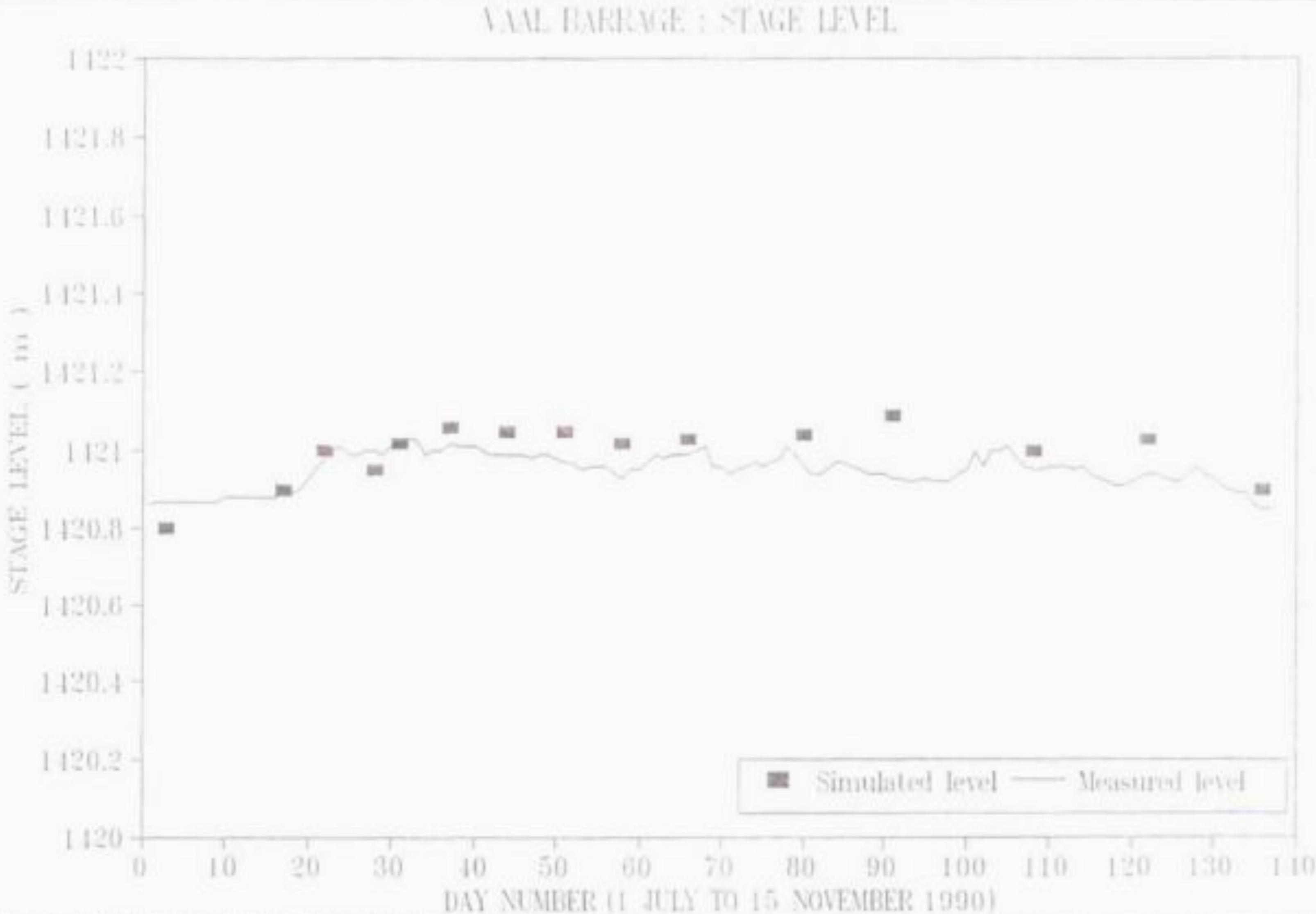
Preliminary simulation of the water level in the Barrage using a first estimate of the volume of the water body.

FIGURE 4.48



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Simulated and measured water levels in the Vaal Barrage using updated bathymetric data.

FIGURE 4.49

CE-QUAL-W2 calibration: water quality of the Vaal Barrage In simulating the water quality of the Vaal Barrage, CE-QUAL-W2 requires the following input:

- initial (boundary) conditions for each simulated constituent,
- time varying constituent concentration and flow rate of the tributary inflows and point sources,
- time varying constituent concentration and flow rate of the Vaal River forming the main inflow to the model branch, at Lethabo Weir, and
- measured constituent concentrations in the Vaal Barrage from which to calibrate and verify the simulated data.

The Vaal Barrage simulation exercise is used to determine the ability of CE-QUAL-W2 to simulate the total dissolved salts and electrical conductivity of the water body. However, in addition to TDS and EC, preliminary calibration was also carried out for phosphate, algal biomass and suspended solids using the transfer of calibration parameters from the Inanda Dam simulation exercise described in Section 4.4.

Initial (boundary) conditions The boundary conditions provide the model with the starting conditions of the Vaal Barrage, and include temperature, conductivity, TDS, suspended solids, phosphate and algal biomass. The boundary conditions may be described using either (1) a single value, (2) a vertical profile file, or (3) a longitudinal profile file. A single value is used when the water body is uniform concentration along the longitudinal and vertical axes. A vertical profile file is used when there is vertical gradients in a variable and no variation along the longitudinal axis. A longitudinal profile file is used when gradients exist in a water quality variable both in the longitudinal and vertical axes. The data requirements increase dramatically when the longitudinal profile file is required because a value must be given to each cell in the computational grid.

No data were available to describe the longitudinal and vertical variation in conductivity of the Barrage at the starting date (midnight, 30 June 1990). Data, however, were available from the Rand Water Board for 4 July 1990. The data for 4 July were used in the development of a longitudinal profile file for conductivity. Appendix A4.4 shows an example of the longitudinal profile file used in the Barrage simulation. To overcome problems caused by using data for 4 July, the simulation period overlapped the beginning of the release by a period of three weeks. The "warming-up" period of three weeks was considered sufficient time for the model to stabilize and simulate correctly the longitudinal variation in conductivity before the release occurred on 21 July. Measured conductivity data at the surface and bottom of the Barrage were provided by the RWB. The conductivity values for the cells between the surface and bottom layers were estimated using linear interpolation. Measured data showed the Barrage was vertically mixed with minimal difference between the conductivity at the surface and bottom. TDS concentration data were not available for the starting conditions but derived from the conductivity data using the equation given below

$$TDS = EC * 6.45 \qquad \ldots (4.3)$$

where TDS is the TDS concentration (mg/l), EC is the electrical conductivity (mS/m), and the value 6.45 derived from measured TDS and EC data for the Barrage. The starting (boundary) values for temperature, suspended solids, algae, phosphate, ammonia, nitrate and dissolved oxygen were input to the model in the form of a vertical profile file using data from the RWB and DWA&F, see Appendix A4.4. Where insufficient data were available to develop longitudinal profile files, vertical profiles were used.

Constituent concentration data for the tributaries:

Data on the constituent concentrations were obtained for the following tributaries and inflows:

- Klip, Suikerbosrand, Taaibos Spruit and Rietspruit, with data provided by DWA&F (HRI), and DWA&F (Hydrology),
- Point source discharges to tributaries, with data provided by DWA&F (Highveld Region).

Data bases were developed for each tributary and formatted as CE-QUAL-W2 compatible data files. Water samples were collected every 2 to 3 days which allowed time series of constituents to be developed using linear interpolation. No sophisticated in-filling methods were used because sufficient data were available to allow the use of linear interpolation. Figures A4.6.8 to A4.6.14 show the measured chemical data and associated hydrograph for the Klip River. The Klip River receives discharges from point and nonpoint sources, nonpoint source contributions include urban and mining areas (Funke, 1984). Figures A4.6.15 to A4.6.19 show the measured chemical data and hydrograph for the Suikerbosrand Spruit which receives inflows from both point and nonpoint sources. Figures A4.6.20 to A4.6.24 show the measured chemical data and hydrograph for the Rietspruit which receives occasional discharges from point sources (Vanderbijlpark wastewater treatment works). Treated effluent from SASOL 1 is discharged intermittently into the Leeuspruit and the appropriate water quality data formatted into a time series of input data.

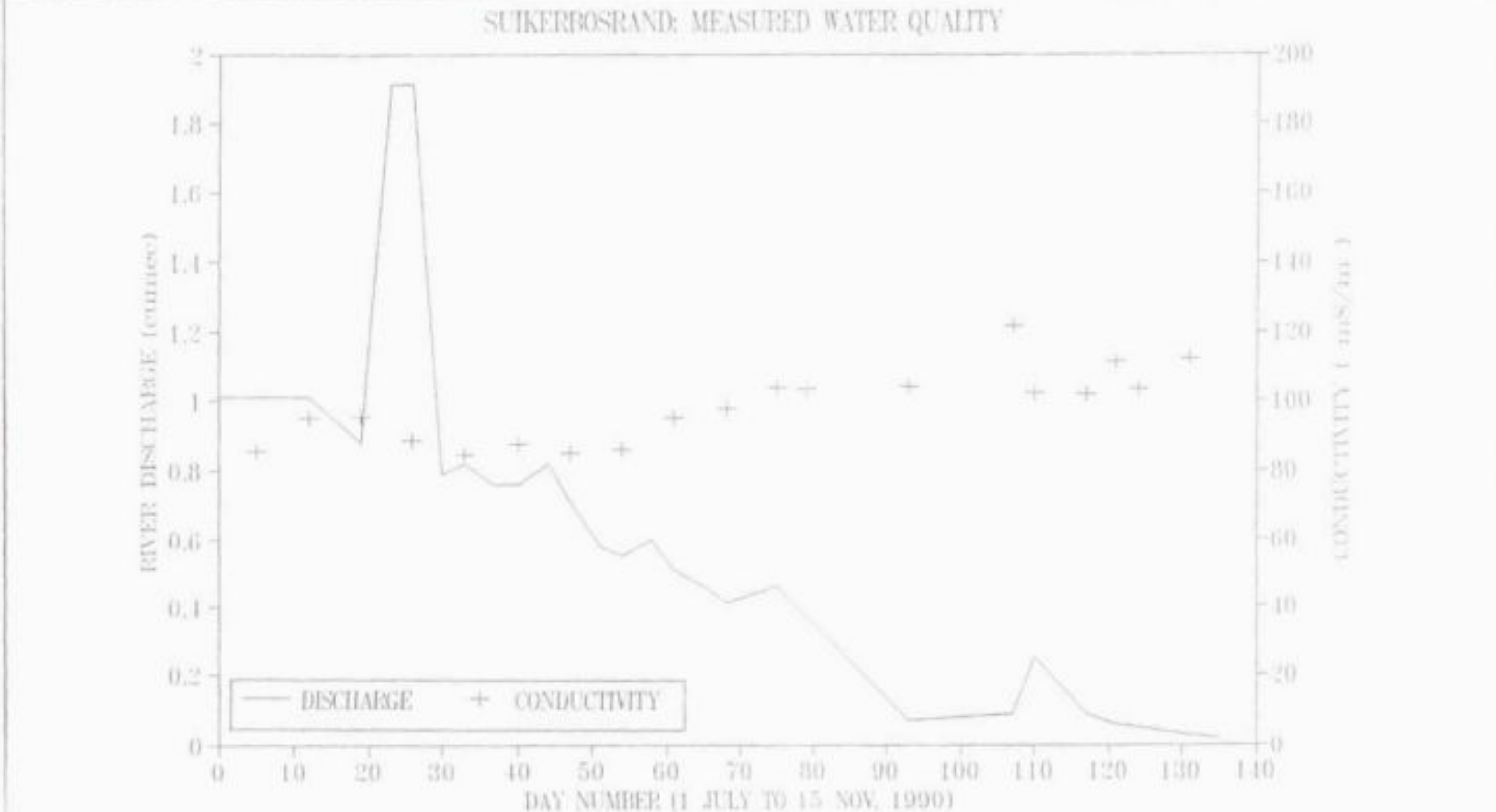
During the simulation period, treated wastewater from Vereeniging Municipality was discharged directly into the Barrage at an average effluent rate of 0.14 cumec with TDS concentration of 460 mg/l and phosphate concentration of <0.1 mg/l. The flux for the wastewater was calculated as 64 g TDS/s and 0.014 g P/s. The Klip River, in comparison, had an average flow rate of 8 cumec with an average TDS concentration of 670 mg/l and phosphate concentration of 0.40 mg/l. This gives an average flux for the Klip of 5120 g TDS/s and 3.2 g P/s. In terms of TDS and phosphate flux, wastewater from Vereeniging contributed 1 percent of the flux delivered by the Klip River. These flux calculations for TDS and phosphate show that the wastewater input to the Barrage from Vereeniging could be excluded from the model simulations. Should it have been evident that the model was underestimating the TDS and EC, an input file would have been developed which describes the time varying quality and flow rate of the Vereeniging wastewater stream.

Chemical constituent concentration of the Vaal River at the upstream boundary (Lethabo Weir): Data for the upstream boundary were obtained from the chemical data base of the Directorate of Hydrology (DWA&F). Additional chemical data were obtained from the monitoring survey carried out by the Hydrological Research Institute (DWA&F). Data measurements were recorded on a frequent basis, every 2 to 3 days, which allowed simple linear interpolation to infill the data set, see Figures 4.50 and 4.52. Appendix A4.4 shows the water quality data for stations monitored by DWA&F on a routine basis.

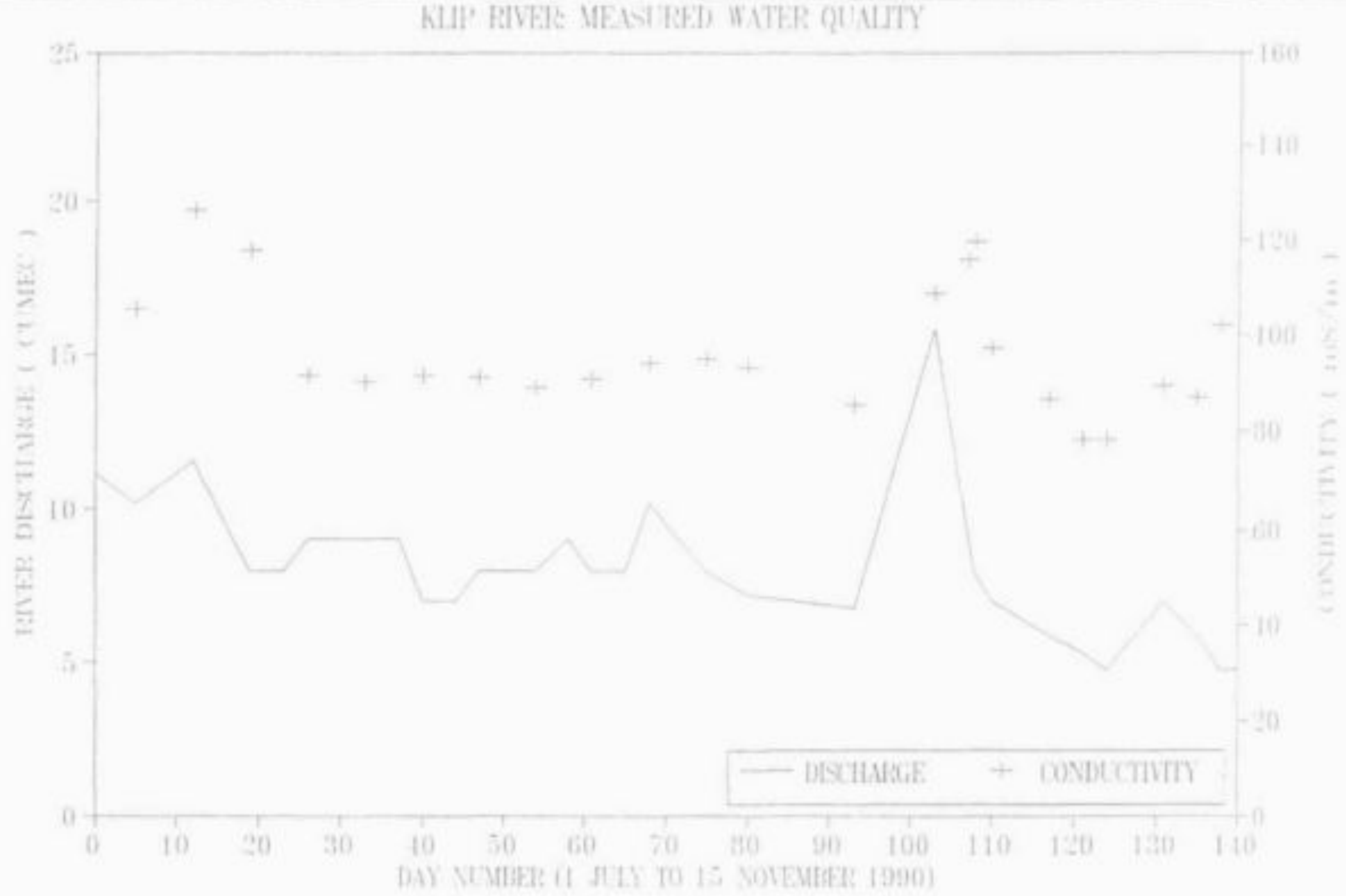
Chemical constituent data measured in the Vaal Barrage: To assess the ability of the model to simulate the longitudinal and vertical variation in water quality of the Vaal Barrage, measured data are required from discrete points along the Barrage and at various depths. Data were provided by:

- The Rand Water Board, who collected weekly samples at fixed sampling points along the length of the Barrage. Analyses included: conductivity, dissolved oxygen, chlorophyll-a, secchi depth, and water temperature. Samples were collected from the surface and bottom of the water body.

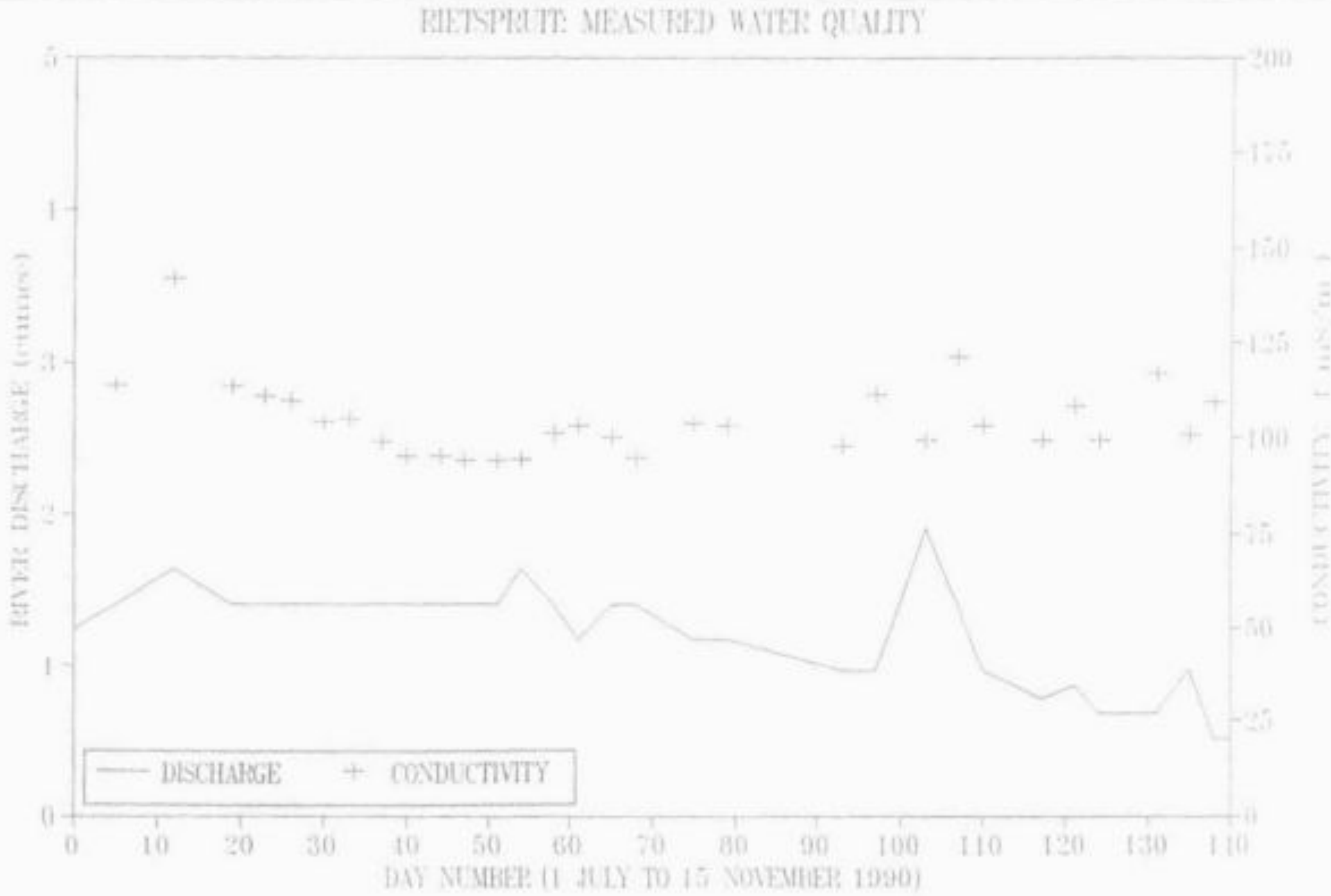
- The Hydrological Research Institute, who collected samples at points along the length of the Barrage and also recorded depth profiles for conductivity, dissolved oxygen, and temperature. Surface samples were collected and analyzed for major ion analysis as well as turbidity and chlorophyll-a. Major ion analyses include: TDS, conductivity, pH, major anions and cations as well as phosphorus and nitrogen species.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured conductivity and discharge data for the Suikerbosrand River during the simulation period.	FIGURE 4.50



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured conductivity and discharge data for the Klip River during the simulation period.	FIGURE 4.31



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Measured conductivity and discharge data for the Rietspruit during the simulation period.

FIGURE 4.52

4.5.3 Results of simulation: Vaal Barrage

Calibration of the thermal dynamics of the Vaal Barrage The program METDATA was used to pre-screen the data and provide preliminary calibration of the water surface water temperatures. The meteorological data file was then used with CE-QUAL-W2 to evaluate the stratification and heat budget of the water body.

Initial runs showed the model overestimated the degree of stratification. To overcome this, the wind sheltering coefficient, WSC, was adjusted so that the wind had greater influence on the water body. The wind coefficient may range from 0 to 1, a value of 1 indicates the wind has maximum influence on the water body. The wind coefficient was increased from a value of 0.4 to 0.6. In the simulation of TDS, the model did not produce sufficient vertical mixing. The wind coefficient was readjusted from a value of 0.6 to 0.8. The value of 0.8 gave optimum results.

The thermal dynamics forms a vital component of the calibration of CE-QUAL-W2, see Figure 4.39. The thermal dynamics has a direct influence on the stratification process, vertical and longitudinal mixing, which in turn influences the mixing depth, vertical gradients in water quality and the mixing characteristics of inflowing water masses. Figures 4.53 and A4.6.25 to A4.6.28 (in Appendix A4.6) show the two-dimensional plots of the variation in water temperature of the Barrage for specific days. At the beginning of the simulation period (Day 1 to 27), the Barrage was uniform in longitudinal and vertical temperature and was completely mixed. The released water from the Vaal Dam was less dense then the water in the Barrage and when entering the Barrage it flowed on the surface. By Day 59, the release water plunged at the point of confluence with the Taaibos Spruit.

Results of the water temperature calibration and verification show the ability of the model to simulate the temperature regime, thermal dynamics and heat exchange of the Vaal Barrage. The result of the temperature calibration are shown in:

(1) Figures A4.6.29 to A4.6.31 show the variation in surface water temperature at the segments along the length of the Barrage for a specific date, and

(2) Figures 4.54 and A4.6.32 to A4.6.35 show time series plots of the surface water temperature variation at selected segments in the Barrage.

Figure 4.53

Two-dimensional plot of the simulated and measured water temperature in the Vaal Barrage.

Simulation Day: 4

Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▼
Withdrawal ▲

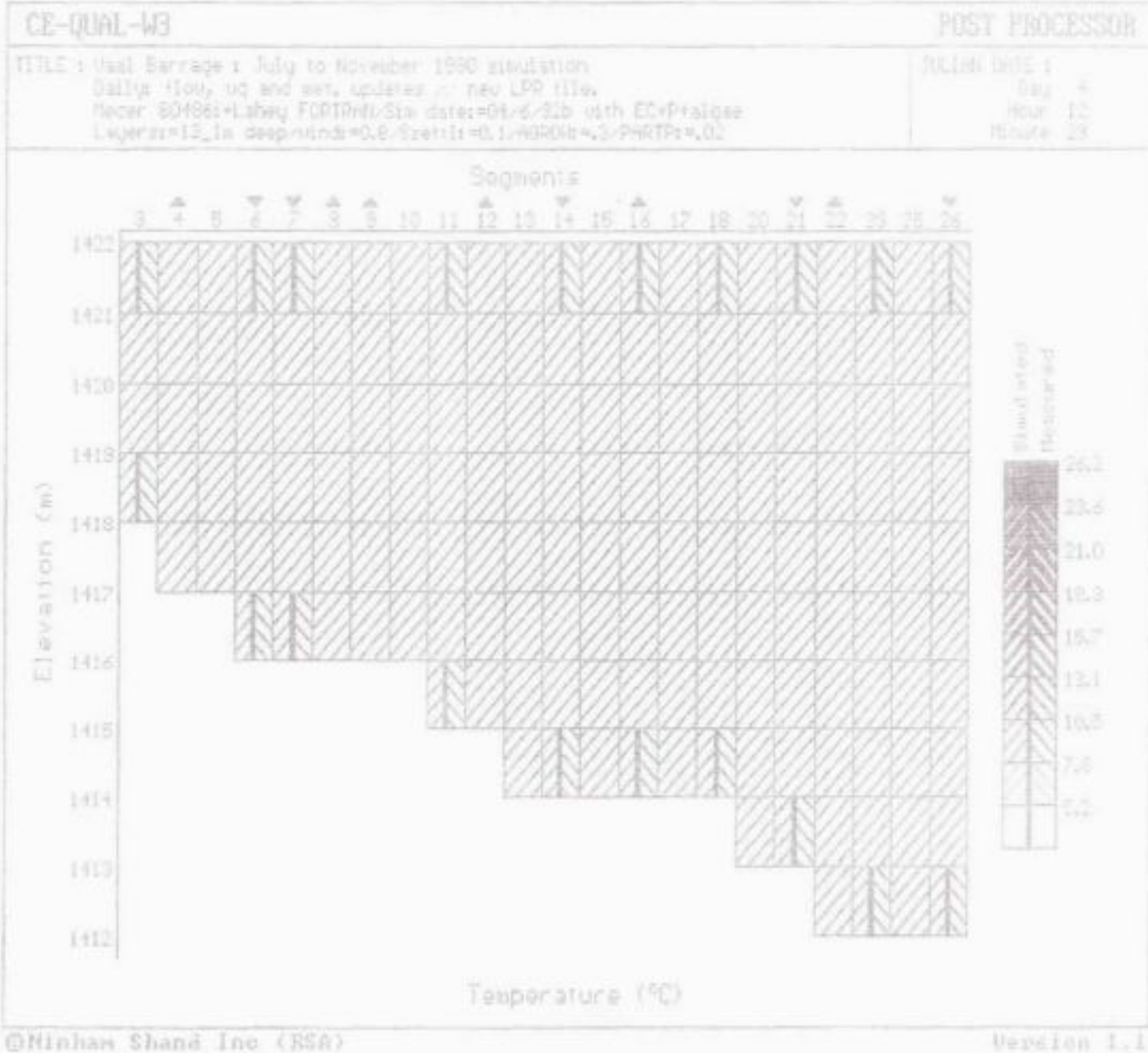
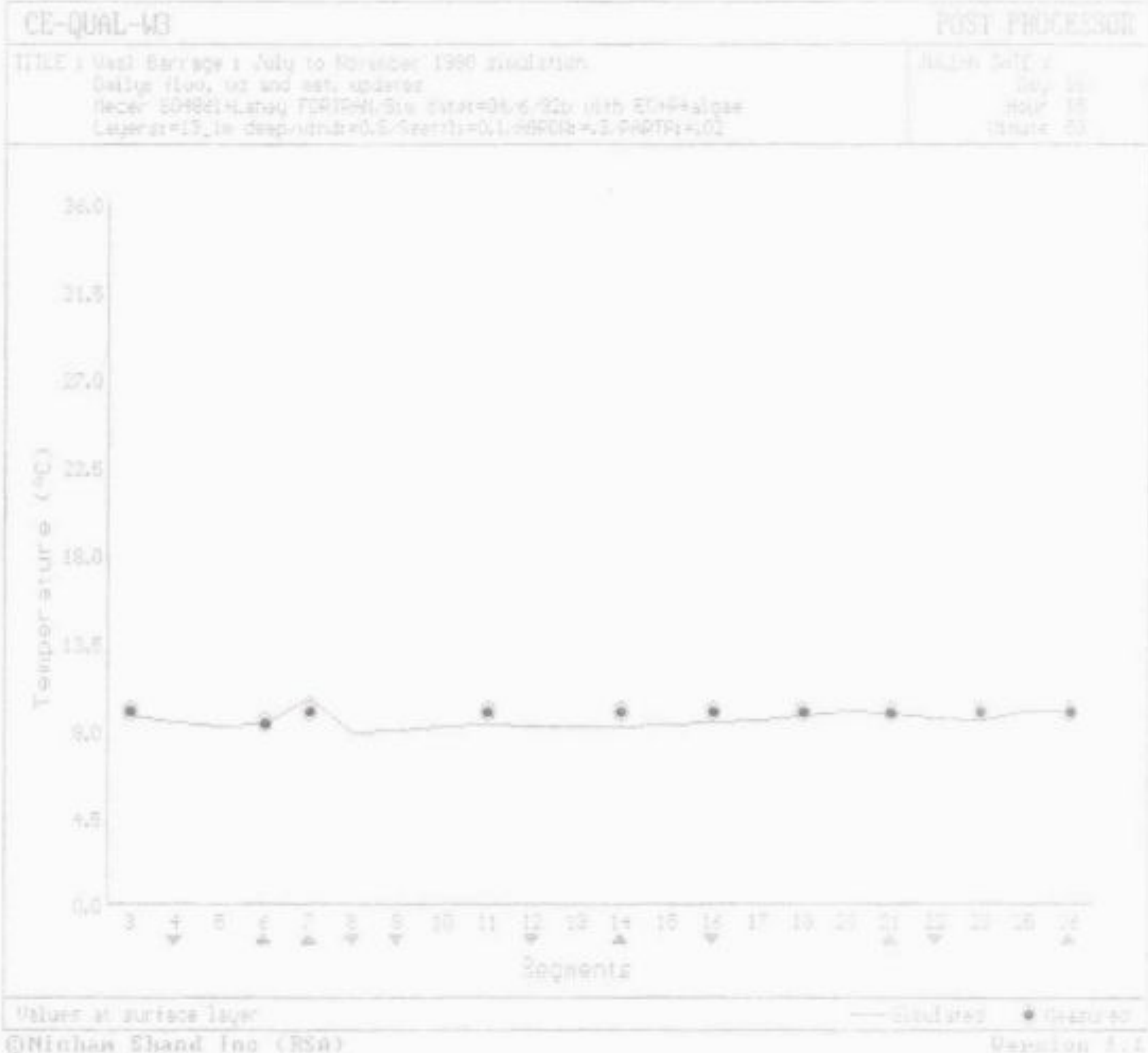


Figure 4.54

Plot showing the simulated and measured surface water temperature at Segments 3 to 26 in the Vaal Barrage.

Day number 18

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.



Calibration and verification of the conductivity (water quality) simulation: CE-QUAL-W2 does not directly simulate conductivity but has the option to simulate a "tracer" constituent. For the purposes of this investigation, the "tracer" was used to simulate the variation in electrical conductivity (EC) of the Vaal Barrage. Accordingly, the input data files were formatted with conductivity data as the "tracer".

Figure 4.55 shows the temporal variation in conductivity at Lethabo Weir, the upstream boundary. The release water from Vaal Dam causes a dramatic reduction in the conductivity of the Vaal Barrage at Lethabo Weir. Figure 4.55 shows the close correspondence between the simulated and measured conductivity values. Initial runs showed that the longitudinal and vertical gradients in conductivity were pronounced during the beginning of the simulation period. Therefore, a longitudinal profile file had to be used to describe the boundary (starting) condition. The longitudinal profile file uses a conductivity value for the starting conditions in each computation cell, see Figure A4.4 for an example of the file.

Figures A4.6.32 to A4.6.35 show the measured and simulated conductivity values for Segment 6 (at the confluence with the Suikerbos Spruit), Segment 14 (at the confluence with the Taaibos Spruit), Segment 18, and Segment 26 (at the Barrage). Comparison between measured and simulated data show CE-QUAL-W2 is capable of providing good simulation of the conductivity of the Barrage. The slight discrepancy between measured and simulated values for Segments 7 and 11 may be caused by incomplete lateral mixing in the surface layer. The model assumes that a given cell is averaged laterally. The position of the water quality sampling point relative to the inflows, Klip, Suikerbosrand and Taaibos Spruits, could account for the differences between simulated and measured values. The model however provides no calibration leeway for the simulation of conductivity (tracer). Should the model have provided a poor correspondence between simulated and measured values, the problem could have been caused by unrepresentative constituent concentrations in the input data files, or problems in the calibration of the hydrodynamics and/or thermal dynamics.

The good correspondence between measured and simulated data shows (1) CE-QUAL-W2 provides a good description of the real world system, (2) the input data are representative of the quality of the water entering the Barrage, and (3) the hydrodynamics and thermal dynamics are simulated correctly.

Figure 4.57 shows the simulated conductivity for Segment 6 (at the confluence with the Suikerbosrand River) with the (1) wind coefficient set at 0.4 and (2) with the wind coefficient set at 0.8. It was observed that the wind coefficient with value of 0.8 improved simulation

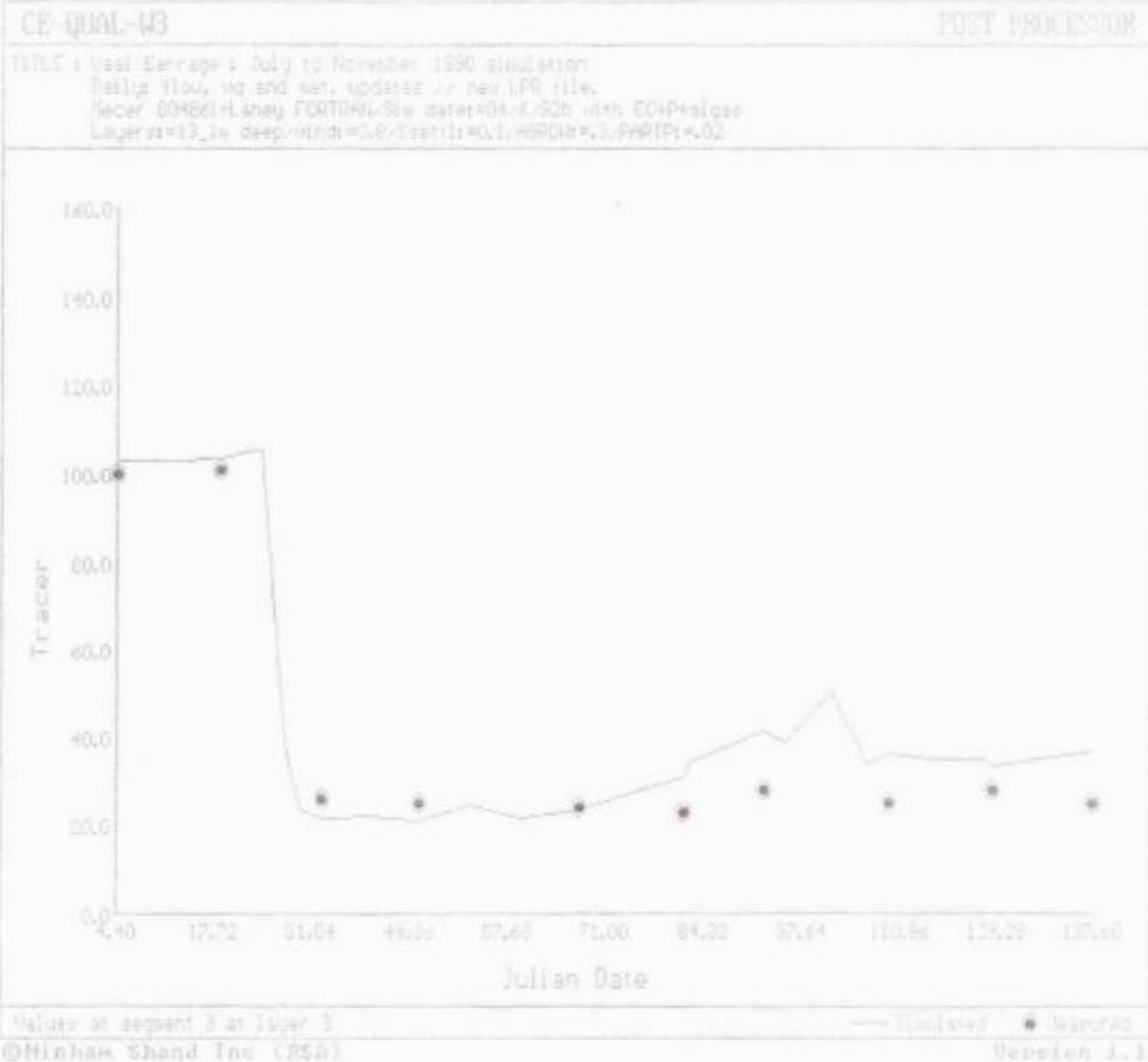
Figure 4.55

Time series plot of the simulated and measured electrical conductivity in the Vaal Barrage at:

Segment number 3

SURFACE LAYER

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.



Tracer: Conductivity
Units: mS/m

Figure 4.56

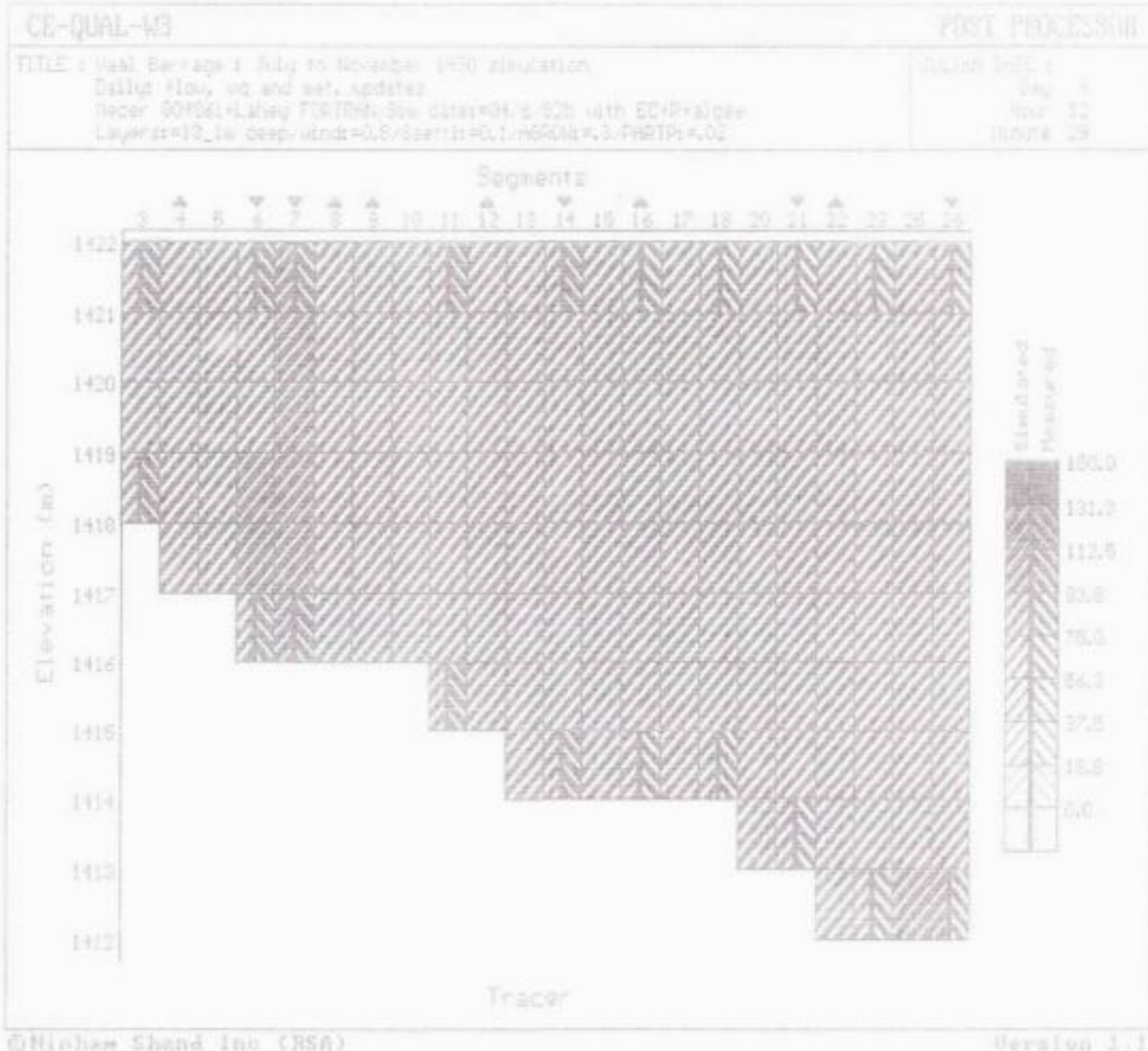
Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

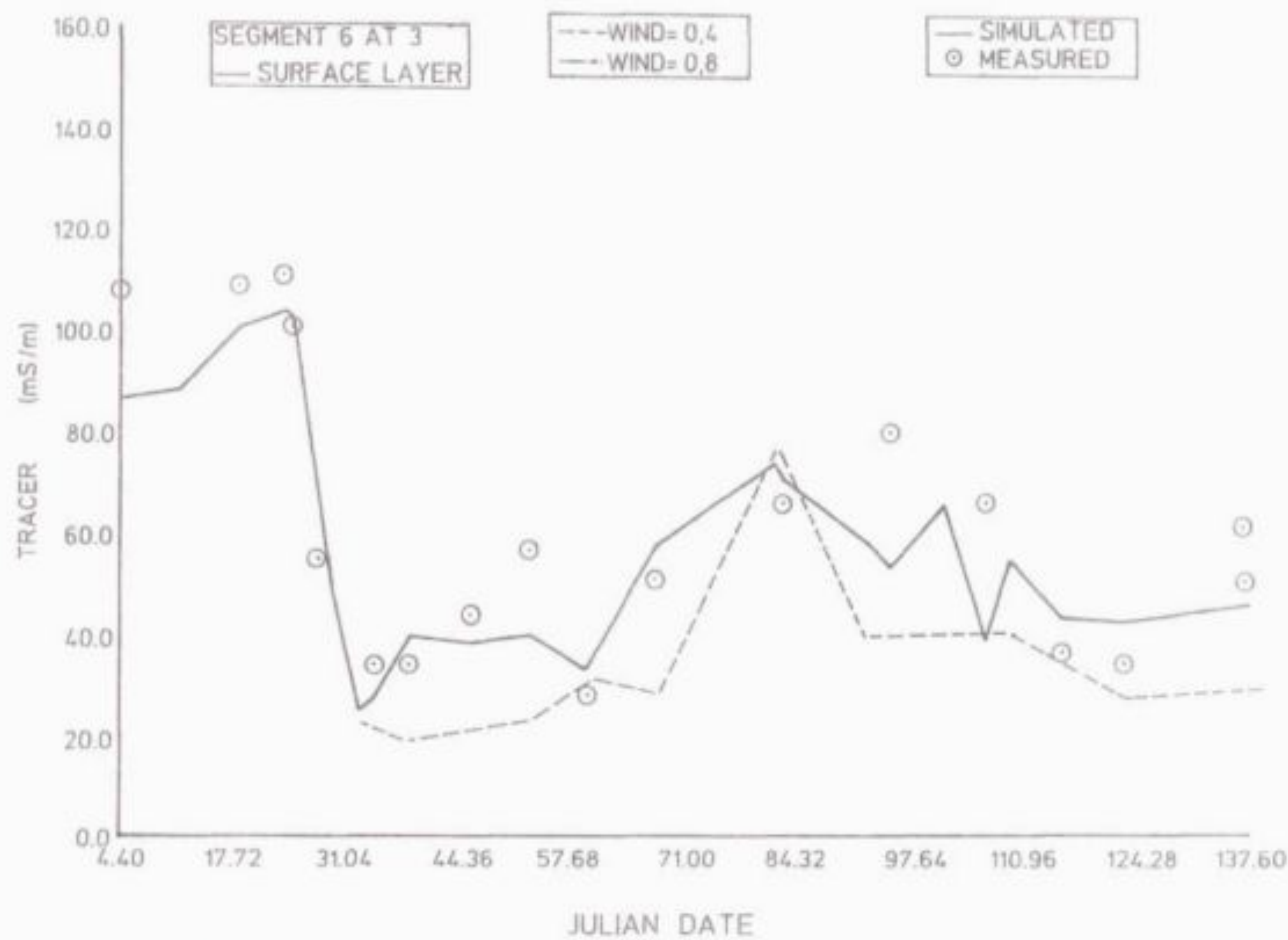
Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 4

Day of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity





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Simulated and measured conductivity of the surface water at Segment 6 in the Vaal Barrage. The solid line shows the simulated conductivity using a wind coefficient with value 0.8, and the broken line with value of 0.4.

FIGURE 4.57

of the conductivity by increasing the vertical mixing characteristics of the Barrage. This adjustment to the wind coefficient shows the importance of "fine tuning" of the calibration coefficients, which can only be done once the other components are suitably calibrated.

Figures 4.56 and A4.6.36 to A4.6.44 show the two-dimensional plots for the measured and simulated conductivity in the Barrage prior to the release (Day 4), and after the release was made (Days 29 to 137). Comparison of the measured and simulated values shows the model provides a good description of the vertical and longitudinal gradients in conductivity.

- Figure 4.56 shows the conductivity at Day 4, before the release. Figure A4.6.36 shows the beginning of the release with the Vaal Dam water flowing over the more dense high TDS water in the Barrage. There is minimal vertical mixing of the two waters.
- Figure A4.6.39 shows the conductivity in the Barrage at Day 45, where the release has passed up to Segment 13 and the leading edge submerges.
- Figure A4.6.40 shows the conductivity data for Day 59, which is over a month after the beginning of the release. The release water has passed through to Segment 23 and the leading edge submerged to the lower layers.
- Figure A4.6.41 shows the conductivity data for Day 67 and the release water has become evenly distributed along longitudinal and vertical axes.
- Figure A4.6.43 shows the conductivity data for Day 109. The combined influence of the high conductivity inputs to the Barrage has caused the low conductivity of the release to become virtually undetectable. However, a rainfall/runoff event has input low TDS water causing a decrease in the conductivity by Lethabo Weir, at Segment 3.

Figures A4.6.45 to A4.6.62 show the measured and simulated conductivity of the surface waters at segments along the length of the Barrage on specific days, each plot shows the progression of the Vaal Dam release along the length of the Barrage.

Total dissolved salts: Figures 4.55 and A4.6.53 to A4.6.62 show the two-dimensional plots for the TDS concentration on specific days during the simulation period. Comparison between the simulated and measured values shows the model provides a good description of the variation in TDS in the Barrage. As with the conductivity simulation, no calibration leeway was available. To verify the simulated TDS, comparison was made between the simulated values and the measured data presented graphically by Thirion (1991). Thirion (1991) reports that the Barrage was mixed vertically on 19 September 1990 (Day 81).

Figure 4.58

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 4

Units: mg/l
Variable: TDS

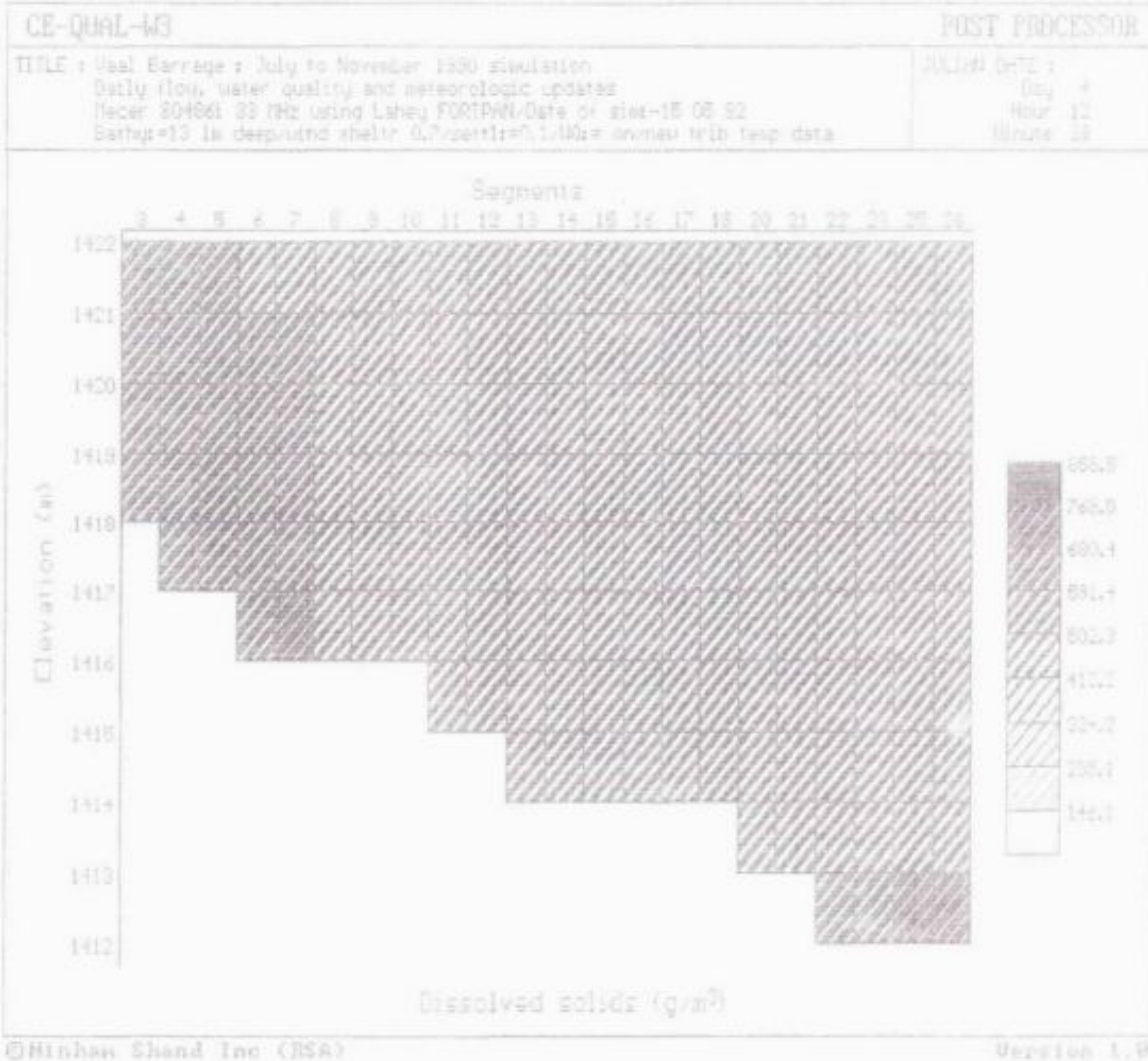


Figure 4.59

Plot showing the simulated conductivity profiles at Segment 14 in the Vaal Barrage.

Day numbers:
67, 81, 82 and 95

Segment 14 is located near the confluence with the Taaibos Spruit.

The plot shows the change in vertical mixing between day 67 and 81.

Units: mS/m
Tracer: conductivity

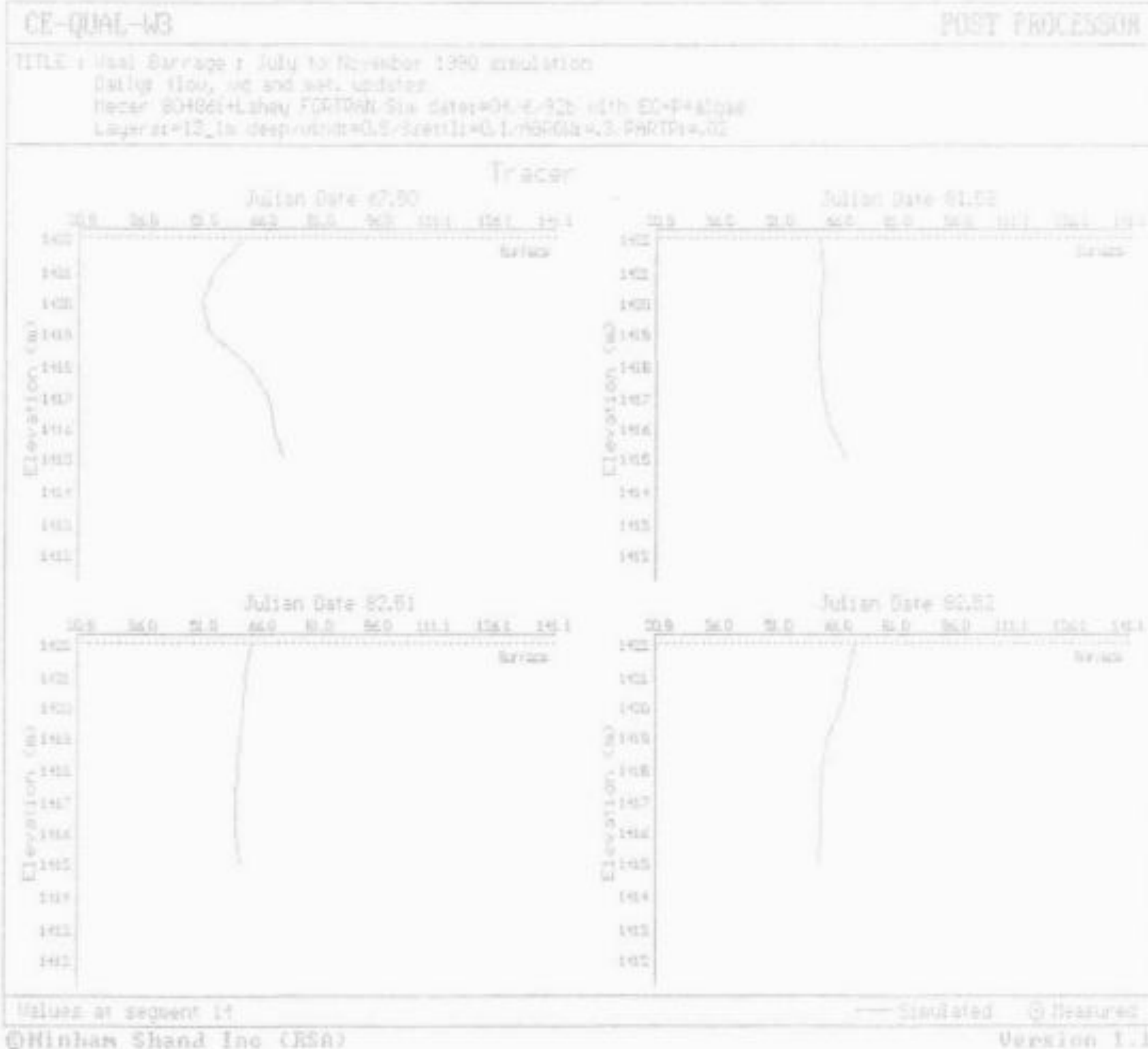


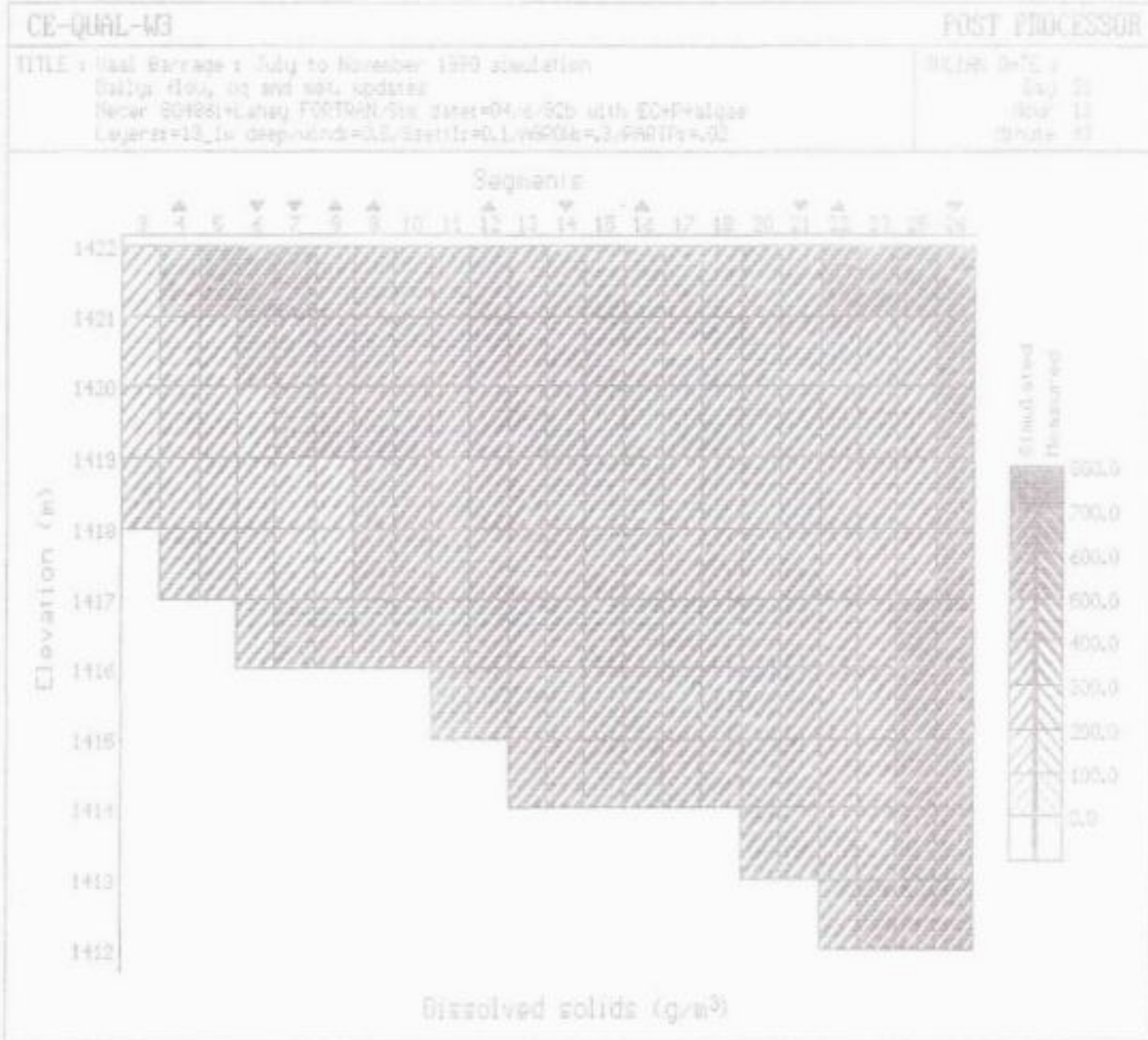
Figure 4.60

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 81

Note: vertical mixing in most segments

Units: mg/l
Variable: TDS
Inflow: ▲
Withdrawal: ▼



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Figures 4.58 to 4.60 show that CE-QUAL-W2 also simulates vertical mixing on the same date (Day 81). Thirion (1991) shows in graphical form that high salinity water was present in the bottom of the Barrage at the confluence with the Rietspruit. In Figure 4.61, CE-QUAL-W2 shows the presence of the high salinity water at the confluence with the Rietspruit. The simulation shows the high salinity water is derived from the Rietspruit and confined to the position because of the mixing and density characteristics of the Barrage.

Calibration and verification of the hydrodynamic behaviour: Horizontal and vertical water movement (Vector plots):

Figures 4.62 and A4.6.67 to A4.6.79 show the two-dimensional plots of the horizontal and vertical (vector) movement of water within the Barrage. No measured flow velocity data were available to verify the simulations from CE-QUAL-W2. However, information obtained from the water quality simulations provides information on the mixing patterns which agree with the vector plots shown. The vector plots provide the following information on the movement of water.

- The Klip and Suikerbosrand Rivers cause a localised down-welling of water which is verified by comparing the measured and simulated TDS and conductivity of the bottom layers of Segments 6 and 7, see Figure 4.62 and Figure A4.6.67 to Figure A4.6.79 (in Appendix A4.6).

- Wind action causes longitudinal water movement, the direction is governed by the orientation of the segment and the prevailing wind direction. The meandering nature of the Barrage and orientation of the segments is such that for a given wind direction, the surface water may move in opposite directions on a given day, see Figures 4.62 and A4.6.68.

- The combination of points of down-welling and wind action cause circular currents, see Figure 4.62. These currents are seen to cause substantial vertical mixing which results in uniformity in the surface and bottom TDS and conductivity, particularly in the segments at the lower end of the Barrage.

Figure 4.61

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 137

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: TDS

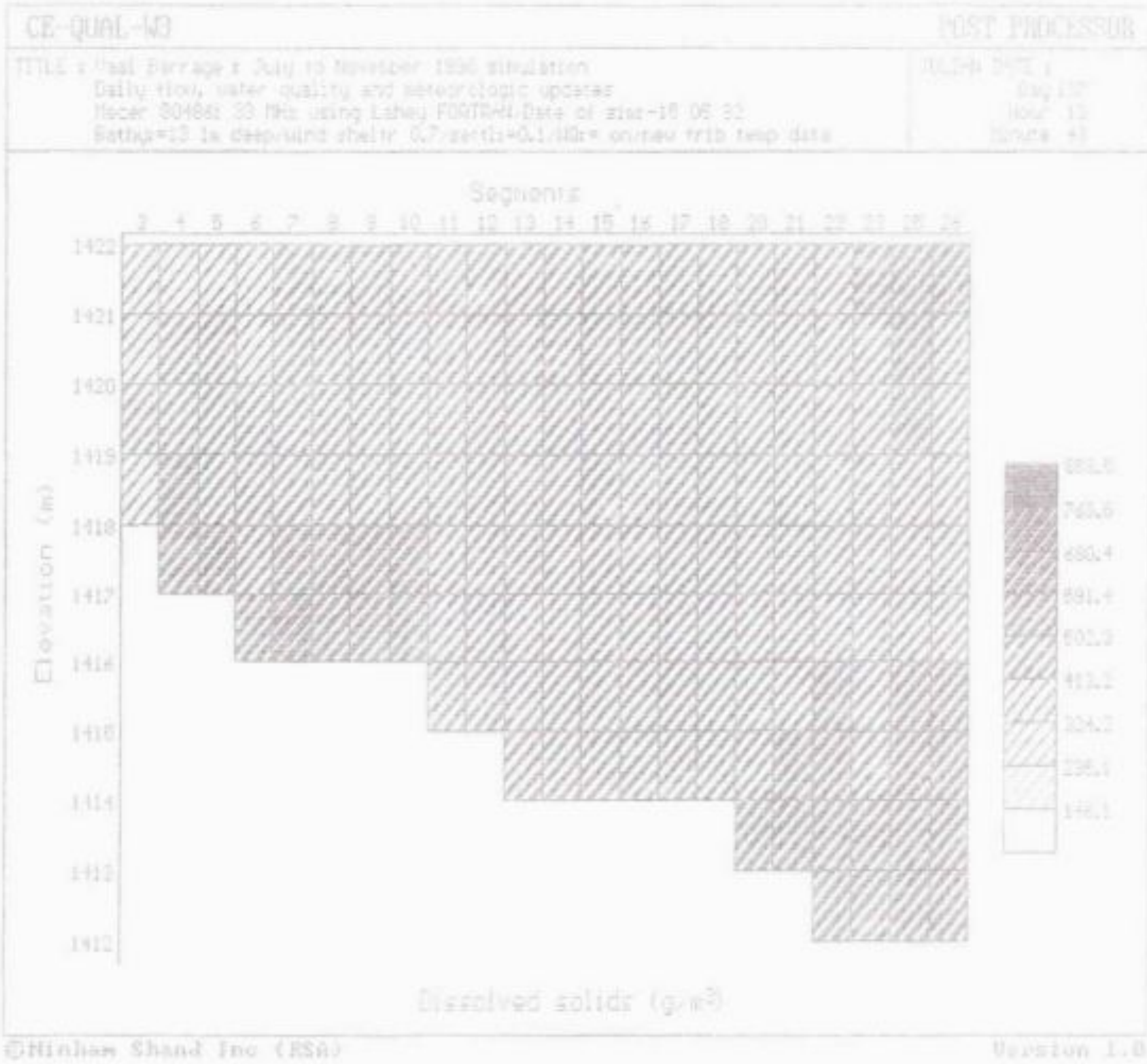


Figure 4.62

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 4

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▼
Withdrawal: ▲

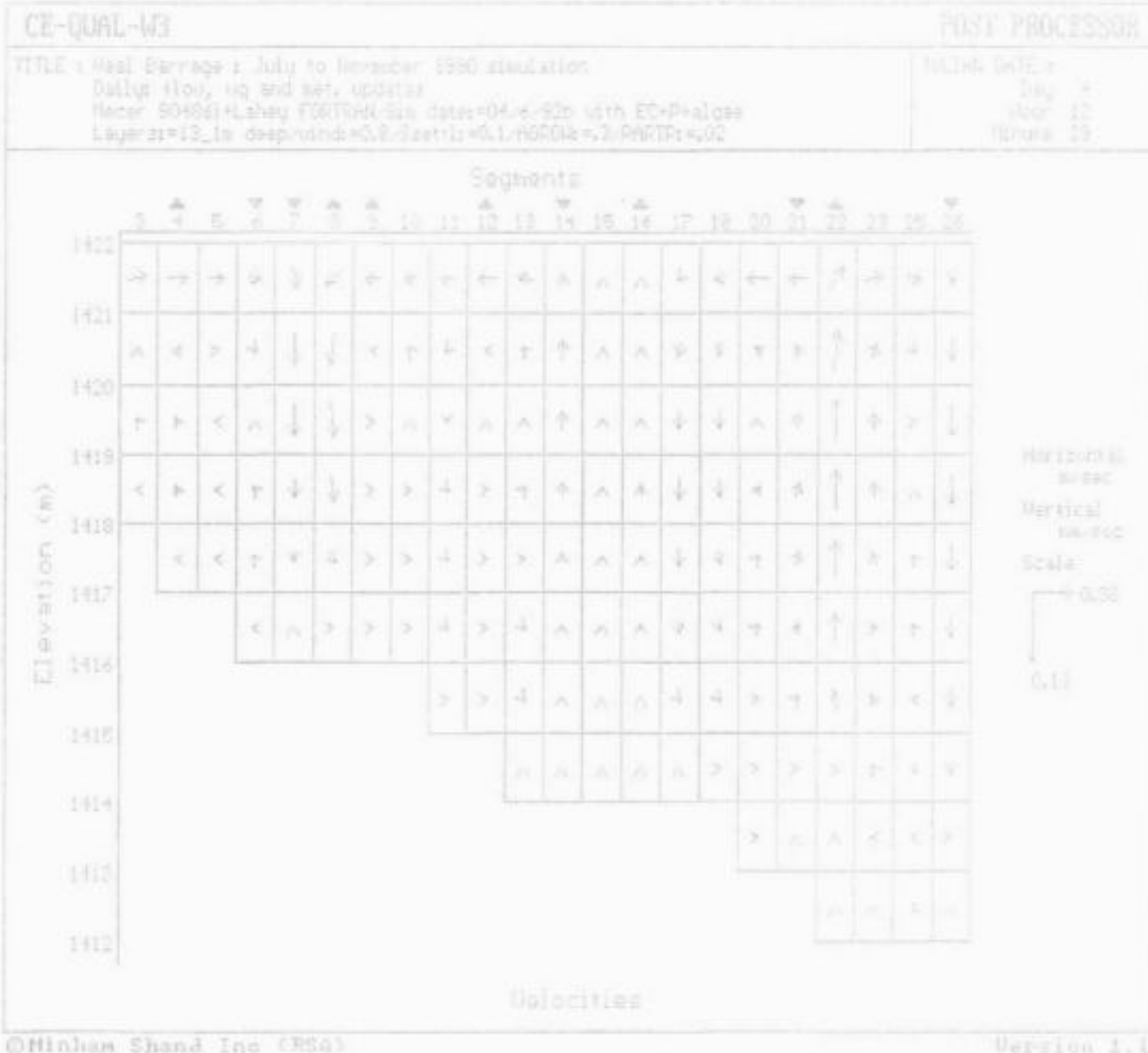


Figure 4.63

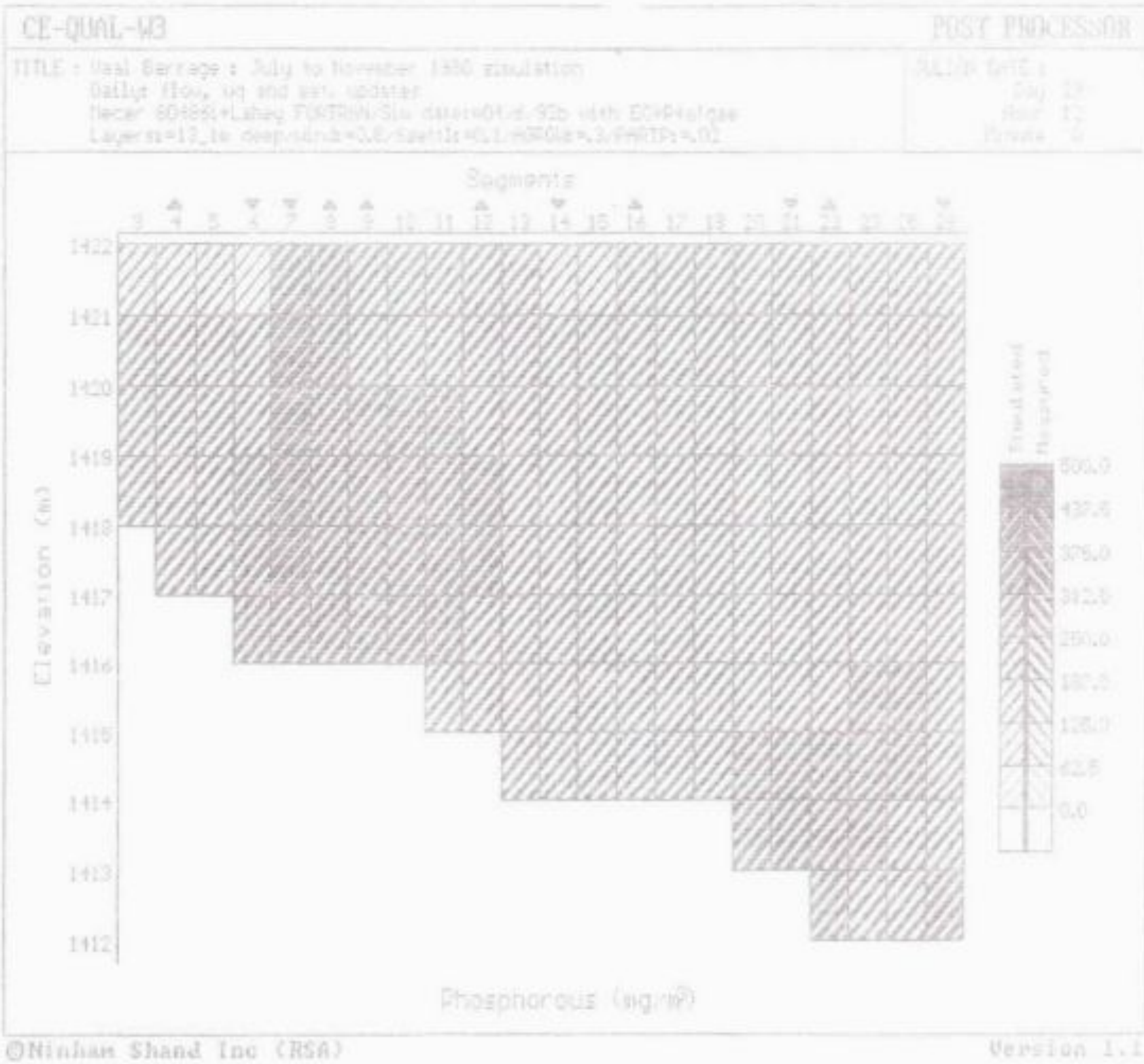
Two-dimensional plot showing the simulated phosphate concentration in Segments 3 through to 26 in the Vaal Barrage.

Day number: 23

Beginning of release from Vaal Dam: Day 21

Variable: Phosphate
Units: $\mu g/l$

Inflow: ▾
Withdrawal: ▴



Preliminary calibration of suspended solids, algal biomass and phosphate:
Suspended solids: Figures A4.6.63 to A4.6.66 (in Appendix A4.6) show the preliminary calibration of CE-QUAL-W2 for suspended solids. Turbidity measurements were available from the HRI surveys of the Barrage. The suspended solids concentration data were derived from the turbidity measurements using the equation given below

$$[SS] = NTU * f \qquad .... (4.4)$$

where [SS] is the suspended solids concentration (mg/l), NTU is the turbidity measurements (NT Units), and f, a conversion factor with value of 2.4. The conversion factor was calculated from a set of water samples collected from the Barrage and analyzed for suspended solids concentration and turbidity.

In the Inanda Dam simulation, the coefficient governing the settling of suspended solids, SETTL, had a value of 0.4 m/day. In the Vaal Barrage simulation, a value of 0.4 was used but caused rapid settling of suspended solids. Eventually CE-QUAL-W2 was calibrated for suspended solids using a settling rate of 0.1 m/day. Figures A4.6.63 to A4.6.66 show the two-dimensional plots for suspended solids concentration. The release water from the Vaal Dam is shown to have a high turbidity, and causes a plume of highly turbid water to progress along the length of the Barrage. It was unfortunate that no measured suspended solids data were available to calibrate and verify the simulated suspended solids values.

Phosphate and algal biomass: Preliminary investigation was carried out to determine the ability of CE-QUAL-W2 to simulate the phosphate and algal biomass concentrations in the Vaal Barrage. The calibration of CE-QUAL-W2 for algal biomass and phosphorus is dependent on the suitable calibration and simulation of the hydrodynamics, thermal dynamics, and suspended solids data. In the Inanda Dam simulation, the suspended solids concentration was shown to have a major influence on the phosphate concentration because of the adsorption of phosphorus onto particulate matter. CE-QUAL-W2 uses a partioning coefficient, PARTP, to account for the adsorption rate of phosphate onto suspended particulate matter. To provide a first estimate of the suitable calibration, the phosphate partioning coefficient, PARTP, was set to a value of 0.3. The in-lake phosphate concentration decreased dramatically, and after a number of model runs the coefficient was decreased to a value of 0.1. The value of 0.1 for PARTP implies a low rate of adsorption of phosphate onto the suspended matter. In terms of the algal biomass, the same values were used for the "algal" coefficients as used in the Inanda Dam simulation, see Table 4.2. The full calibration and verification of the phosphate and algal biomass was not completed for

Figure 4.64

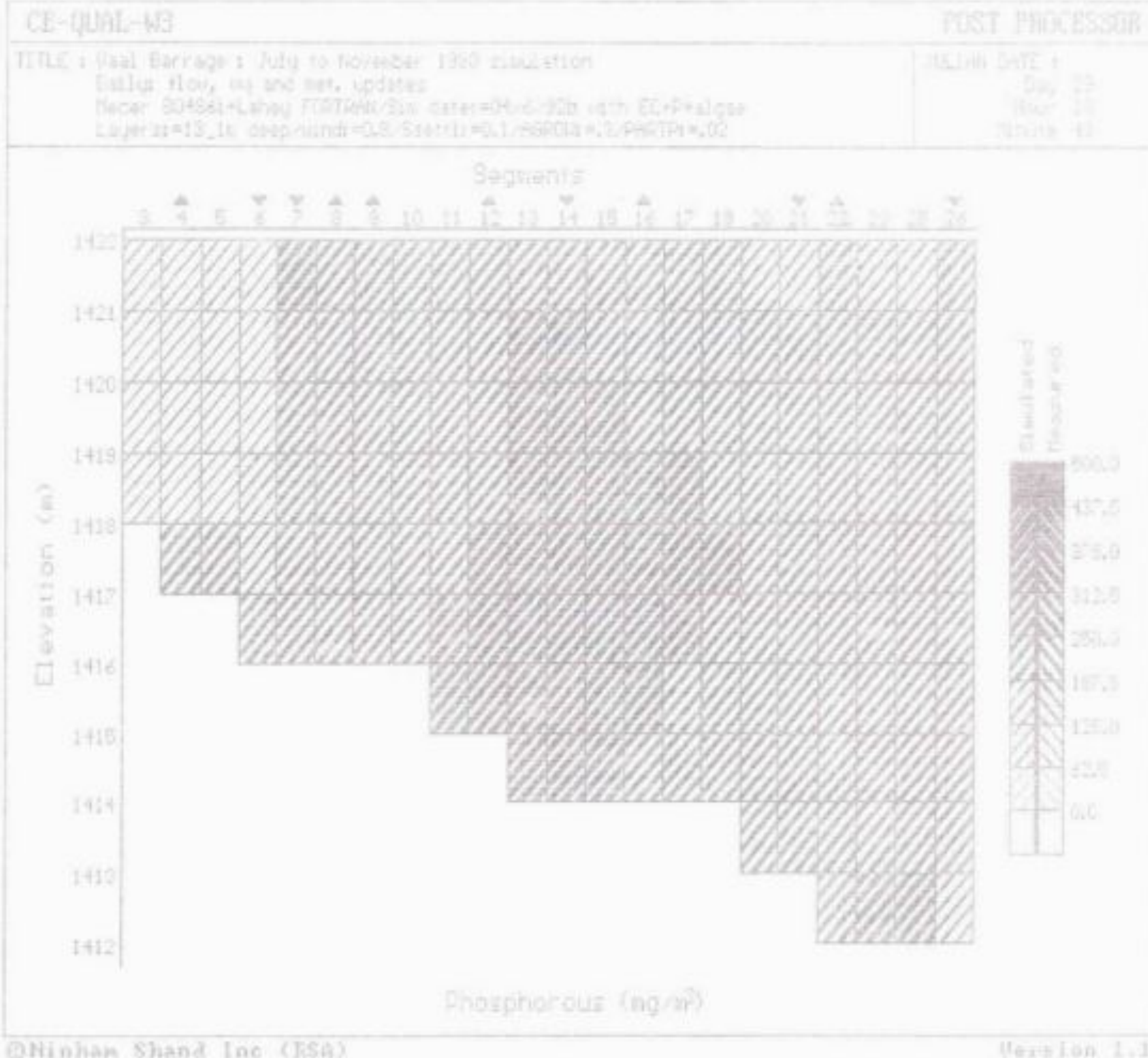
Two-dimensional plot showing the simulated phosphate concentration in Segments 3 through to 26 in the Vaal Barrage.

Day number: 29

Beginning of release from Vaal Dam: Day 21

Variable: Phosphate
Units: $\mu g/l$

Inflow: ▾
Withdrawal: ▴



lack of time and budget but from the preliminary work valuable information was obtained:

- The Klip River delivers the highest loading of phosphate to the Barrage. The inflowing water from the Klip and Rietspruit enters the Barrage in the lower layers causing a plume of high concentrations of phosphate in the bottom waters, see Figure 4.63 - Segments 7 and 26.

- The release of water from the Vaal Dam causes a displacement of the phosphate delivered by the Klip River, see Figure 4.64. Some 20 days after the beginning of the release, the phosphate from the Klip River moves along the bottom of the Barrage causing a widespread plume of high phosphate concentration, see Figure 4.65.

- The algal biomass and growth is associated with the input of high nutrient concentrations from the Klip, Suikerbosrand, and Rietspruit Rivers.

- The down-welling of phosphate from the tributary inflows to the bottom layers of the Barrage causes algal growth both in the surface and lower layers, see Figure 4.66.

- Prior to the release from Vaal Dam, algal growth is pronounced at the point of confluence with the Klip and Suikerbosrand Rivers. The release water from Vaal Dam displaces the algal biomass along the length of the Barrage and mixes some algae into the deeper waters. Comparison of the simulated and measured algal values from the Rand Water Board shows the algal growth and distribution is simulated satisfactorily by the model.

- The calibration and verification procedure was not completed for algal and phosphate dynamics but shows the ability of the model to simulate these variables even though approximate values of the calibration coefficients were used.

Assessment of the influence of releases from the Vaal Dam on the TDS concentration of the Vaal Barrage:

Releases of water with low TDS and nutrient concentration are made from the Vaal Dam to improve the quality of the Barrage during the winter low runoff period. The releases are made to dilute the high TDS water delivered to the Barrage, primarily from the Klip River. It has been accepted that a release and blending strategy offers the best method for controlling the TDS concentration to below 600 mg/l. The limit of 600 mg/l for TDS has been used as a guideline to protect the users of the Barrage water. Users have found that water with TDS concentration exceeding 600 mg/l causes accelerated corrosion and scaling

Figure 4.65

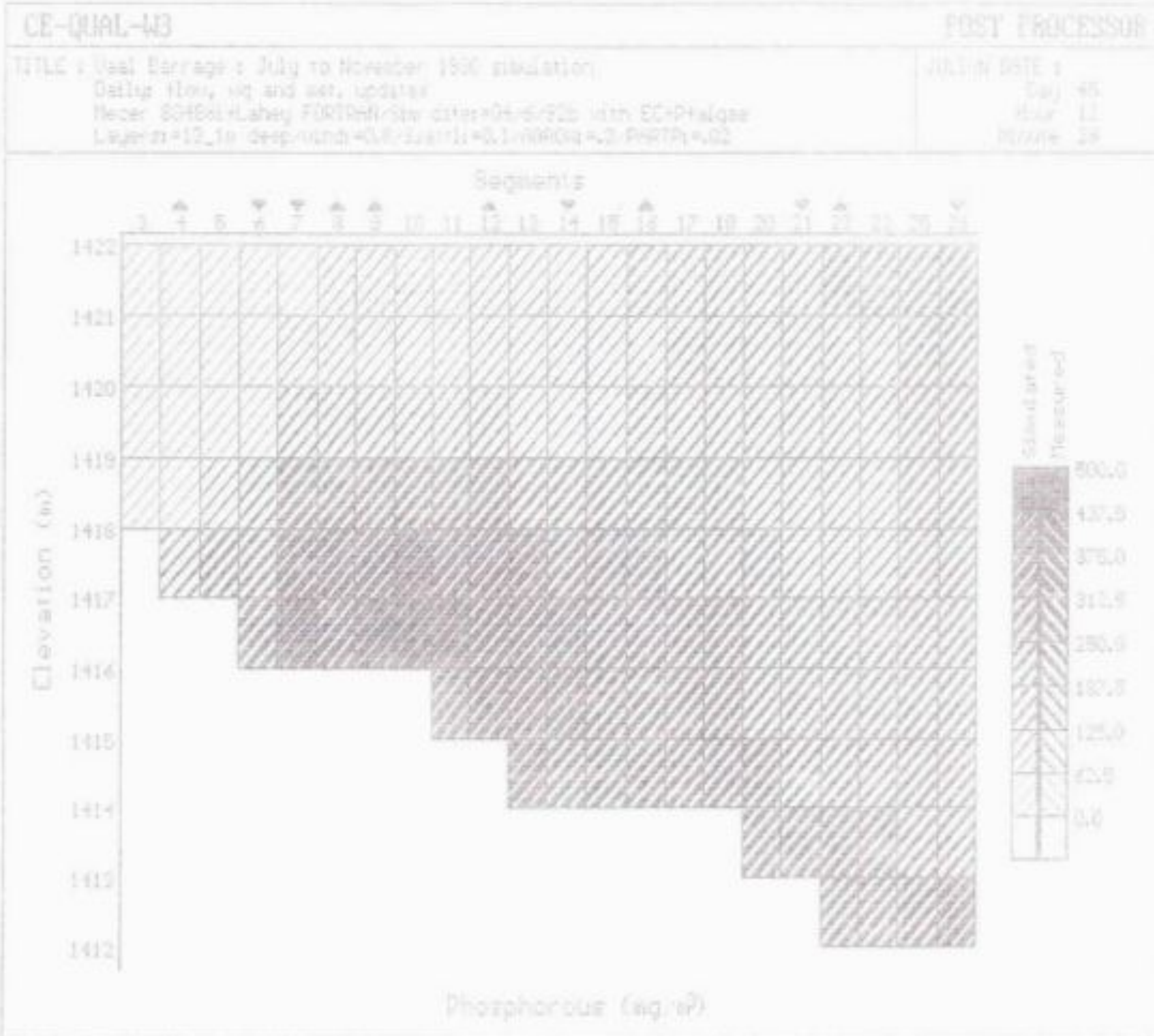
Two-dimensional plot showing the simulated phosphate concentration in Segments 3 through to 26 in the Vaal Barrage.

Day number: 45

Beginning of release from Vaal Dam: Day 21

Variable: Phosphate
Units: µg/l

Inflow: ▾
Withdrawal: ▴



Version 1.1

Figure 4.66

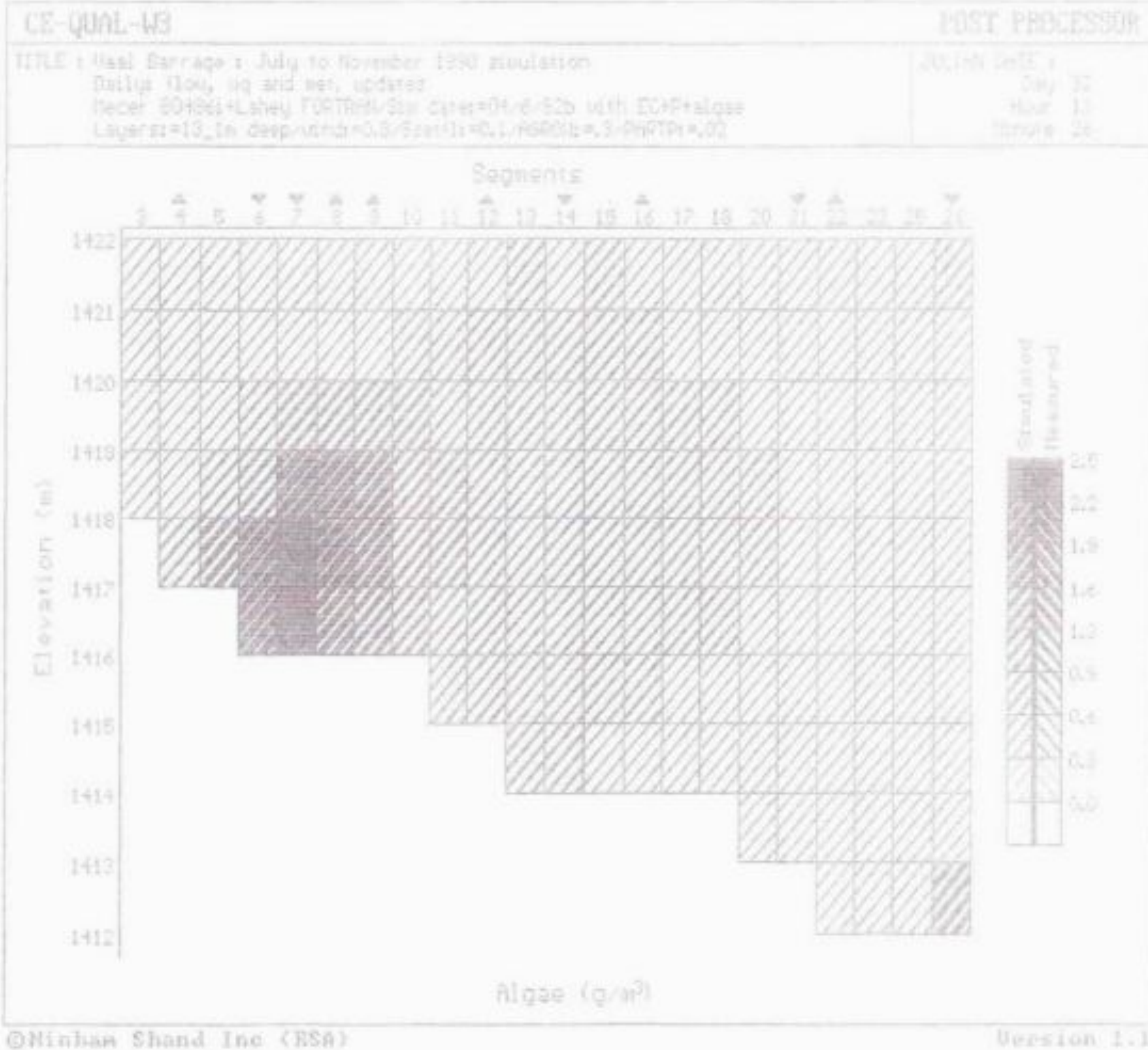
Two-dimensional plot showing the simulated algal biomass in Segments 3 through to 26 in the Vaal Barrage.

Day number: 32

Beginning of release from Vaal Dam: Day 21

Variable: algal biomass
Units: mg/l
(dry weight)

Inflow: ▾
Withdrawal: ▴



in pipes and machinery, as well as being detrimental to certain agricultural users (Thirion, 1991).

Figures 4.67 to 4.72 show (1) time series plots of the TDS concentration at the main abstraction points, with the TDS concentrations shown at selected depths and (2) the TDS concentration blending limit of 600 mg/l. TDS time series plots have been produced for:

- Segment 4 - RWB at Pump 3 Suikerbos, see Figure 4.67,
- Segment 8 - Vereeniging Municipality, see Figure 4.68,
- Segment 9 - RWB at Pump 1, see Figure 4.69,
- Segment 12 - RWB at Pump 2, see Figure 4.70,
- Segment 16 - ISCOR, see Figure 4.71,and
- Segment 23 - SASOL, see Figure 4.72.

Figures 4.67 to 4.72 show that the release of water from the Vaal Dam causes the TDS concentration to decrease in the upper layers (surface to 2 metre depth). In the lower layers, the release had little influence on the TDS concentration. In the lower end of the Barrage, at the SASOL abstraction point, the concentration of TDS showed little variation during the period of the release, see Figure 4.72. The plots show that abstraction of water from the Barrage should be made as near as possible to the water surface. At the Barrage, the release of water from the Vaal Dam causes a gradual decrease in salinity, and vertical mixing results in minimal difference between the surface and bottom waters,

4.5.4 Conclusions from the CE-QUAL-W2 simulation: Vaal Barrage

1. CE-QUAL-W2 successfully simulates the two-dimensional variation in conductivity and TDS of the Vaal Barrage. No leeway was available for the calibration of the model except that the wind coefficient could be adjusted to influence the degree of vertical mixing.

2. The CE-QUAL-W2 simulation exercise on the Vaal Barrage shows the hydrodynamics, thermal dynamics and water quality are coupled and have a direct influence on the mixing characteristics of the Barrage. The model shows that the inflowing tributaries generally discharge into the bottom layers of the Barrage. The release water from Vaal Dam causes minimal mixing and simply displaces the high TDS water. After a number of weeks, longitudinal and vertical mixing occurs between the low TDS release water and the high TDS water of the Barrage. Mixing

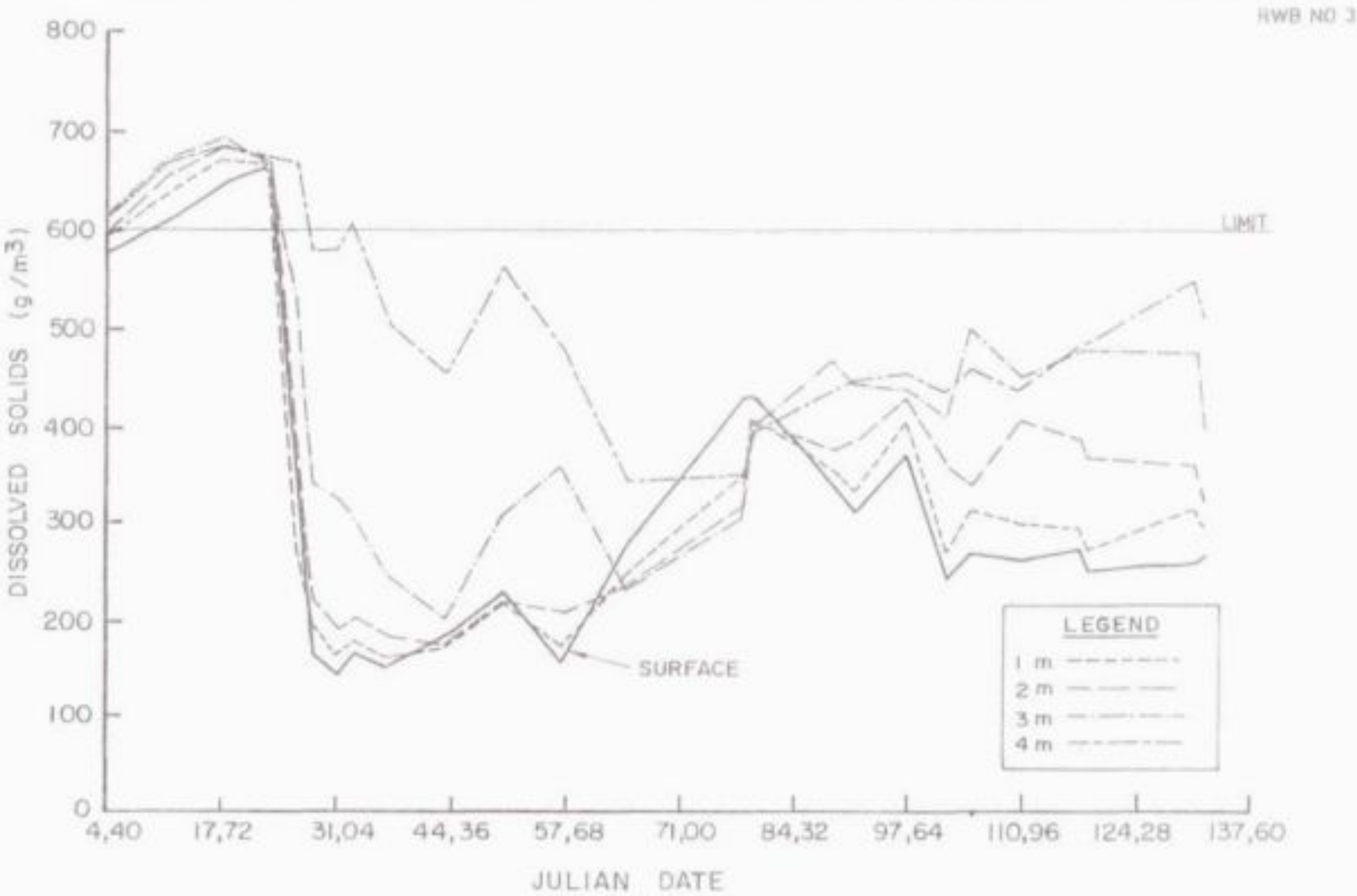


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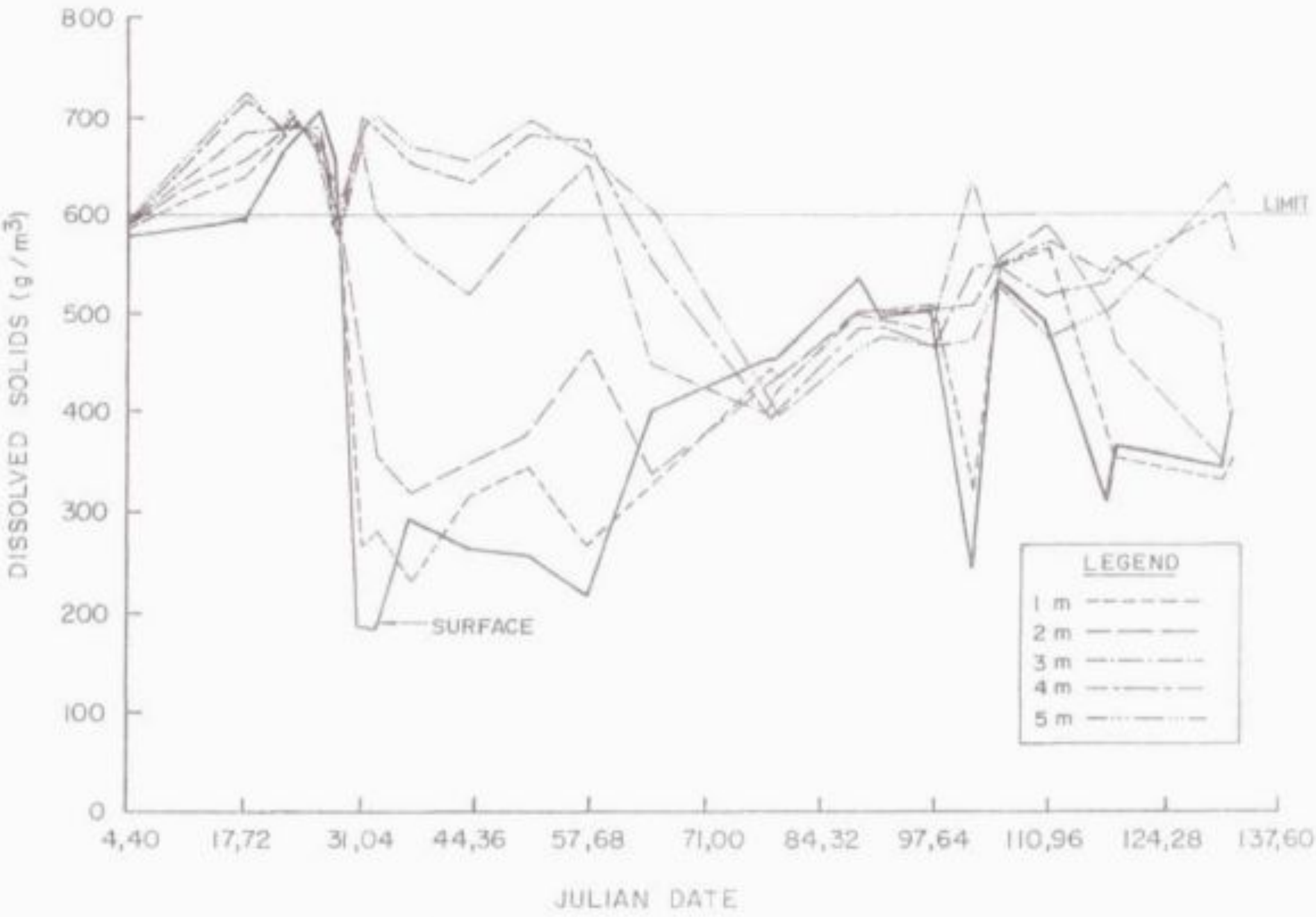
FIGURE 4.67

Time series of simulated total dissolved solids concentration data at 1 metre intervals in depth for the abstraction point: Rand Water Board number 3 at Segment 4.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Simulated total dissolved solids concentration of the Barrage at 1 metre intervals in depth for the Vereeniging abstraction point at segment 8.	FIGURE 4.68

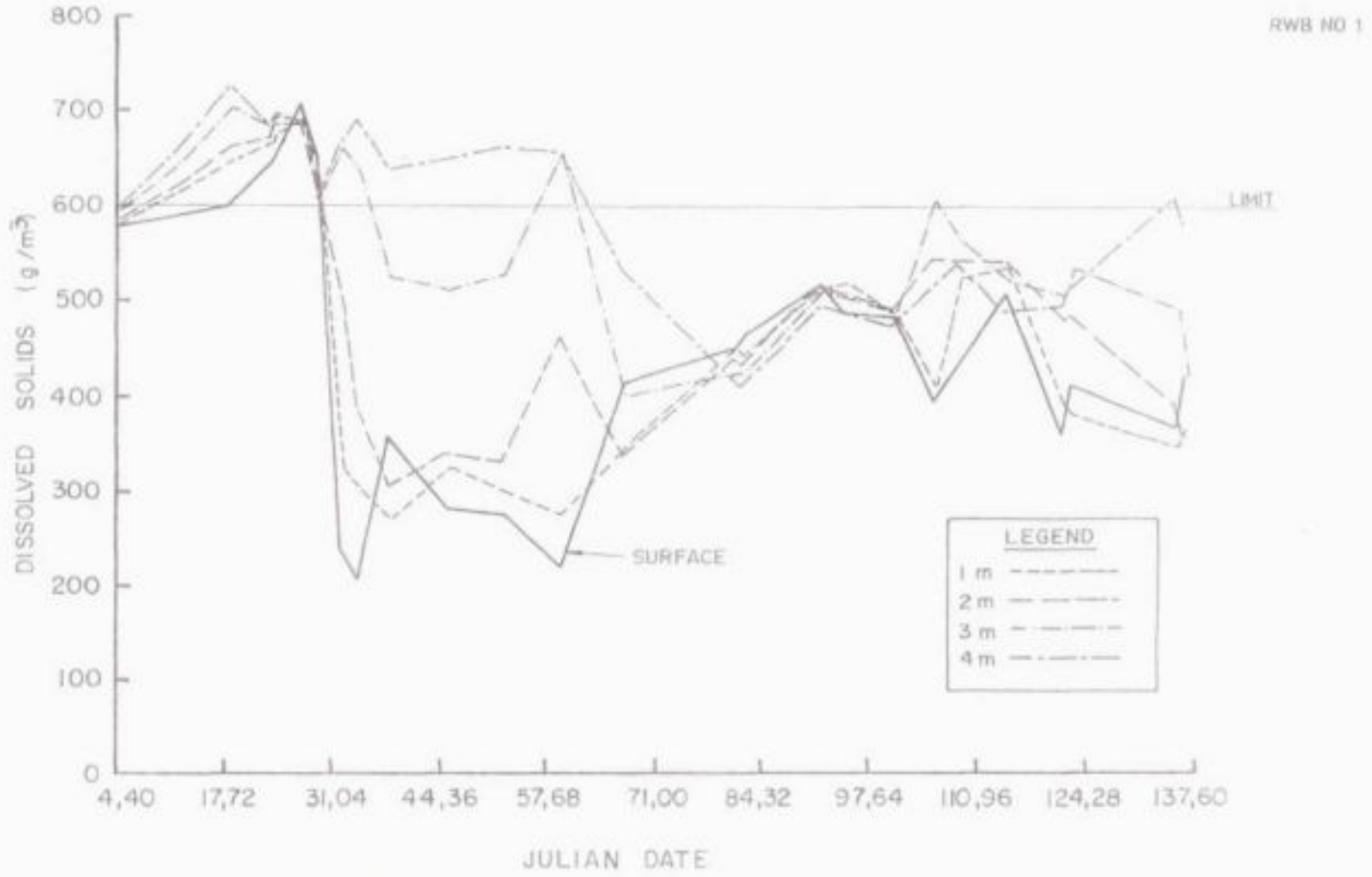


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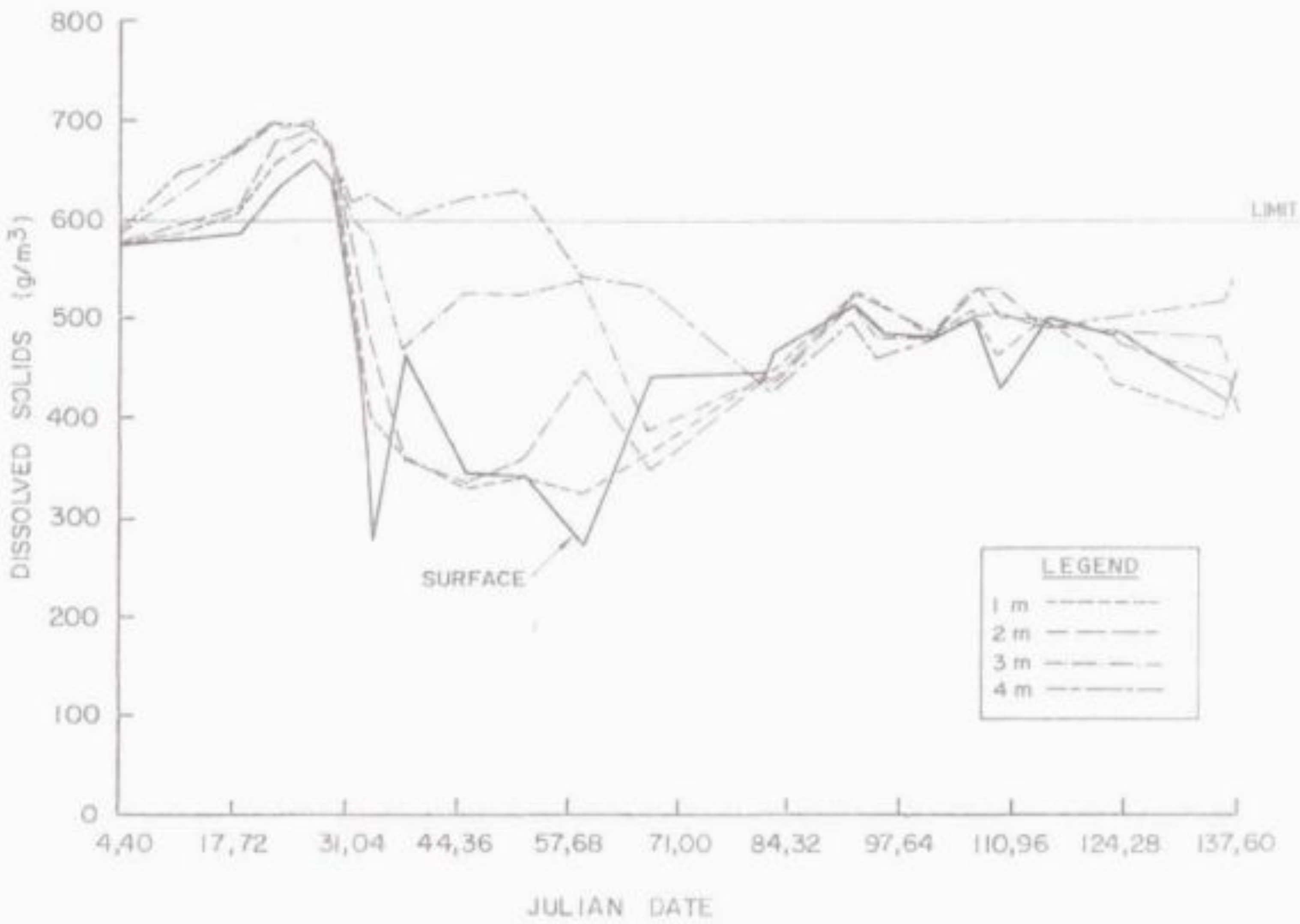
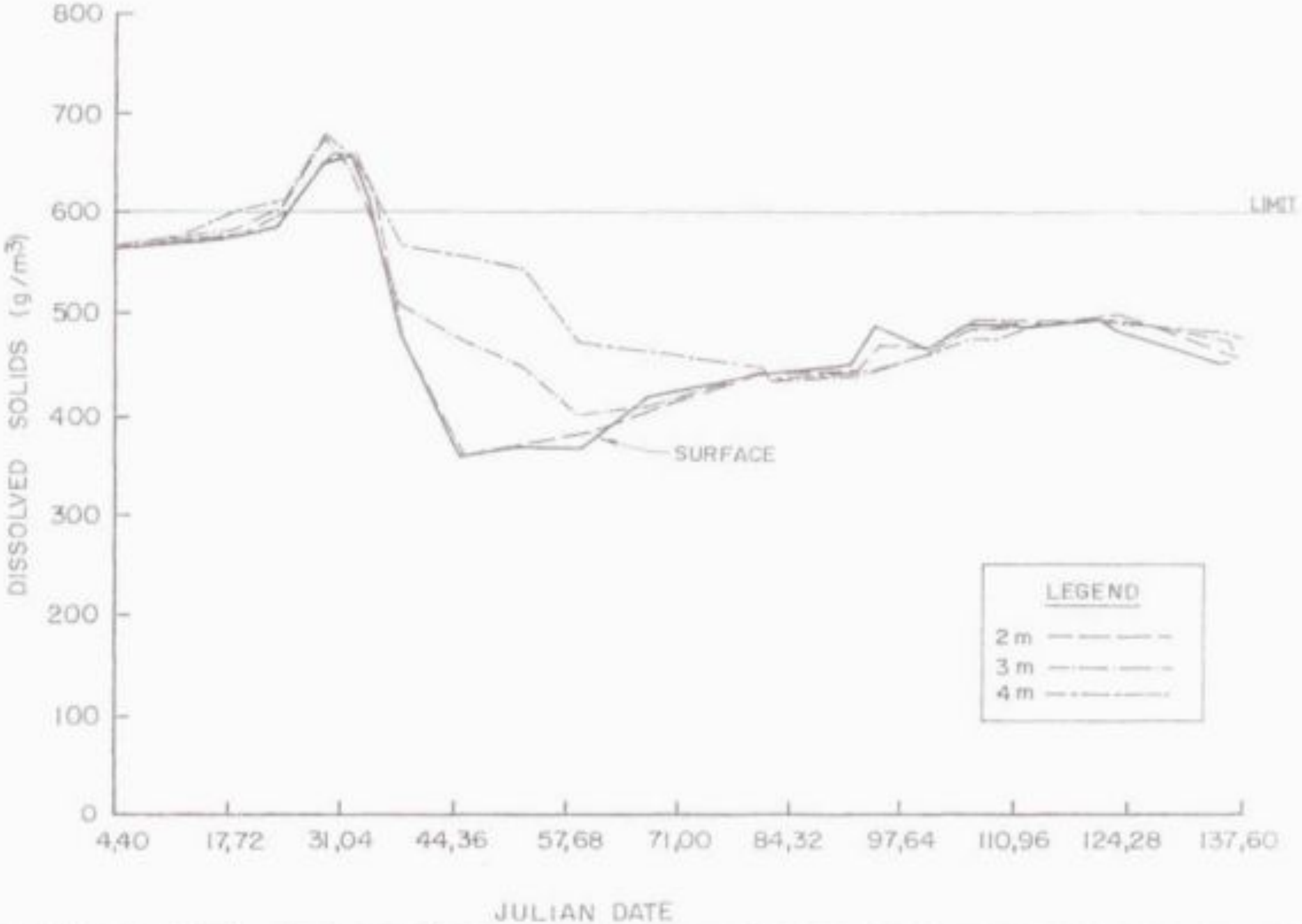
FIGURE 4.69

Simulated total dissolved solids concentration of the Barrage at 1 metre intervals in depth for the Rand Water Board abstraction point number 1 at Segment 9.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Simulated total dissolved solids concentration of the Barrage at 1 metre intervals in depth for the Rand Water Board abstraction point number 2 at segment 12.	FIGURE 4.70



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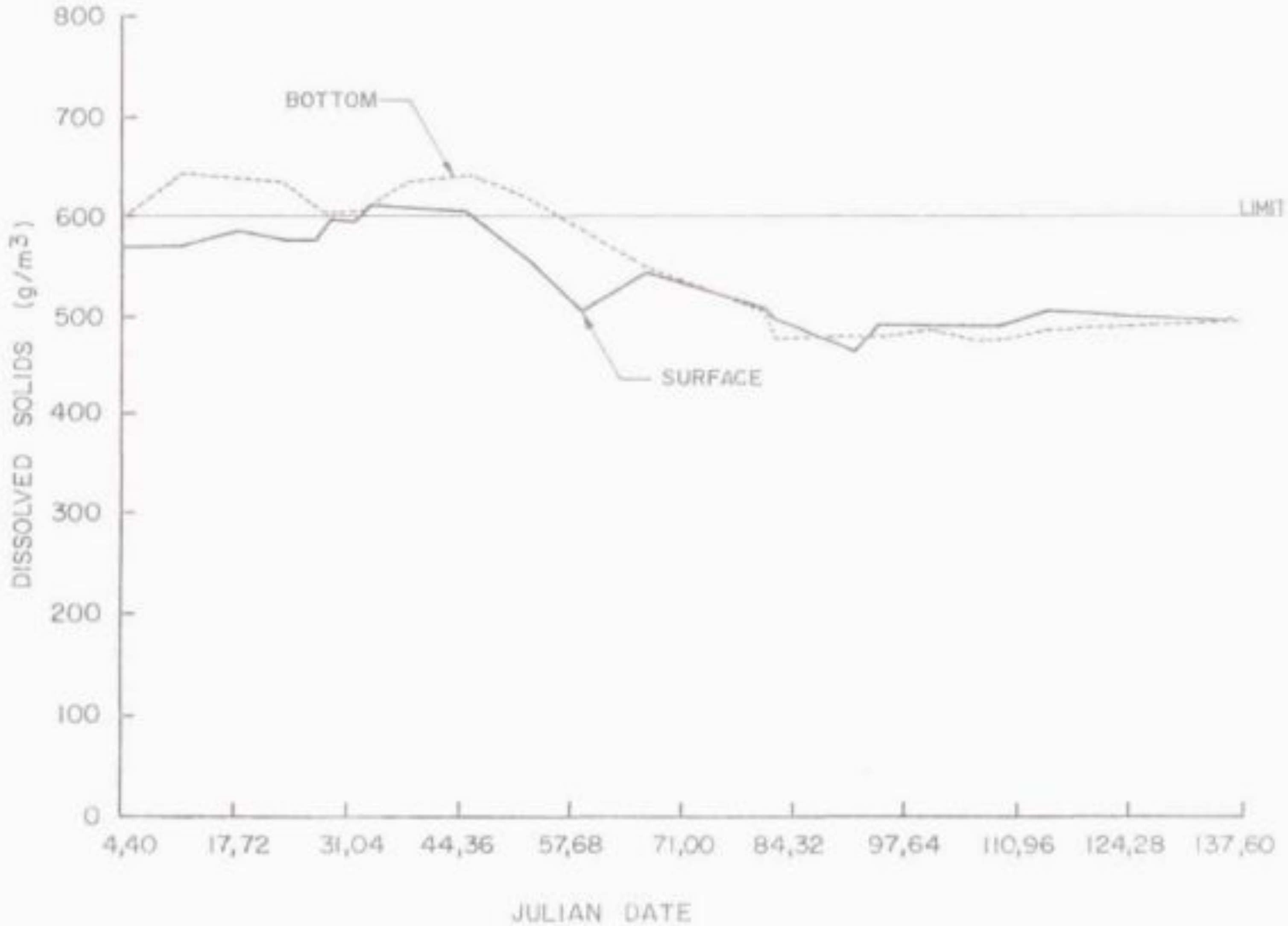
Simulated total dissolved solids concentration of the Barrage at 1 metre intervals in depth for the ISCOR abstraction point at segment 16.

FIGURE 4.71



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Simulated total dissolved solids concentration of the Barrage at surface and bottom layers for the SASOL abstraction point at segment 22.

FIGURE 4.72

continues as the release passes along the length of the Barrage. Some 50 days after the beginning of the release, the Barrage becomes vertically mixed and comparatively uniform in TDS concentration.

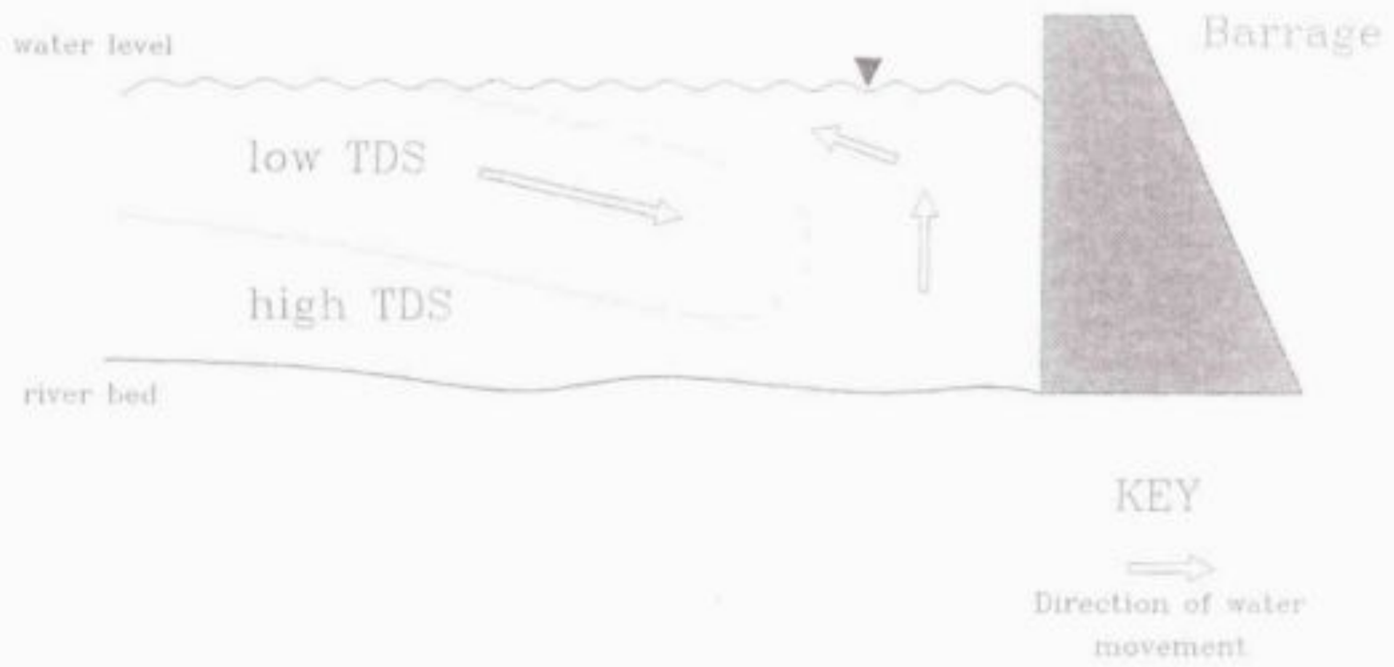
3. When the leading edge of the release water reaches the wall of the barrage it submerges and mixes into lower waters. Figure 4.73 shows a schematic of the plunge-point of the release water. This effect was verified and checked against measured conductivity data recorded by Thirion (1991).

4. The Barrage acts as a two-dimensional reactor, showing laminar flow patterns, plug flow, and intricate longitudinal and vertical mixing patterns. The simulation shows that a two-dimensional modelling approach is necessary to simulate the vertical and longitudinal mixing patterns. A one-dimensional modelling approach is therefore inappropriate for water quality modelling of the Vaal Barrage.

5. The calibration of CE-QUAL-W2 for phosphate and algal biomass was incomplete but provided useful information on the distribution and variation of these water quality variables. In the case of suspended solids, insufficient measured data were available to achieve an accurate calibration. CE-QUAL-W2 however provided an acceptable simulation of the change in suspended solids along the length of the Barrage when compared with the measured turbidity data.

6. To enhance, and possibly improve, water quality simulations the following waterbody configuration may be appropriate:
   - Increase the number of segments from 26 to 52, thereby decreasing the length from 2000 metres to 1000 metres.
   - Increase the number of layers from 13 to 26 so that each layer is decreased from 1000 mm to 500 mm deep.

7. CE-QUAL-W2 provides detailed information on the water quality of the Vaal Barrage. Such information would play a vital role in the development of catchment management plans for the Barrage. In such a case, CE-QUAL-W2 could be used to provide information on:
   - The optimum abstraction depth at each of the points along the Barrage for domestic and industrial water use.
   - The time frame for abstraction, relative to the date of the releases made from the Vaal Dam.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Schematic showing the plunging effect of the low TDS water released from the Vaal Barrage.	FIGURE 4.73

* How water should be released from the Vaal Dam to maximise mixing characteristics in the Barrage.
* The minimum volume of water released from the Vaal Dam to achieve the necessary blending conditions at specific points in the Barrage. Such information could then be used to develop a set of operating rules for the freshening of the Barrage.
* In the case of Rand Water Board, CE-QUAL-W2 could be used to select between the three main abstraction points and thereby avoid water with high TDS concentration.
* CE-QUAL-W2 could be used to determine the optimum load of nutrients which can be discharged into the Barrage to minimize the eutrophication problems. Such information could form the basis of wasteload allocation investigations for each of the main tributaries delivering nutrients to the Barrage.
* CE-QUAL-W2 can be used to design a monitoring system by identifying key variables and key positions in a water body where water quality problems emerge. CE-QUAL-W2 could be used to identify areas where vertical mixing exists and thereby provide the optimum position to obtain a representative sample of a waterbody.
* Management of the water quality of the Vaal River below the Barrage requires information on the quality of the water being released from the Barrage. CE-QUAL-W2 provides a unique opportunity to simulate a time series of data for the released water. This has particular importance when releases are made from the Vaal Dam, the conductivity and TDS of the Barrage is shown to vary dramatically making weekly water sample collection strategies ineffective for management information purposes.

In summary, CE-QUAL-W2 provides a detailed description of the water quality, hydrology, hydrodynamics and thermal regime of the Vaal Barrage. For the effective management of the water quality of a water body, CE-QUAL-W2 could be used to provide description of the governing processes within the system. Such information could be used in: wasteload allocation investigation exercises, design and evaluation of release strategies for water quality management, design and evaluation of blending options, and evaluation the influence of physical changes to a system such as by using diversion canals.

4.6 ENHANCEMENTS TO THE SOURCE CODE AND COMPUTER PROGRAMS

- The "Front End" of the program comprises the output to the screen during a model simulation. The "Front End" was redeveloped so that the user can determine the speed and position of the model computation and simulation point. This was found particularly useful in model calibration runs when the simulation was terminated at a specific Julian day number.

- The "Restart" option was improved by making it possible for the user to interrupt the simulation at any point and then restarting from that point later.

- Batch-files were created for compiling, running and editing output. The batch file used to run the model checks the status of existing files to prevent over-writing existing output files, and calculates an elapsed time for the computation run time.

- The source code has been changed to account for reservoirs which have a convoluted layout such as Inanda Dam and Vaal Barrage. The use of a single orientation for each branch was found to be a considerable constraint on the simulation.

- The source code of CE-QUAL-W2 was modified to output a binary file suitable for input to the postprocessor.

- When using the tributary inflow for the Vaal Barrage simulation, coding errors were found in the subroutine reading time varying data. The subscripts had been entered incorrectly which was readily detected and rectified.

- In the application of CE-QUAL-W2, a number of data files remain "open" during the computation. The operating system, DOS, will only support a maximum of 15 files open at any one time. In the Vaal Barrage simulation, the number of files "open" exceeded the DOS limit, giving a "file handle" error. This problem was overcome by reformatting and linking associated files to reduce the number of open files. All temperature, flow and water quality data files for the tributaries were linked into three files. The problem may also be overcome by purchasing a Lahey routine "MAXFILES" and compiling the code with this library. The library allows a maximum of 255 files to be open at any one time.

4.7 CONCLUSIONS

General:

Predictive capabilities: CE—QUAL—W2 provided good predictive capabilities in the simulation of the thermal dynamics, hydrodynamics and water quality of Inanda Dam and Vaal Barrage.

Adaptation of model: The model was found to be appropriate for use on South African reservoirs. Minor changes were made to the source code so that each segment could be orientated independently to account for the meandering shape of many reservoirs.

Calibration of model: Calibration of CE—QUAL—W2 was time consuming because of the coupling between the thermal dynamics, hydrodynamics and water quality. The calibration of the thermal dynamics was readily achieved once the program METDATA was developed to pre-screen the input data set. Calibration of the hydrodynamics was comparatively easy. The time spent in the calibration of CE—QUAL—W2 for the water quality components was governed by the variables being simulated. The calibration of TDS, conductivity (tracer) and suspended solids was straightforward. However, calibration for phosphate, algal biomass and dissolved oxygen required a large allocation of time. Calibration coefficients for the thermal and hydrodynamic aspects were taken from the user documentation. In the case of algal and phosphate, numerous model runs were necessary to select the appropriate coefficient values. The range of values used in the phosphate and algal dynamics was "narrow" compared with the other coefficients used.

Use of model in management and planning decision making: The model is capable of providing information on the governing processes within a water body. Such information could be used in: wasteload allocation investigations, evaluation of release strategies and blending options. Time and budget constraints did not permit the detailed use of CE—QUAL—W2 as a tool for the management of water quality.

Case studies: Inanda Dam and Vaal Barrage

Detailed conclusions for these two case studies included in this chapter i.e. Inanda Dam and the Vaal Barrage are given in Sections 4.4.4. and 4.5.4. For reasons of economy they are not repeated in this section.

Model application

The model is found to be an inherently powerful numerical modelling tool. The calibrations and simulations performed in this chapter are only an indication of the simulation potential of CE-QUAL-W2. The user of the model however **must** have good knowledge of the following subjects

- Hydrodynamics
- Aquatic biology
- Hydro-chemistry
- Numerical methods
- Computer hardware
- FORTRAN coding and programming
- Data assembly and in-filling techniques.

Water quality modelling requires not only knowledge in the subjects listed above but also experience in their integration. In this regard the use of the model is complicated and a time consuming task. However, once configured the model has the potential to deliver valuable information on the water quality behaviour of the reservoir.

Model capabilities

Hydrodynamics: The model predicts water surface elevations, velocities and temperatures. The model can be used to provide a volume balance in comparatively complex water bodies which have multiple inflows and outflows.

Water quality: The model permits up to 20 constituents to be simulated in addition to temperature. The user has the option to select which constituents require simulation. The model CE-QUAL-W2 is suited to water quality simulations of reservoirs, where:

1. The spatial and temporal resolution requires the use of a model with coupled hydrodynamic and quality components.

2. Where time varying two-dimensional simulations are required.

3. Assessment of impacts of changes in loadings, system design, operation or

other forcing factors on the distribution of thermal energy and certain biological and chemical materials in two-dimensions. For Example, CE-QUAL-W2 could be used in wasteload allocation investigations.

4. Assessment of water quality in reservoirs and rivers in terms of criteria used in the assessment of fitness for use. The post processor has the ability to show graphically the concentration limits for a given variable and thus indicate areas in a water body experiencing problems.

The model could be used to determine the impact of the lateral inflows on the water quality of the reservoir at the dam wall.

Long term simulations: The model uses an implicit solution for the water surface elevation that eliminates the surface gravity wave restriction on the time step. This permits long time steps during simulation resulting in decreased computational time. As a result, CE-QUAL-W2 can simulate water quality over long time periods.

Head boundary conditions: The model has been adapted to accommodate upstream and downstream head boundary conditions which makes the model applicable to estuarine conditions and where the inflows are unknown.

Multiple branches: The branching algorithm allows the model to be applied to geometrically complex waterbodies such as dendritic reservoirs or estuaries with many freshwater inflows. A different longitudinal spacing can be specified for each branch.

Variable vertical spacing: The model allows the user to specify layers with varying height. However, the layer heights will be constant in each branch.

Hydrodynamics independent from water quality: The model allows the hydrodynamics (including temperature) to be simulated independently from the water quality constituents. However, the water quality constituents are not decoupled from the hydrodynamics. Storage requirements for long term hydrodynamic output to drive the water quality model quickly become prohibitive, necessitating a limitation on the grid size. In addition, for many computers, reduction in computer time becomes minimal when the data necessary to drive water quality simulations are being read every time step.

Autostepping: The model includes a variable time step algorithm that ensures that numerical stability requirements imposed by the solution scheme are not being violated.

Restart: The user can make the model output results during a simulation which can be used later to restart the simulation from that particular point in time.

Layer/segment addition and subtraction: During a simulation the model will automatically adjust the vertical position of the surface layer and upstream segment for a rising and falling stage level.

Multiple inflows and outflows: The model is designed to include inflows from point and nonpoint sources, branches, and precipitation. Outflows are either specified as outlets at a branch downstream or as lateral withdrawals. Although evaporation is not considered an outflow it is included in the water budget.

Time varying boundary conditions: The model accepts time-varying inputs at the frequency that they occur independent of other time varying inputs. These include meteorological data, temperature data etc.

Output: The user may select the type and frequency of output from the model. Output is currently available for hard copy and restarts. A post processor is developed to provide graphical interpretation of the output from the model.

Model limitations

Hydrodynamics and transport: The governing equations are laterally and layer averaged. Lateral averaging assumes that lateral variations in velocity, temperature, and constituent are negligible. The user must decide whether lateral averaging will have a detrimental influence on the simulation results.

Water quality: The interactions of the aquatic ecosystems are complex and variable. The numerical methods of the model have been developed to describe the various processes. As improved mathematical expressions are derived, so will the model be improved accordingly. The model incorporates the following constraints.

- **One algal compartment**. The model includes a single algal compartment and thus can not simulate the succession of algal species from say diatoms to blue-greens. In particular, temperature dependency for different algal groups and **nitrogen fixation for blue-greens is not incorporated in the model.**

- **No zooplankton**. The model does not include zooplankton grazing on algae or their recycling of nutrients.

- **No macrophytes**. The model does not include the influence of macrophytes on water quality.

- **Sediment oxygen demand**. The model does not have a sediment compartment that models the kinetics in the sediment and at the sediment-water interface. This places a limitation on the long-term predictive capabilities of the water quality portion of the model.

Availability of data: Water quality, meteorological and hydrological data are required to describe boundary conditions, calibrate and verify the model. In the Inanda Dam simulation, problems were experienced with the meteorological data which required the development of a program to pre-screen and verify the data set (METDATA). The water quality data set for Inanda Dam was suited to the requirements of CE—QUAL—W2 and showed the value of a well designed monitoring system. In the case of the Vaal Barrage, the meteorological and water quality data set met the needs of CE-QUAL-W2. However, the lack of bathymetric data required detailed analysis of the volume/stage relationship for the Vaal Barrage.

Computer limitations: CE-QUAL-W2 places a large computational burden on the computer. Most computations are performed using 32 bit single precision. Double precision is only used in selected calculations. It is essential an appropriate computer is used to run the model. Reduction in computation time, however, has been achieved through selective choice of segment and layer configuration.

4.8 RECOMMENDATIONS

- Based on the case studies for Inanda Dam and Vaal Barrage, the model should be used to provide information for the management and operation of the water quality of waterbodies in South Africa.

- In-filling data sets forms a crucial component of the use of the model. The methods used in this investigation were deemed adequate in terms of the objective of the study; infilling methods should receive more detailed research effort as they can have an important influence on the predictive ability of such models.

- It is recommended that water quality monitoring systems address the data input requirements of models such as CE—QUAL—W2. Key water quality variables which should be given high priority in monitoring systems include:

  Suspended solids
  Phosphorus (soluble ortho- and total)
  Nitrogen-species (nitrate and ammonia)
  Algal biomass and chlorophyll-α
  Dissolved oxygen and water temperature
  Total coliform
  TDS and electrical conductivity

- Ideally, the variables shown above should be measured at discrete intervals throughout the depth profile. However, as a minimum data requirement, samples should be taken at the surface, mid-depth (metalimnion) and bottom waters (hypolimnion). The sampling points should be positioned along the length of a water body so that longitudinal gradients in water quality can be evaluated. Single measurements taken of the surface water at the dam wall provide no useful information on longitudinal and vertical gradients in water quality

- In terms of the meteorological data, problems were experienced in the simulation of the thermal dynamics of Inanda Dam. The simulation exercise shows the importance of meteorological data measurements being recorded in close proximity to the reservoir.

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APPENDIX A4.1

METEOROLOGICAL DATA SCREENING AND VERIFICATION PROGRAM: "METDATA"

By
A J Bath

Contents:

1 BACKGROUND

The thermal dynamics, wind mixing and heat energy input to a water body play an important role in the water quality and distribution of constituents in a water body. CE-QUAL-W2 uses a method devised by Edinger *et al*. (1974) to determine the thermal dynamics in water bodies allowing the simulation of (i) water temperature with depth, (ii) stratification and destratification, (iii) mixed depth governed by wind action, and (iv) the movement of water. The work of Edinger *et al*. (1974) provides a unique method for simulating the thermal dynamics of water bodies, and has been used for designing the cooling ponds at thermal power stations.

In describing the thermal method devised by Edinger *et al*. (1974) it is important to understand the seasonal changes which generally occur in a deep lake in the mid-latitudes. In simplified terms, the cycle begins with a uniform cool vertical temperature profile through late winter. As the spring season develops, more heat is added from the atmosphere during day time than is lost during the night. The heat is mixed downward from the surface by wind action, and by convection associated with evaporation cooling at night. During calm periods late in spring, heat is absorbed near the surface is mixed downwards slowly resulting in a warm upper layer, the lake is then "stratified". The stability of the interface between upper and lower layers hinders the downward mixing of the surface, less dense, water into the more dense cool water at the bottom. The lake will stay stratified during the summer months with the warm upper layer (epilimnion) increasing in depth as heat mixes across the interface (thermocline). In autumn, as the days become cooler convection mixing occurs with the epilimnion deepening and the thermocline becoming weak. Eventually, wind mixing causes vertical mixing during the winter months. The cycle begins again during the spring.

All water bodies dissipate heat to the atmosphere by back-radiation, evaporation and conduction, while receiving heat from solar radiation and long wave atmospheric radiation. The following section describes the mechanisms of heat exchange and the methods developed for their calculation, developed by Edinger *et al.* (1974).

The processes of surface heat loss are back-radiation, evaporation and conduction. Their magnitudes are dependent on the temperature of the water surface. The rate of back-radiation is proportional to the fourth power of the absolute temperature of the water surface. The heat conducted from the surface is proportional to the difference between the water surface temperature and the air temperature. Heat loss through evaporation, or gained through condensation, is proportional to the difference between the water surface temperature and the dew point temperature of the overlying air.

Short wave radiation is the radiant energy passing directly from the sun to the earth. The intensity of the short wave radiation reaching the atmosphere of the earth is calculated from the "solar constant". The intensity of the radiation received on any portion of the atmosphere varies with the latitude, time of day and season. The amount of short wave radiation reaching the surface of the earth depends on adsorption by ozone, scattering by dry air, adsorption by suspended particles and the adsorption and scattering by water vapour. Short wave radiation is more readily measured then calculated.

Long wave radiation depends on the air temperature and humidity, and increases as the moisture content of the air increases. It constitutes the major thermal input to a water body at night and on warm cloudy days. Unlike short wave radiation, atmospheric radiation is more conveniently calculated than measured. Water sends energy back to the atmosphere in the form of long wave radiation. Back-radiation is reported to account for a substantial portion of the heat loss from a water body. Assuming the water body is a black-body, the heat loss through back-radiation may be calculated from the Stephan-Boltzmann fourth power law. Evaporation causes heat loss from the water body to the atmosphere. Each kilogram of water which leaves as water vapour removes its latent heat of vaporization ($2.45*10^6$ Joules). This amount of heat is also regained through condensation, when the water temperature falls below the dew point temperature. Edinger *et al.* (1974) describe a method of calculating the evaporation as a function of the wind speed, and the difference between the saturated water vapour pressure at the water surface temperature and the water vapour pressure of the overlying air. Heat energy can leave or enter a water body by conduction if the air temperature is greater than or less than the water surface temperature. Edinger *et al.* (1974) developed a simplified and refined theory of surface heat exchange that combines the heat dissipation roles of evaporation, conduction and back radiation into a single exchange coefficient.

2 THEORY AND PROGRAM DEVELOPMENT

Equilibrium temperature concept

The bulk temperature of a large mixed body of water under natural conditions, T_w, tends to increase of decrease with time according to whether the sum of the heat inputs (short wave solar radiation and atmospheric radiation) and heat outputs is positive, or negative. The rate of change of temperature may be given by

$$dT_w/dt = \Sigma H / \rho C h \qquad \text{.... (A4.1)}$$

where, ρ, C and h are the density of water (1000 kg/m^3), heat capacity of water (4186 J/kg/°C) and water depth (m) respectively. ΣH is expressed in units of power intensity (W/m^2). Edinger *et al.* (1974) demonstrate that Equation A4.1 may be transformed to yield

$$dT_w/dt = K(E - T_w) / \rho C h \qquad \text{.... (A4.2)}$$

where, K is a heat exchange coefficient (W/m^2/°C) which is dependent on the water temperature and wind speed. The equilibrium temperature, E, is defined as the hypothetical water surface temperature at which the net rate of surface heat exchange would be zero. The full equilibrium temperature theory given by Edinger *et al.* (1974) shows two terms are coupled via water temperature and meteorological conditions. Equation A4.2 therefore requires iterative methods to be used in its application.

Brady, Graves and Geyer (1969) show that variation in the equilibrium temperature may be conveniently estimated using the relationship

$$E = T_d + H_s/K \qquad \text{.... (A4.3)}$$

where T_d is the dewpoint temperature (°C), H_s is the gross rate of short wave solar radiation (W/m²) and K is the same exchange coefficient as used in Equation A4.2. The dewpoint temperature generally stays comparatively constant during the day. Equation A4.3 shows that the equilibrium temperature, E, will show hourly variation during the day. At night, E approaches the dew point temperature which acts like a relatively invariant datum for periods of 24 hours, or less. On an annual basis, both T_d and H_s are much greater in the summer months compared with during the winter.

Of the three heat exchange components, Brady, Graves and Geyer (1969) show that the positive contribution from atmospheric radiation nearly cancels the negative contribution from the back-radiation, leaving a small negative residual which is balanced by a small positive conductive term. Thus, when the sun is not shining, water temperature tends towards the dewpoint temperature as if its final equilibrium is determined solely by evaporative heat loss. Edinger *et al.* (1974) state that the water temperature response lags behind that of the equilibrium temperature, E, and that T_w = E is an instantaneous occurrence and only occurs twice a day.

The value of the heat exchange coefficient, K, enters Equation A4.2 in two places: one directly as the coefficient of proportionality for converting the temperature difference (E - T_s) into an equivalent rate of heat storage, and the other indirectly, as the divisor of the solar radiation component in the approximation for the equilibrium temperature, E, see Equation A4.3. Thus K has two seemingly distant but reciprocal interpretations: as a multiplier and other times as a divisor for converting between temperature differences and corresponding rates of heat transfer per unit area. All these interpretations for K are equivalent and demonstrate the use of this parameter in representing the combined role of evaporation, conduction and back-radiation in the equilibrium temperature concept.

Surface heat exchange coefficient (K)

The surface heat exchange, K, is shown alone to be a key component for converting between surface water temperature changes and corresponding rates of heat transfer per unit area.

Using the theory and concepts described above for the equilibrium temperature and heat exchange to represent the combine influence of all surface heat exchange processes, the dynamic temperature response of a confined volume of vertically mixed water may be represented by

$$DT/dt = K\,(E - T_s)/\rho\ C\ h \qquad \text{.... (A4.8)}$$

where T_s is the surface water temperature (°C), t is the time (seconds), K is the exchange coefficient (W/m²/°C), E is the equilibrium temperature (°C), ρ is the density of water and C the heat capacity of water, and h the mixed depth (m). Edinger states that the term "confined volume" may include the epilimnion of a lake during periods of minimal inflow.

Program development

The use of Equations A4.1 to A4.8 enable the verification of the meteorological data input to the model CE-QUAL-W2 prior to full application of the model. The program uses the list of data shown below in conjunction with the above equations to calculate the surface water temperature of the mixed layer. Graphical output enables comparison between the measured and simulated surface water temperatures. Adjustments can be made to the wind speed and the solar radiation to ascertain the influence on temperature, T_s, and mixed depth, h. The program allows export of the meteorological data set, once calibrated and screened, in a CE-QUAL-W2 compatible format.

CE-QUAL-W2 uses the following input meteorological variables:

1. equilibrium temperature
2. dewpoint temperature
3. wind speed and direction
4. coefficient of surface heat exchange
5. short wave solar radiation

METDATA allows the processing of these variables, and once verified exported in ASCII format.

3 APPLICATION OF METDATA: INANDA DAM, NATAL

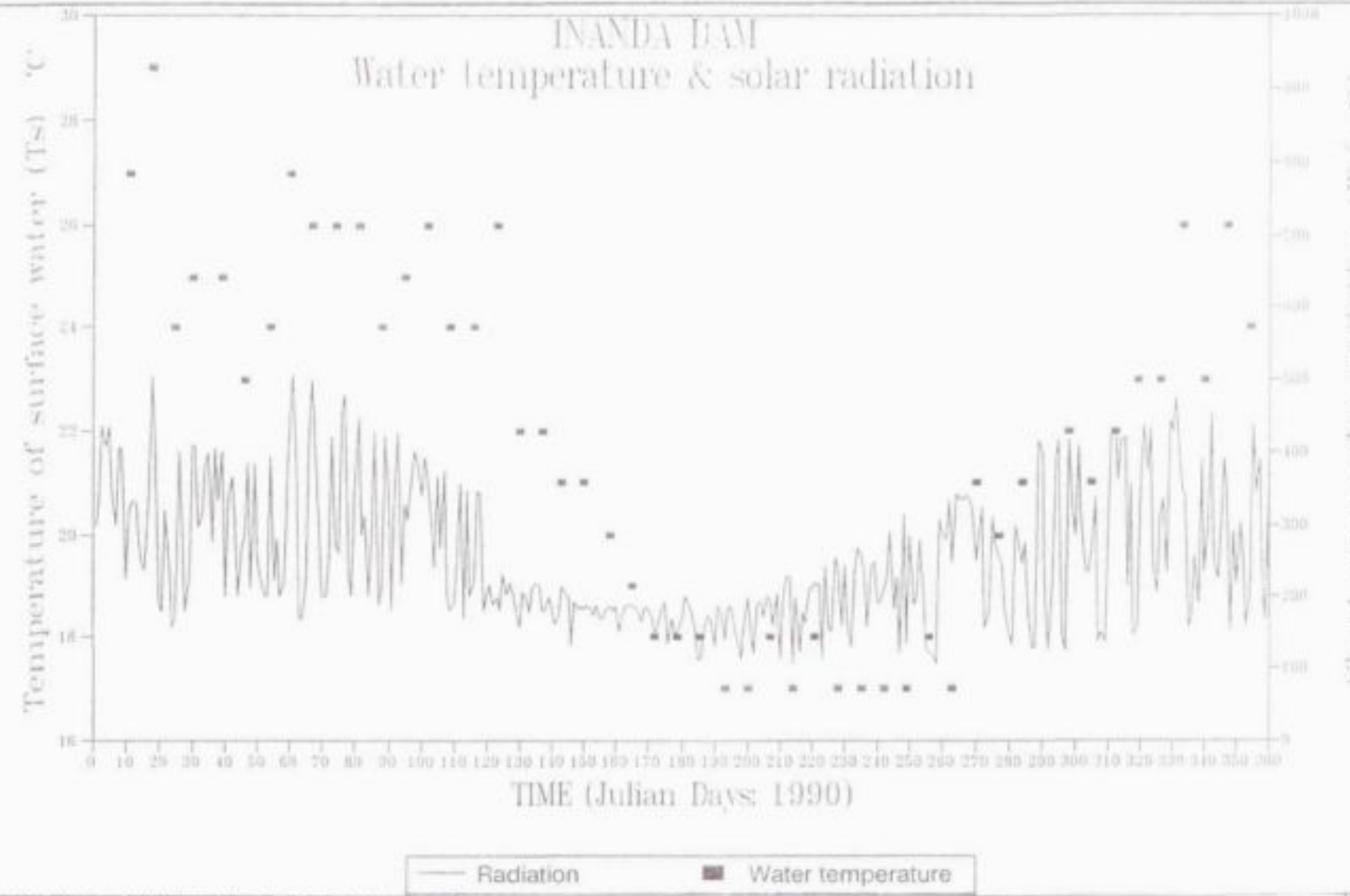
The program METDATA was used to screen and verify the meteorological data set for the Inanda Dam simulation. Air temperature, dew point temperature, wind speed and direction data were obtained from the Weather Bureau Station at Mount Edgecomb, some 16 km from Inanda Dam. Short wave solar radiation was only available at Durban Airport, located some 30 km from Inanda Dam. Water temperature profile data were measured by Umgeni Water at five positions in the dam and measurements taken at 2 metre intervals of depth.

METDATA was used to simulate the surface water temperature of Inanda Dam from the meteorological data recorded at Mount Edgecomb and Durban Airport. It was found that there was little agreement between the measured and simulated data. By reducing the wind by 80 percent improved the simulated water temperatures for the last half of the year. In the first half of the year there was considerable discrepancy between measured and simulated water temperature. The discrepancy in the simulated temperature resulted in CE-QUAL-W2 destratifying Inanda Dam one month prematurely. CE-QUAL-W2 simulated the destratification of Inanda Dam on Julian day number 80 instead of Julian day 110 (19 April 1990).

Using two simple adjustment factors it was possible to increase the short wave solar radiation input to Inanda Dam to effectively retard the simulated date of destratification. Figure A4.1 shows the short wave solar radiation data are highly variable and follow a cyclical pattern over a yearly period. The original short wave radiation data were adjusted by:

- Differentially adjusting the data for Julian days 1 to 200, so that day 1 receives a 10 percent increase, and day 200 zero increase.
- Taking the adjusted data for days 60 to 120, and multiplying the data values by a factor of 1.3. The factors were derived by testing a range of values and comparing the measured and simulated water temperatures in Inanda Dam.

Comparison between the simulated and measured water temperature showed that the above method, although crude, caused an overall improvement in the simulated temperatures, see Figure A4.2, and delayed the vertical mixing to Julian day 110. The problems experienced with the short wave solar radiation have not explained but may be attributed to differences in localised meteorological conditions during the end of the summer. Durban Airport is situated 1 km from the coast and experiences mist during the summer which are localised weather conditions. Similarly, Inanda Dam experiences misty conditions during the early winter which are restricted to the inland areas.



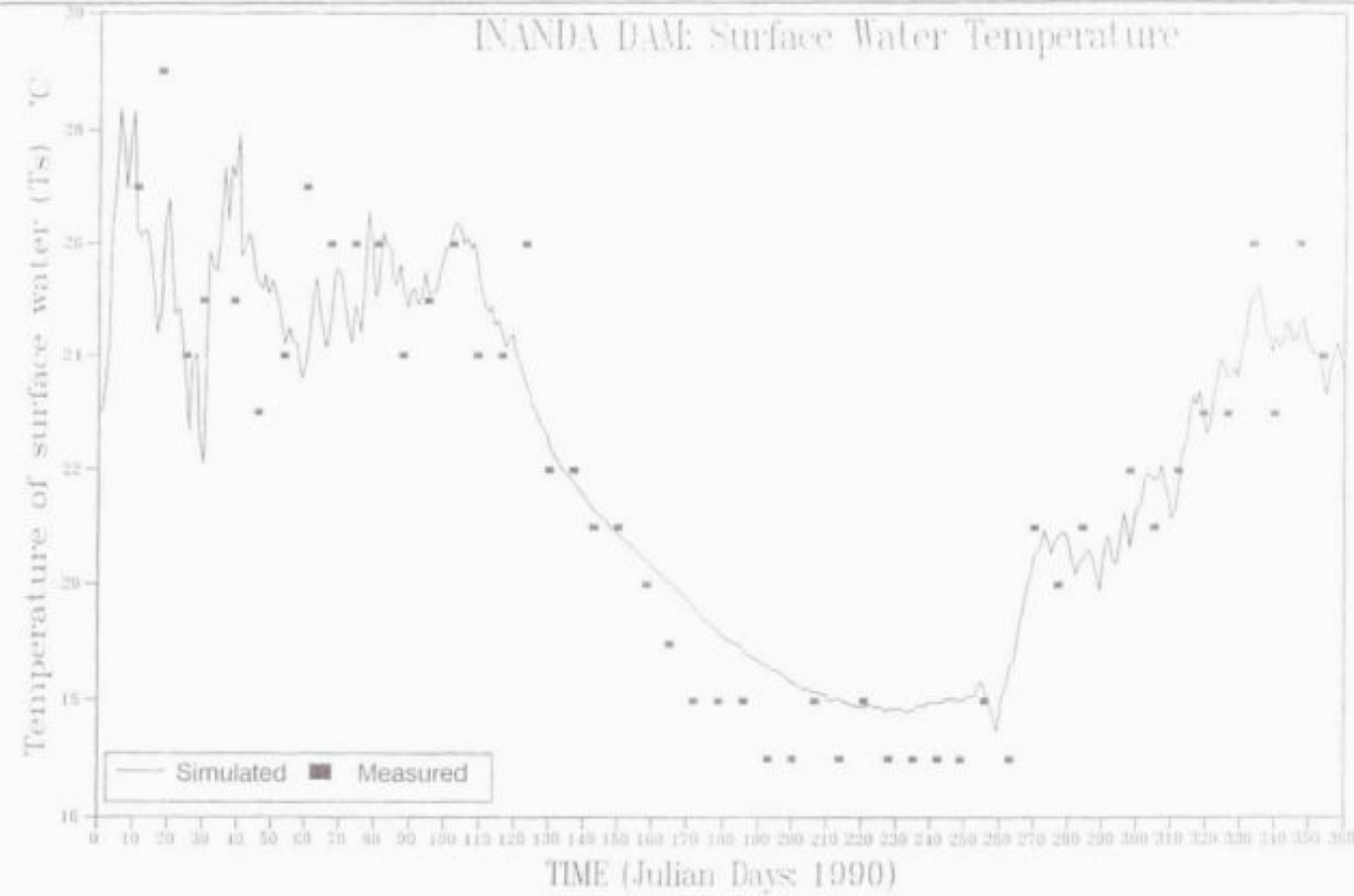
NINHAM SHAND

UNIVERSITY OF CAPE TOWN

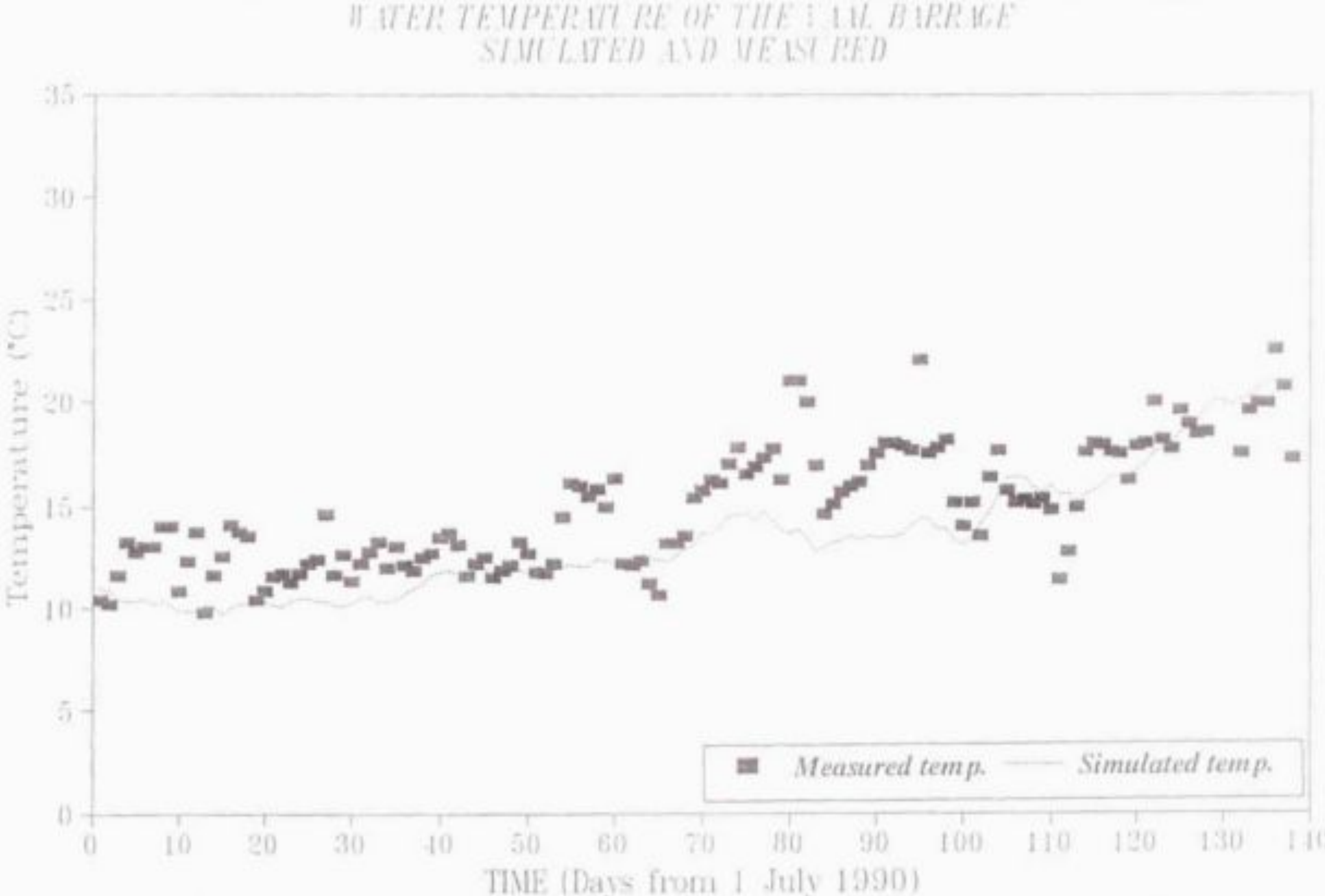
WATER RESEARCH COMMISSION

Time series plot of solar radiation and measured surface water temperature for Inanda Dam during the period January to December 1990. The solar radiation is measured at Durban Airport.

FIGURE A4.1



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Simulated and measured surface water temperature of Inanda Dam during simulation period January to December 1990. The simulated water temperature is derived using the program METDATA with adjusted solar radiation data.	FIGURE A4.2



NINHAM SHAND

UNIVERSITY OF CAPE TOWN

WATER RESEARCH COMMISSION

Simulated and measured surface water temperature of the Vaal Barrage during the simulation period 1 July to 15 November 1990. The simulated data were produced by the program METDATA.

FIGURE A4.3

6 REFERENCES:

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APPENDIX A4.2

POST PROCESSOR
PROGRAM: "POST"

By:
N van Beest and A J Bath

1. INTRODUCTION

In 1989, the hydrodynamic/salinity model DYRESM was used for the first time in South Africa to simulate the hydrosalinity in Laing Dam (Görgens and Forster, 1989). During use of the DYRESM, no computerised presentation graphical software was available to assist in the calibration and verification of the model. The program DYPLOT was developed to assist in the calibration of DYRESM. DYPLOT uses the output file from DYRESM and produces a series of depth profile plots of temperature and salinity.

2. POST PROCESSOR: "POST"

The program POST was developed as an extension of the program DYPLOT to incorporate additional graphical routines so that more complex data sets could be assessed. Changes were made to the program to allow a selection of graphical formats to be available to the user. The graphical tools include: a time series plot, a longitudinal profile plot, depth profile plot, and two-dimensional plot. In summary, Figures A4.1 to A4.5 show the format of graphical presentation output available using POST. The program POST uses an integrated menu system and dialogue boxes to help the user.

Figure A4.1 shows a time series plot for a single constituent. The time series plot allows the user to compare simulated and measured data using both lines and symbols to represent the two data sets, see Figure A4.1. For example, the plot can be used to examine the temporal variation in conductivity at a given point in a water body.

Figure A4.1

Time series plot showing the simulated and measured conductivity (tracer) in the surface layer at Segments 3 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir at the upstream end of the Vaal Barrage.

Release start day: 21

Units: mS/m
Tracer: conductivity

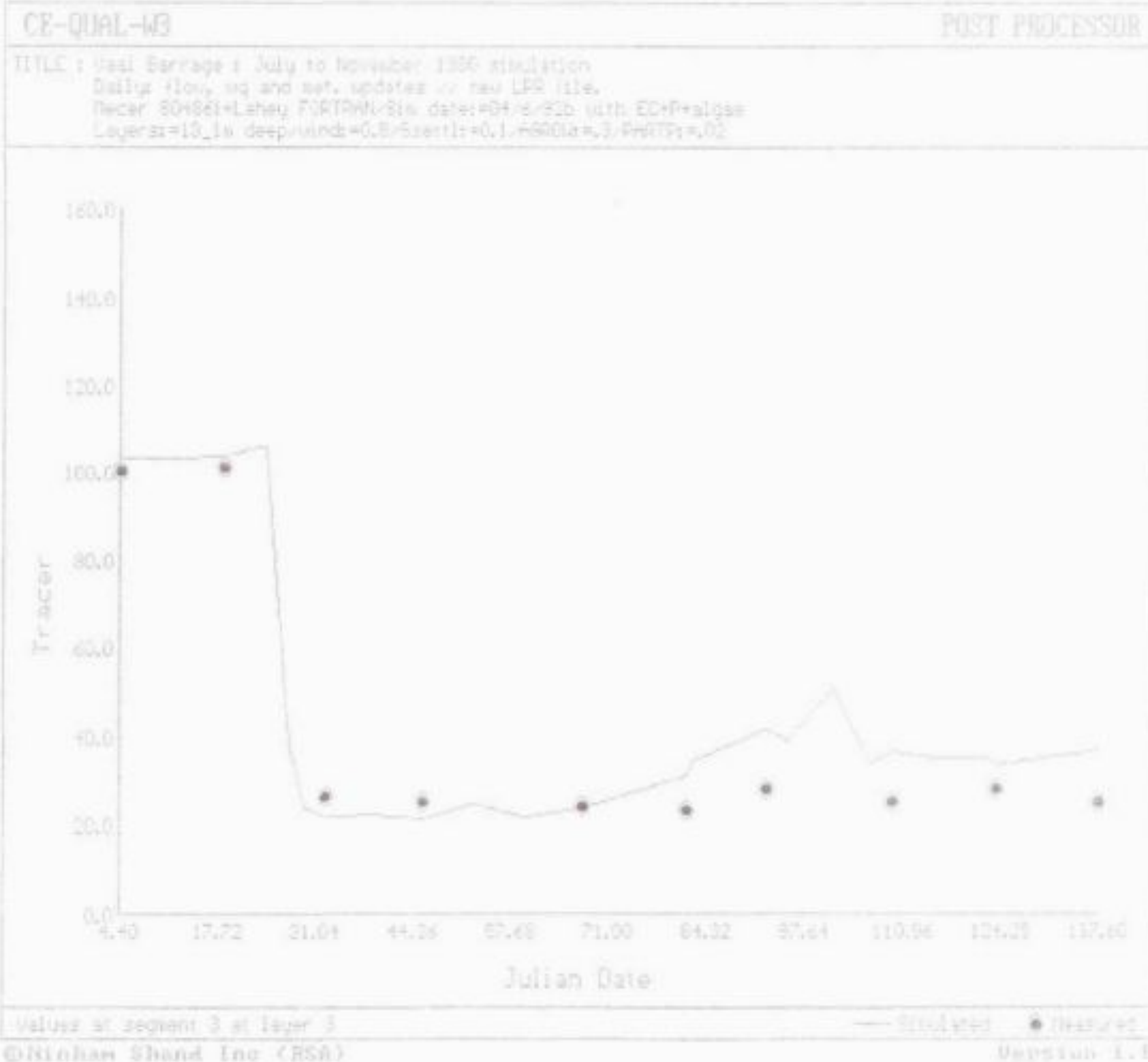

Figure A4.2

Spatial comparison plot showing the simulated and measured conductivity (tracer) in the surface layer at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and 26 at the Vaal Barrage.

Units: mS/m
Tracer: conductivity

Inflow: ▲
Withdrawal: ▼

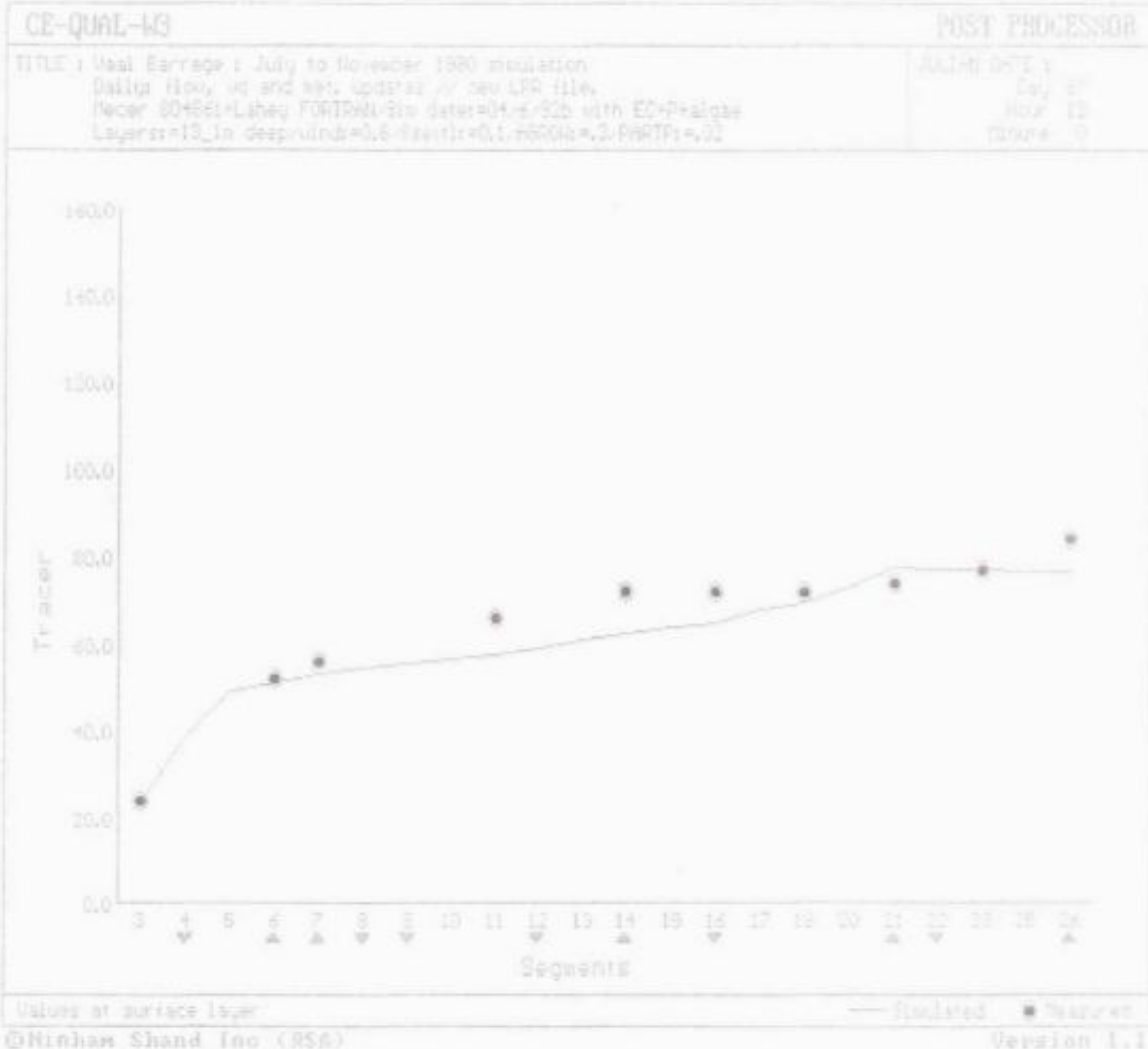

Figure A4.3

Depth profile plots for the simulated and measured conductivity (tracer) at Segment 26 in the Vaal Barrage.

Segment 26 is located at the Vaal Barrage.

Tracer: conductivity
Units: mS/m
Depth: metre

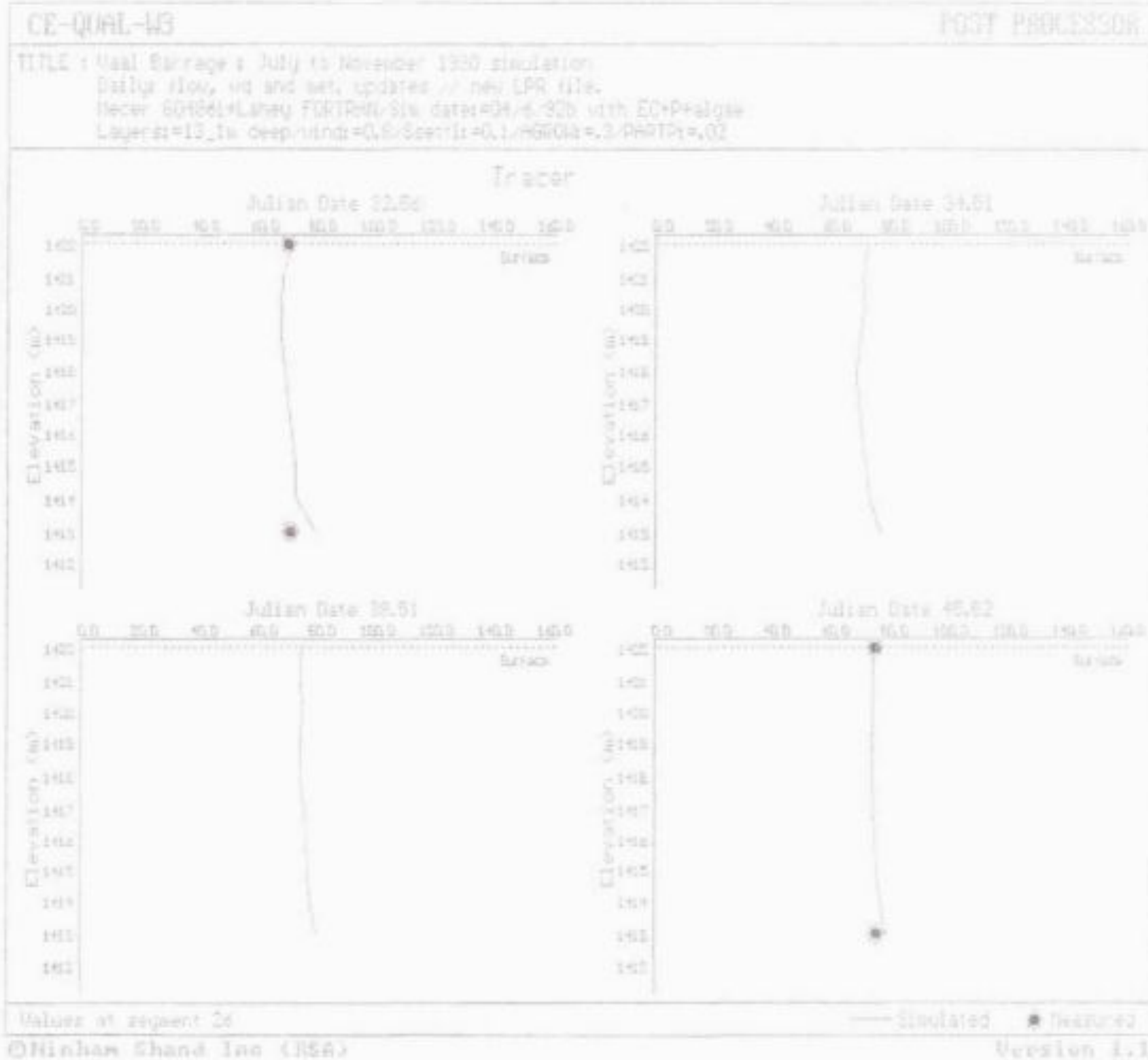

Figure A4.4

Two-dimensional plot for the simulated and measured conductivity (tracer) at all Segments and layers in the Vaal Barrage.

Simulation Day: 67

Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

Tracer: conductivity
Units: mS/m
Depth: metre

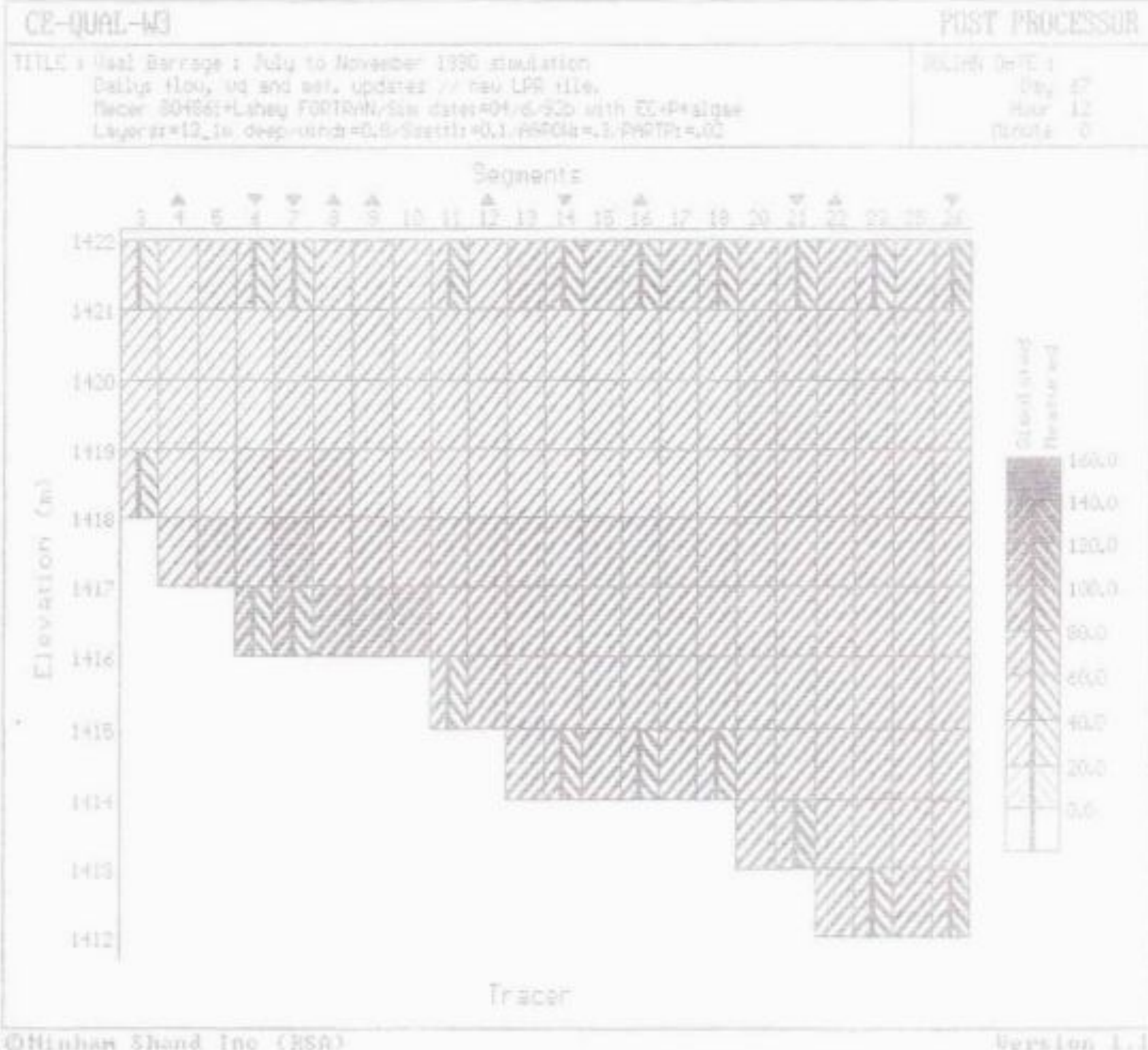

Figure A4.5

Two-dimensional plot for the simulated movement of water in the Vaal Barrage.

Simulation Day: 52

Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

Scale:
Horizontal: m/s
Vertical mm/s

Inflow: ▼
Withdrawal ▲

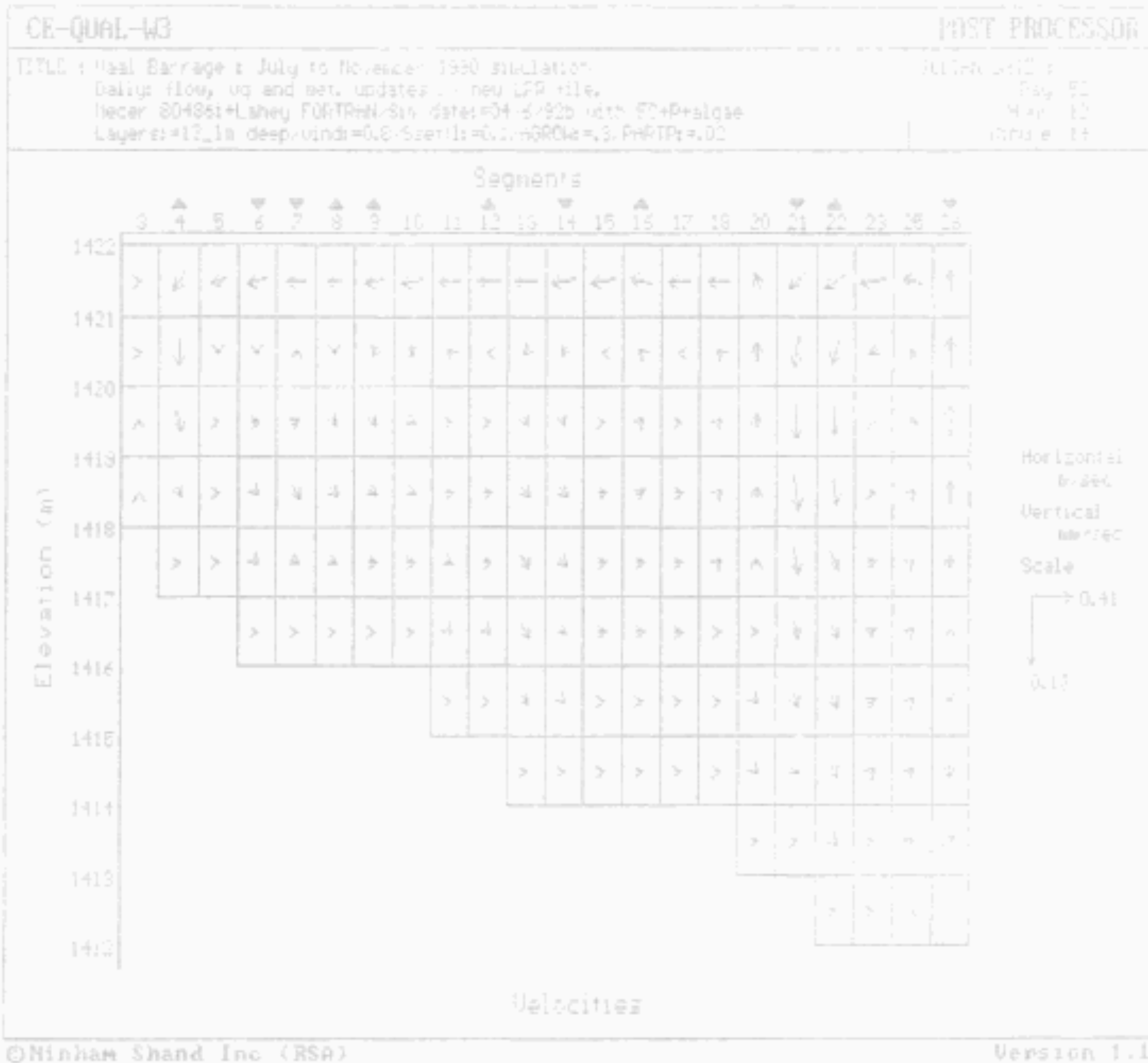

Figure A4.2 shows the longitudinal profile plot. This plot allows the presentation of data for discrete points along the length of a water body, for a given date. For example, Figure A4.2 shows the use of this plot to present the variation in conductivity along the length of the Vaal Barrage.

Figure A4.3 shows the depth profile plots. These plots are used to present measured and simulated data at specific depths, for a given point and date. For example, Figure A4.3 shows measured and simulated tracer (conductivity) data at 2 metre intervals at a given point in the Vaal Barrage.

Figure A4.4 shows the two-dimensional plot which is used to present data recorded both the longitudinal and vertical axes of a water body. The program allows (i) both simulated and measured data to be presented and (ii) allows the user to change the scale of the plot.

Figure A4.5 shows the use of the two-dimensional plot to present vector plots representing the vertical and horizontal movement of water in a water body. The program calculates the arrow symbol for given simulated horizontal and vertical velocity components.

3. REFERENCE:

Görgens, AHM and Forster SF (1989)

"Application of a hydrodynamic model to Laing Dam to investigate the impact of proposed low-salinity imports", Proceedings of the Fourth South African National Hydrological Symposium, Pretoria, November 1989.

APPENDIX A4.3

CEQUAL
INPUT DATA FILES
INANDA DAM
SIMULATION: 1 JANUARY TO 31 DECEMBER 1990

In summary the input files comprise:

Control file contains parameters used to run the model. The format of the file has been developed to take advantage of a full screen text editor. The file includes:

- Time step control
- Initial conditions
- Layer height
- Branch geometry and configuration
- Output file control
- Restart options
- Constituent computations
- Constants for the chemical, biological and physical processes.
- Filenames used for input and output data files.

Bathometric file Contains the widths of each of the active cells of each segment.

Meteorological file Contains daily data of the met. data used by the model. The data includes temperature, dew point temperature, short wave solar radiation, and surface heat exchange.

Constituent file Contains the daily data of the chemical concentration of the inflows into the impoundment. The file is repeated for each branch which has an upstream boundary condition.

Inflow files Contain the numeric values of the discharge and temperature of the inflow(s).

Outflow files Contains numeric values of the discharge of the outflows from the impoundment.

Longitudinal profile file
Contains vertical profiles for each segment used to initialize the computational grid at the start of the simulation.

Vertical profile file
Contains the vertical data for selected chemical constituents.

1. LONGITUDINAL PROFILE FILE: INANDA DAM

```
Longitudinal profile data file INANDA 90 plus grid restrictions
Segment 2
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     26.1
Segment 3
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     26.1
Segment 4
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     26.1     24.2     24.0     23.9
Segment 5
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     26.1     24.2     24.0     23.9
Segment 6
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     26.1     24.2     24.0     23.9     23.6
Segment 7
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     26.1     24.2     24.0     23.9     23.6     23.3
Segment 8
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     26.1     24.2     24.0     23.9     23.6     23.3     22.6
Segment 9
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     28.0     27.4     27.1     26.2     25.0     24.1     22.3     22.2
Segment 10
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     28.0     27.4     27.1     26.2     25.0     24.1     22.3     22.2     22.2
Segment 11
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     28.0     27.4     27.1     26.2     25.0     24.1     22.3     22.2     22.0
    21.6     21.3     21.0     21.0
Segment 12
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    30.0     28.0     27.4     27.1     26.2     25.0     24.1     22.3     22.2     22.0
    21.6     21.3     21.1     21.0
Segment 13
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    31.0     27.1     26.9     26.6     26.2     25.1     24.4     23.8     22.9     22.8
    22.6     22.3     21.9     21.5
Segment 14
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    31.0     27.1     26.9     26.6     26.2     25.1     24.4     23.8     22.9     22.8
    22.6     22.3     21.9     21.5     21.3     21.2
Segment 15
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    29.9     26.8     26.4     26.3     26.0     24.1     23.5     23.2     23.0     22.6
    21.6     21.3     21.1     20.9     20.4     20.4     20.2
Segment 16
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    29.9     26.8     26.4     26.3     26.0     24.1     23.5     23.2     23.0     22.6
    21.6     21.3     21.1     20.9     20.4     20.4     20.2     19.9
Segment 17
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    29.9     26.8     26.4     26.3     26.0     24.1     23.5     23.2     23.0     22.6
    21.6     21.3     21.1     20.9     20.4     20.4     20.2     19.9     19.9
Segment 18
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    29.9     26.8     26.4     26.3     26.0     24.1     23.5     23.2     23.0     22.6
    21.6     21.3     21.1     20.9     20.4     20.4     20.2     19.9     19.9
Segment 19
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    29.9     26.8     26.4     26.3     26.0     24.1     23.5     23.2     23.0     22.6
    21.6     21.3     21.1     20.9     20.4     20.4     20.2     19.9     19.9
Segment 20
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    29.9     26.8     26.4     26.3     26.0     24.1     23.5     23.2     23.0     22.6
    21.6     21.3     21.1     20.9     20.4     20.4     20.2     19.9     19.9
Segment 21
TEMP LPR       T1       T1       T1       T1       T1       T1       T1       T1       T1
    28.1     27.4     26.3     24.9     23.6     21.9     20.9     20.8     20.5     20.4
    20.4     20.3     20.2     20.2     20.2     20.0     20.0     20.0     19.9
```

2. CONTROL FILE FOR CEQUAL SIMULATION: VAAL BARRAGE

```
Inanda Dam control file for CE-QUAL-W2

TITLE C ...............................TITLE.....................................
        Inanda Reservoir simulation: January to December 1990
        Daily met.flow & quality updates/WIND:=0.2/PO4rel=0.003/SOD=.5
        Mecer 80486! using Lahey FORTRAN// Simulation with trib at 5+9
        26 layers & segs//PartP=0.005//SSetl=0.4/AGROW=0.3//Run:=5/6/92 C

TIME CON  TMSTRT   TMEND
             1.5   201.5

DLT CON     NDLT  MINDLT
               1    60.0
DLT DATE    DLTD    DLTD    DLTD    DLTD    DLTD    DLTD    DLTD    DLTD    DLTD
             1.5
DLT MAX   DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX
         10800.0
DLT FRN     FDLT    FDLT    FDLT    FDLT    FDLT    FDLT    FDLT    FDLT    FDLT
             0.9
SURFACE       KT      IZ   DATUM
               4    0.72  101.00
HEIGHT         H       H       H       H       H       H       H       H       H
             2.0     2.0     2.0     2.0     2.0     2.0     2.0     2.0     2.0
             2.0     2.0     2.0     2.0     2.0     2.0     2.0     2.0     2.0
             2.0     2.0     2.0     2.0     2.0     2.0     2.0     2.0
ORIENT      PHIO    PHIO    PHIO    PHIO    PHIO    PHIO    PHIO    PHIO    PHIO
           2.854   2.854   1.695   2.320   2.728   2.964   2.964   3.118   2.111
           1.994   0.995   5.661   0.545   1.370   1.685   2.597   2.919   3.498
           2.950   2.561   2.634   2.514   3.270   3.244   3.979   3.979
BRANCH G      US      DS     UHS     DHS     DLX
               2      25       0       0   747.7
INIT CND   ITEMP  IICETH   WTYPE
            -2.0     0.0   FRESH
CALCULAT   VOLBC   PQINC   EVAPC    ICEC  PRCIPC   WINDC    QINC   QOUTC   HTEXC
             OFF      ON     OFF     OFF     OFF      ON      ON      ON      ON
WSC NUMB    NWSC
               1
WSC DATE    WSCD    WSCD    WSCD    WSCD    WSCD    WSCD    WSCD    WSCD    WSCD
             1.5    40.5
WSC COEF     WSC     WSC     WSC     WSC     WSC     WSC     WSC     WSC     WSC
             0.2
HYD COEF      AX     IDX   FAZDZ   CHEZY
            10.0     1.0    0.14    70.0
N OUTLET    NOUT    NOUT    NOUT    NOUT    NOUT    NOUT    NOUT    NOUT    NOUT
               1
O LAYER     KOUT    KOUT    KOUT    KOUT    KOUT    KOUT    KOUT    KOUT    KOUT
              23
WDR COMP    NWDC
             OFF
W SEGMNT     IWD     IWD     IWD     IWD     IWD     IWD     IWD     IWD     IWD
               0
W LAYER      KWD     KWD     KWD     KWD     KWD     KWD     KWD     KWD     KWD
               0
TRB COMP  NTRIBC
              ON
TRIB SEG   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB
               5       9
DST TRIB  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC
             OFF
SNAPSHOT    FORM     HPR     HPR     HPR
            LONG     OFF     OFF      ON
SHRT SEG   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF
               2       3       6       9      13      15      17      20      25
LONG SEG   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF
               2       3       5       6       8       9      10      11      13
              14      15      17      19      20      22      24      25
SNP PRNT    SNPC    NSNP
              ON      30
SNP DATE    SNPD    SNPD    SNPD    SNPD    SNPD    SNPD    SNPD    SNPD    SNPD
             4.5    11.5    18.5    25.5    32.5    39.5    46.5    53.5    60.5
            67.5    74.5    80.5    88.5    95.5   102.5   109.5   116.5   123.5
           130.5   137.5   143.5   150.5   158.5   172.5   186.5   200.5   221.5
           235.5   249.5   263.5
SNP FREQ    SNPF    SNPF    SNPF    SNPF    SNPF    SNPF    SNPF    SNPF    SNPF
           100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0
```

	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
	100.0	100.0	100.0						
PST PRNT	PSTC	NPST	NPSTST						
	ON	30	24						
PST DATE	PSTD	PSTD	PSTD	PSTD	PSTD	PSTD	PSTD	PSTD	PSTD
	4.5	11.5	18.5	25.5	32.5	39.5	46.5	53.5	60.5
	67.5	74.5	80.5	88.5	95.5	102.5	109.5	116.5	123.5
	130.5	137.5	143.5	150.5	158.5	172.5	186.5	200.5	221.5
	235.5	249.5	263.5						
PST SEG	NPSTSG	NPSTSG	NPSTSG	NPSTSG	NPSTSG	NPSTSG	NPSTSG	NPSTSG	NPSTSG
	2	3	4	5	6	7	8	9	10
	11	12	13	14	15	16	17	18	19
	20	21	22	23	24	25			
RESTART	RSOC	NRSO	RSIC						
	OFF	4	OFF						
RSO DATE	RSOD	RSOD	RSOD	RSOD	RSOD	RSOD	RSOD	RSOD	RSOD
	124.5	200.5	273.5	315.5					
CST COMP	CCOMPC								
	ON								
CST ACT	ACC	ACC	ACC	ACC	ACC	ACC	ACC	ACC	ACC
	OFF	ON	ON	OFF	ON	ON	ON	ON	ON
	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
	OFF	OFF							
CST ICON	CIC	CIC	CIC	CIC	CIC	CIC	CIC	CIC	CIC
	0.0	-2.0	0.0001	-1.0	2.022	0.867	-2.0	0.667	-1.0
	-1.0	-1.0	-2.0	0.0	10.00	30.0	7.0	0.0	0.0
	0.0	0.1							
CST PRNT	CPR	CPR	CPR	CPR	CPR	CPR	CPR	CPR	CPR
	OFF	ON	ON	OFF	ON	ON	ON	ON	ON
	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
	OFF	OFF							
CST UPDT	KFREQU	RFREQU							
	12	24							
CIN CON	INACC	INACC	INACC	INACC	INACC	INACC	INACC	INACC	INACC
	OFF	ON	ON	ON	ON	ON	ON	ON	ON
	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
	OFF	OFF							
CTR CON	TRACC	TRACC	TRACC	TRACC	TRACC	TRACC	TRACC	TRACC	TRACC
	OFF	ON	ON	ON	ON	ON	ON	ON	ON
	ON	ON	ON	OFF	OFF	OFF	OFF	OFF	OFF
	OFF	OFF							
CDT CON	DTACC	DTACC	DTACC	DTACC	DTACC	DTACC	DTACC	DTACC	DTACC
	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	OFF	OFF							
CPR CON	PRACC	PRACC	PRACC	PRACC	PRACC	PRACC	PRACC	PRACC	PRACC
	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF	OFF
	OFF	OFF							
EX COEF	EXH2O	EXINOR	EXORG	BETA					
	0.75	0.15	0.3	0.45					
COLIFORM	COLQ10	COLDK							
	1.04	1.4							
S SOLIDS	SSETL								
	0.4								
DOMDECAY	LABDK	LRFDK	REFDK	LDT1	LDT2				
	0.12	0.01	0.001	2.0	20.0				
ALGAE	AGROW	AMORT	AEXCR	ARESP	ASETL	ASATUR	ALGDET		
	0.30	0.001	0.01	0.02	0.00	30.0	0.80		
ALG TEMP	AGT1	AGT2	AGT3	AGT4					
	10.0	26.0	30.0	35.0					
DETRITUS	DETDK	DSETL	DDT1	DDT2					
	0.06	0.50	4.0	30.0					
PHOSPHOR	PO4REL	PARTP	AHSP						
	0.003	0.005	0.006						
AMMONIA	NH3REL	NH3DK	PARTN	AHSN	NH3DT1	NH3DT2			
	0.18	0.05	0.05	0.080	2.0	32.0			
NITRATE	NO3DK	NO3DT1	NO3DT2						
	0.25	2.0	32.0						
SEDIMENT	SEDDK	SDT1	SDT2	SDT3	SDT4	CO2REL			
	0.06	0.0	5.0	35.0	40.0	0.1			
S DEMAND	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD	SOD
	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	
IRON	FEREL	FESETL							
	0.5	2.0							

```
STOICHMT   O2NH3   O2DET  O2RESP   O2ALG   O2LAB    BIOP    BION    BIOC
            4.57     1.4     1.1     1.4     1.4   0.011    0.08    0.45
O2 LIMIT   O2LIM
           0.000
VPR FILE................................VPRFN....................................
        INVPR.NPT
LPR FILE................................LPRFN....................................
        INLPR.NPT
RSI FILE................................RSIFN....................................
        INRSI.NPT
MET FILE................................METFN....................................
        INMET.NPT
QWD FILE................................QWDFN....................................
        not used
QIN FILE................................QINFN....................................
        INQIN.NPT
TIN FILE................................TINFN....................................
        INTIN.NPT
QDT FILE................................QDTFN....................................
        not used
TDT FILE................................TDTFN....................................
        not used
PRE FILE................................PREFN....................................
        not used
TPR FILE................................TPRFN....................................
        not used
EUH FILE................................EUPFN....................................
        not used
EDH FILE................................EDNFN....................................
        not used
QOT FILE................................QOTFN....................................
BR01    INQOT.NPT
CIN FILE................................CINFN....................................
BR01    INCIN.NPT
CDT FILE................................CDTFN....................................
BR01    not used
CPR FILE................................CPRFN....................................
BR01    not used
TUH FILE................................TUPFN....................................
BR01    not used
CUH FILE................................CUPFN....................................
BR01    not used
TDH FILE................................TDNFN....................................
BR01    not used
CDH FILE................................CDNFN....................................
BR01    not used
QTR FILE................................QTRFN....................................
        INQTR.NPT
TTR FILE................................TTRFN....................................
        INTTR.NPT
CTR FILE................................CTRFN....................................
        INCTR.NPT
SNP FILE................................SNPFN....................................
        INSNAP.OPT
PST FILE................................PSTFN....................................
        INPOST.OPT
RSO FILE................................RSOFN....................................
        INRSO.OPT
```

3. VERTICAL PROFILE FILE: INANDA DAM SIMULATION

```
CE-QUAL-W2 Vertical profiles for Inanda 1990

TDS            C1      C1      C1      C1      C1      C1      C1      C1      C1
            143.0   143.0   143.0   143.0   143.0   143.0   143.0   143.0   143.0
            145.0   148.0   149.0   155.0   157.0   160.0   170.0   175.0   177.0
            280.0  1000.0  1100.0  1111.0

PO4            C1      C1      C1      C1      C1      C1      C1      C1      C1
            0.010   0.010   0.010   0.010   0.010   0.010   0.010   0.010   0.010
            0.010   0.010   0.010   0.010   0.010   0.030   0.050   0.050   0.050
            0.050   0.050   0.050   0.050

NH4            C1      C1      C1      C1      C1      C1      C1      C1      C1
             0.05    0.05    0.05    0.05    0.05    0.05    0.05    0.05    0.05
             0.05    0.05    0.05    0.05    0.05    0.05    0.06    0.07    0.07
             0.10    0.10    0.10    0.10

NO3            C1      C1      C1      C1      C1      C1      C1      C1      C1
              0.5     0.6     0.6     0.6     0.6     0.6     0.6     0.6     0.6
              0.6     0.6     0.6     0.6     0.6     0.6     0.6     0.6     0.6
              1.1     1.1     1.1     1.1
```

4. WATER QUALITY DATA FILE: INANDA DAM CHEMICAL DATA FOR UPSTREAM BOUNDARY: UMGENI RIVER

INANDA DAM constituent inflow data file for 1990 (4 june 92)

JDAY	Ssolids	Clfrm	Dsolid	L DOM	R DOM	Algae	Detrit	PO4	NH4	NO3	O2
1.0	38.4	0.005	132.2	0.86	1.260	0.15	0.5	0.07	0.01	1.00	7.1
2.0	31.3	0.005	132.2	0.86	1.260	0.15	0.4	0.07	0.01	1.00	6.5
3.0	55.2	0.007	123.5	1.22	1.260	0.15	0.6	0.06	0.01	1.00	6.2
4.0	31.3	0.005	132.2	0.86	1.260	0.15	0.4	0.07	0.01	1.06	6.3
5.0	31.4	0.005	132.1	0.87	1.260	0.15	0.4	0.07	0.01	1.06	6.8
6.0	31.4	0.005	132.1	0.87	1.260	0.15	0.4	0.07	0.01	1.06	4.2
7.0	28.9	0.004	138.0	0.68	1.260	0.15	0.4	0.07	0.01	1.06	7.8
8.0	28.9	0.004	137.9	0.68	1.260	0.15	0.4	0.07	0.01	1.06	9.0
9.0	29.0	0.004	137.9	0.69	1.260	0.15	0.4	0.07	0.01	1.06	7.8
10.0	40.6	0.005	132.0	0.87	1.260	0.15	0.5	0.07	0.01	1.06	7.2
11.0	28.9	0.004	137.9	0.69	1.260	0.15	0.4	0.07	0.08	1.22	8.0
12.0	53.0	0.006	127.2	1.05	1.260	0.15	0.6	0.06	0.08	1.22	6.7
13.0	28.9	0.004	137.8	0.69	1.260	0.15	0.4	0.07	0.08	1.22	5.9
14.0	26.4	0.003	145.5	0.50	1.260	0.15	0.3	0.08	0.08	1.22	6.9
15.0	38.3	0.004	137.8	0.69	1.260	0.15	0.5	0.07	0.08	1.22	5.9
16.0	78.2	0.008	119.8	1.42	1.260	0.15	0.9	0.06	0.08	1.22	5.8
17.0	22.6	0.001	165.6	0.22	1.260	0.15	0.3	0.11	0.08	1.22	6.0
18.0	46.4	0.003	141.5	0.59	1.260	0.15	0.5	0.08	0.04	1.14	5.1
19.0	211.5	0.013	106.5	2.44	1.260	0.15	1.6	0.05	0.04	1.14	5.2
20.0	265.8	0.014	104.9	2.60	1.260	0.15	0.7	0.05	0.04	1.14	7.4
21.0	728.2	0.033	82.3	6.46	1.260	0.15	3.4	0.03	0.04	1.14	7.4
22.0	82.1	0.007	122.6	1.27	1.260	0.15	0.4	0.06	0.04	1.14	6.6
23.0	26.7	0.003	144.6	0.52	1.260	0.15	0.3	0.08	0.04	1.14	5.5
24.0	38.7	0.004	137.0	0.71	1.260	0.15	0.5	0.07	0.04	1.14	6.0
25.0	65.8	0.006	126.5	1.09	1.260	0.15	0.6	0.06	0.05	1.79	7.1
26.0	82.1	0.007	122.5	1.27	1.260	0.15	0.5	0.06	0.05	1.79	5.6
27.0	33.3	0.006	128.3	1.01	1.260	0.15	0.4	0.06	0.05	1.79	6.2
28.0	30.8	0.005	133.4	0.82	1.260	0.15	0.4	0.07	0.05	1.79	6.5
29.0	28.2	0.004	139.8	0.63	1.260	0.15	0.3	0.08	0.05	1.79	6.2
30.0	104.8	0.010	114.5	1.76	1.260	0.15	1.1	0.05	0.05	1.79	5.5
31.0	30.8	0.005	133.3	0.82	1.260	0.15	0.4	0.07	0.05	1.79	5.3
32.0	105.4	0.005	131.5	0.89	1.260	0.15	0.4	0.07	0.03	1.31	4.7
33.0	120.6	0.007	121.5	1.33	1.260	0.15	0.7	0.06	0.03	1.31	5.3
34.0	30.8	0.005	133.3	0.83	1.260	0.15	0.4	0.07	0.03	1.31	5.9
35.0	28.2	0.004	139.7	0.64	1.260	0.15	0.3	0.08	0.03	1.31	6.2
36.0	25.6	0.003	148.5	0.45	1.260	0.15	0.3	0.09	0.03	1.31	5.8
37.0	63.0	0.006	128.1	1.02	1.260	0.15	0.7	0.06	0.03	1.31	6.5
38.0	30.8	0.005	133.2	0.83	1.260	0.15	0.4	0.07	0.03	1.31	6.5
39.0	360.3	0.004	140.2	0.62	1.260	0.15	0.3	0.08	0.01	0.42	6.6
40.0	105.7	0.010	114.5	1.76	1.260	0.15	1.2	0.05	0.01	0.42	6.2
41.0	41.3	0.009	117.2	1.58	1.260	0.15	0.5	0.05	0.01	0.42	7.2
42.0	33.3	0.006	128.3	1.01	1.260	0.15	0.4	0.06	0.01	0.42	7.8
43.0	33.3	0.006	128.3	1.01	1.260	0.15	0.4	0.06	0.01	0.42	7.8
44.0	30.7	0.005	133.5	0.82	1.260	0.15	0.4	0.07	0.01	0.42	7.5
45.0	199.0	0.007	124.0	1.20	1.260	0.15	0.6	0.06	0.01	0.42	7.3
46.0	824.9	0.011	111.7	1.97	1.260	0.15	1.0	0.05	0.05	1.00	6.6
47.0	60.1	0.012	109.4	2.17	1.260	0.15	0.7	0.05	0.05	1.00	7.0
48.0	50.3	0.012	109.3	2.18	1.260	0.15	0.6	0.05	0.05	1.00	7.1
49.0	47.1	0.011	111.5	1.99	1.260	0.15	0.6	0.05	0.05	1.00	6.2
50.0	47.1	0.011	111.5	1.99	1.260	0.15	0.6	0.05	0.05	1.00	5.1
51.0	48.3	0.011	111.3	2.01	1.260	0.15	0.6	0.05	0.05	1.00	5.2
52.0	39.0	0.008	119.9	1.42	1.260	0.15	0.5	0.06	0.05	1.00	6.0
53.0	70.7	0.007	123.5	1.22	1.260	0.15	0.4	0.06	0.05	0.95	8.8
54.0	62.5	0.009	116.6	1.62	1.260	0.15	0.7	0.05	0.05	0.95	8.2
55.0	36.4	0.007	123.5	1.23	1.260	0.15	0.4	0.06	0.05	0.95	7.3
56.0	36.6	0.007	123.4	1.23	1.260	0.15	0.4	0.06	0.05	0.95	6.9
57.0	434.2	0.010	113.6	1.82	1.260	0.15	0.9	0.05	0.05	0.95	7.5
58.0	618.9	0.015	102.0	2.92	1.260	0.15	1.3	0.04	0.05	0.95	7.1
59.0	32.4	0.005	130.1	0.94	1.260	0.15	0.4	0.07	0.05	0.95	7.1
60.0	97.0	0.004	135.9	0.74	1.260	0.15	0.4	0.07	0.03	1.24	6.3
61.0	58.0	0.007	124.6	1.17	1.260	0.15	0.7	0.06	0.03	1.24	6.3
62.0	32.9	0.005	129.1	0.98	1.260	0.15	0.4	0.06	0.03	1.24	5.8
63.0	29.4	0.004	136.6	0.72	1.260	0.15	0.4	0.07	0.03	1.24	6.2
64.0	115.5	0.008	119.9	1.42	1.260	0.15	0.9	0.06	0.03	1.24	7.6
65.0	139.4	0.012	108.9	2.21	1.260	0.15	1.0	0.05	0.03	1.24	7.2
66.0	301.5	0.029	85.9	5.60	1.260	0.15	3.0	0.03	0.03	1.24	7.4
67.0	193.7	0.032	83.3	6.21	1.260	0.15	1.5	0.03	0.05	1.03	8.0
68.0	91.2	0.026	88.8	4.97	1.260	0.15	1.0	0.04	0.05	1.03	7.4
69.0	89.4	0.025	89.5	4.85	1.260	0.15	1.0	0.04	0.05	1.03	5.6
70.0	82.9	0.023	91.7	4.42	1.260	0.15	0.9	0.04	0.05	1.03	7.5

5. METEOROLOGICAL DATA : INANDA DAM

CE-QUAL-W2 Met file for Inanda Dam 1990 V. 265565

JDAY	ET	TD	WINDSP	PHI	CSHE	SRO
1.0	24.9	5.3	0.5	1.57	3.64E-06	7.80E-05
2.0	27.1	5.2	0.4	4.01	3.64E-06	9.30E-05
3.0	33.5	5.1	0.1	2.27	3.65E-06	1.38E-04
4.0	31.2	5.1	0.3	1.57	3.71E-06	1.16E-04
5.0	32.5	4.9	0.4	1.57	3.75E-06	1.24E-04
6.0	26.3	4.8	0.3	1.57	3.77E-06	7.38E-05
7.0	23.5	4.5	0.4	4.01	3.76E-06	5.51E-05
8.0	30.5	4.5	0.2	1.57	3.72E-06	1.10E-04
9.0	30.5	4.9	0.5	1.57	3.78E-06	1.08E-04
10.0	19.0	4.7	0.3	4.01	3.77E-06	1.84E-05
11.0	25.5	4.8	0.2	1.57	3.71E-06	7.35E-05
12.0	26.4	5.1	0.2	1.57	3.71E-06	8.04E-05
13.0	26.4	5.2	0.3	2.27	3.72E-06	7.96E-05
14.0	22.9	5.1	0.2	0.00	3.71E-06	5.36E-05
15.0	20.7	5.1	0.4	1.57	3.71E-06	3.95E-05
16.0	20.3	5.0	0.3	1.57	3.68E-06	3.88E-05
17.0	27.8	5.0	0.4	1.57	3.67E-06	9.64E-05
18.0	37.8	5.1	0.5	1.57	3.70E-06	1.68E-04
19.0	31.5	5.3	0.5	0.87	3.74E-06	1.18E-04
20.0	17.0	4.8	0.3	4.01	3.73E-06	8.92E-06
21.0	16.3	4.9	0.1	1.57	3.69E-06	7.46E-06
22.0	25.8	5.1	0.4	1.57	3.68E-06	8.05E-05
23.0	20.1	4.9	0.4	4.01	3.68E-06	3.88E-05
24.0	15.4	5.2	0.1	1.57	3.66E-06	4.53E-06
25.0	16.1	5.1	0.2	0.87	3.63E-06	1.34E-05
26.0	31.5	5.1	0.4	3.14	3.62E-06	1.28E-04
27.0	24.9	5.2	0.1	3.14	3.64E-06	7.53E-05
28.0	16.9	5.3	0.1	0.00	3.65E-06	1.63E-05
29.0	20.4	5.3	0.5	1.57	3.63E-06	4.71E-05
30.0	32.4	5.4	0.5	1.57	3.62E-06	1.35E-04
31.0	31.8	5.3	0.4	1.57	3.67E-06	1.25E-04
32.0	24.4	5.3	0.2	1.57	3.70E-06	6.58E-05
33.0	25.5	5.2	0.5	1.57	3.71E-06	7.50E-05
34.0	29.7	5.2	0.5	0.87	3.71E-06	1.06E-04
35.0	30.9	5.2	0.3	0.87	3.73E-06	1.12E-04
36.0	22.9	5.1	0.2	2.27	3.74E-06	4.95E-05
37.0	31.1	5.1	0.3	2.27	3.72E-06	1.14E-04
38.0	26.4	5.1	0.3	2.27	3.75E-06	7.61E-05
39.0	30.7	5.2	0.5	1.57	3.76E-06	1.09E-04
40.0	17.9	5.3	0.1	4.01	3.76E-06	9.57E-06
41.0	26.7	5.1	0.4	4.01	3.71E-06	8.33E-05
42.0	28.4	4.8	0.3	4.01	3.70E-06	9.65E-05
43.0	24.2	4.9	0.1	0.00	3.70E-06	6.46E-05
44.0	17.9	5.0	0.1	2.27	3.70E-06	1.76E-05
45.0	22.3	4.9	0.4	0.87	3.70E-06	5.28E-05
46.0	23.8	5.2	0.3	4.01	3.69E-06	6.35E-05
47.0	30.0	5.1	0.3	2.27	3.69E-06	1.10E-04
48.0	18.6	5.0	0.2	2.27	3.69E-06	2.53E-05
49.0	29.9	5.0	0.3	1.57	3.69E-06	1.09E-04
50.0	21.6	5.4	0.4	1.57	3.71E-06	4.61E-05
51.0	19.9	5.3	0.1	3.14	3.68E-06	3.46E-05
52.0	18.2	5.2	0.3	4.01	3.68E-06	2.32E-05
53.0	17.8	4.7	0.1	3.14	3.65E-06	2.32E-05
54.0	30.7	5.0	0.2	2.27	3.65E-06	1.18E-04
55.0	19.1	4.7	0.2	4.01	3.65E-06	3.33E-05
56.0	23.6	5.1	0.1	2.27	3.65E-06	6.50E-05
57.0	18.0	4.9	0.2	0.00	3.65E-06	2.52E-05
58.0	19.4	5.0	0.1	2.27	3.64E-06	3.66E-05
59.0	28.1	5.0	0.3	0.87	3.64E-06	1.00E-04
60.0	34.2	5.2	0.2	2.27	3.64E-06	1.44E-04
61.0	38.2	5.2	0.1	2.27	3.66E-06	1.71E-04
62.0	29.9	5.3	0.3	2.27	3.69E-06	1.08E-04
63.0	16.3	5.5	0.2	4.01	3.69E-06	6.38E-06
64.0	15.9	5.0	0.1	0.00	3.67E-06	6.81E-06
65.0	19.6	5.1	0.3	1.57	3.67E-06	3.53E-05
66.0	33.0	4.8	0.1	2.27	3.65E-06	1.35E-04
67.0	37.2	4.6	0.2	2.27	3.66E-06	1.65E-04
68.0	29.6	5.0	0.2	0.87	3.68E-06	1.06E-04
69.0	25.1	5.3	0.2	4.01	3.69E-06	7.13E-05
70.0	18.1	5.2	0.2	2.27	3.69E-06	2.06E-05
71.0	18.2	5.2	0.1	2.27	3.68E-06	2.23E-05

6. BATHYMETRIC DATA : INANDA DAM

```
Bathymet. file for Inanda Dam - 26 layer structure: (V. 19 may 92)

Segment 1
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 2
      0.    120     108.     80.     10.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 3
      0.    140.    134.    123.     61.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 4
      0.    140.    133.    122.    110.     86.     73.     56.      0.      0.
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 5
      0.    480.    402.    318.    233.    194.    166.     70.      0.      0.
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 6
      0.    560.    512.    456.    362.    260.    226.    212.    129.      0.
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 7
      0.    400.    377.    345.    309.    245.    178.    142.    120.     50.
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 8
      0.    690.    670.    630.    590.    550.    530.    415.    300.    250.
    200.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 9
      0.    520.    478.    434.    360.    343.    330.    281.    228.    197.
    156.     75.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 10
      0.    700.    616.    560.    500.    442.    384.    321.    258.    217.
    186.    154.     66.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 11
      0.    570.    554.    533.    509.    480.    434.    395.    373.    314.
    245.    212.    186.    143.     71.     30.     10.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 12
      0.    980.    960.    940.    910.    890.    870.    855.    820.    790.
    755.    660.    250.    210.    190.     50.     50.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 13
      0.   1120.   1096.   1058.   1011.    978.    957.    919.    880.    838.
    792.    728.    515.    267.    198.    169.     25.      0.      0.      0.
      0.      0.      0.      0.      0.      0.

Segment 14
      0.    990.    968.    934.    908.    879.    853.    821.    784.    747.
    708.    665.    617.    524.    406.    309.    226.    105.     76.      0.
      0.      0.      0.      0.      0.      0.

Segment 15
      0.    970.    951.    904.    862.    815.    775.    734.    693.    649.
    606.    569.    527.    485.    400.    240.    125.    110.     85.     10.
```

```
     0.      0.      0.      0.      0.      0.

Segment 16
     0.   1200.   1115.   1084.   1054.   1020.    983.    953.    926.    902.
   879.    849.    809.    768.    686.    503.    310.    303.    280.    131.
    97.      0.      0.      0.      0.      0.

Segment 17
     0.   1100.   1050.   1000.    980.    960.    940.    910.    890.    870.
   840.    820.    780.    750.    680.    660.    610.    450.    320.    250.
   100.     50.      0.      0.      0.      0.

Segment 18
     0.   1480.   1436.   1363.   1296.   1227.   1160.   1105.   1048.    984.
   927.    883.    829.    769.    723.    669.    601.    513.    440.    340.
   230.     25.      0.      0.      0.      0.

Segment 19
     0.   1340.   1311.   1280.   1270.   1250.   1189.   1135.   1089.   1044.
  1011.    966.    909.    855.    795.    724.    644.    560.    492.    428.
   315.     50.      0.      0.      0.      0.

Segment 20
     0.   1780.   1720.   1662.   1599.   1540.   1484.   1423.   1380.   1328.
  1289.   1237.   1168.   1097.   1008.    849.    711.    635.    521.    444.
   399.    234.      0.      0.      0.      0.

Segment 21
     0.    780.    760.    750.    740.    720.    710.    670.    650.    630.
   610.    580.    550.    530.    500.    460.    430.    390.    310.    250.
   230.    200.      0.      0.      0.      0.

Segment 22
     0.    750.    737.    725.    715.    705.    695.    685.    669.    654.
   630.    596.    572.    550.    520.    488.    455.    420.    381.    281.
   202.    185.    122.      0.      0.      0.

Segment 23
     0.    730.    710.    680.    670.    650.    620.    600.    575.    560.
   540.    525.    500.    480.    460.    430.    400.    380.    340.    290.
   240.    220.    150.     20.     20.      0.

Segment 24
     0.    840.    820.    780.    750.    731.    695.    665.    630.    600.
   569.    540.    519.    499.    470.    436.    411.    380.    342.    290.
   247.    198.    135.     60.     20.      0.

Segment 25
     0.    610.    590.    575.    540.    530.    505.    495.    470.    460.
   445.    435.    425.    400.    365.    350.    335.    320.    290.    280.
   250.    225.    180.    100.     45.      0.

Segment 26
     0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
     0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
     0.      0.      0.      0.      0.      0.
```

7. RELEASE HYDROGRAPH DATA: INANDA DAM

CE-QUAL-W2 Outflow Inanda 1990

JDAY	QOUT	QOUT	QOUT	QOUT	QOUT	QOUT	QOUT
1.000	1.140						
2.000	1.140						
3.000	1.140						
4.000	1.140						
5.000	1.140						
6.000	1.140						
7.000	1.140						
8.000	1.140						
9.000	1.140						
10.000	1.140						
11.000	1.140						
12.000	1.140						
13.000	1.140						
14.000	1.140						
15.000	1.140						
16.000	1.140						
17.000	3.400						
18.000	3.400						
19.000	3.400						
20.000	23.170						
21.000	2.800						
22.000	2.800						
23.000	2.800						
24.000	2.800						
25.000	2.800						
26.000	2.800						
27.000	2.150						
28.000	2.150						
29.000	2.150						
30.000	2.150						
31.000	2.150						
32.000	2.150						
33.000	2.150						
34.000	2.150						
35.000	2.150						
36.000	2.150						
37.000	2.150						
38.000	2.150						
39.000	2.040						
40.000	2.040						
41.000	2.040						
42.000	2.040						
43.000	2.040						
44.000	2.040						
45.000	2.040						
46.000	2.040						
47.000	2.040						
48.000	2.040						
49.000	2.040						
50.000	2.040						
51.000	2.040						
52.000	2.040						
53.000	2.040						
54.000	2.040						
55.000	2.040						
56.000	2.040						
57.000	2.040						
58.000	7.820						
59.000	7.820						
60.000	7.820						
61.000	8.120						
62.000	11.440						
63.000	9.320						
64.000	10.170						
65.000	13.460						
66.000	28.480						
67.000	40.130						
68.000	43.060						
69.000	42.030						
70.000	40.130						
71.000	41.020						

8. Example of data provided by Umgeni Water for Inanda Dam

DATE: 17-JUL-91
TIME: 08:44:15
SYSTEM: L.I.M.S.

UNGERI WATER

CONDITIONAL/OTHER SPECIES RESULTS

SAMPLE POINT NO: 11.1 INKHOR-SURFACE-0.3m FROM WALL 01-JAN-88 TO 17-JUL-91

SAMPLE POINT NO: 11.1 INKHOR-SURFACE-0.3m FROM WALL 01-JAN-88 TO 17-JUL-91

SAMPLE POINT NO: 11.1 INKHOR-SURFACE-0.3m FROM WALL 01-JAN-88 TO 17-JUL-91

DATE: 17-JUL-91
TIME: 08:44:15
SYSTEM: L.I.M.S.

UNGERI WATER

CONDITIONAL/OTHER SPECIES RESULTS

SAMPLE POINT NO: 11.1 INKHOR-SURFACE-0.3m FROM WALL 01-JAN-88 TO 17-JUL-91

	DATE	Temperature	Chlorophyll-a	Nitrate	Ammonia	Total phosphor	SRP	TDS	BOD	DO (%)
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

		DATE	Temperature	Chlorophyll-a	Nitrate	Ammonia	Total phosphor	SRP	TDS	BOD	DO (%)
[illegible]	RD003257	900208	26.10	11.80	0.25	0.06	20.00	3.00	-32767	-32767	-32767
[illegible]	RD003894	900215	26.90	8.40	0.59	0.07	7.00	3.00	-32767	-32767	-32767
[illegible]	RD004497	[illegible]	23.30	-32767	[illegible]	[illegible]	[illegible]	[illegible]	-32767	-32767	-32767
[illegible]	RD005056	[illegible]	[illegible]	10.30	[illegible]	[illegible]	[illegible]	[illegible]	-32767	-32767	-32767
[illegible]	RD005607	900308	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	-32767	-32767	-32767
[illegible]	RD015785	910718	-32767	-32767	-32767	-32767	-32767	-32767	-32767	-32767	-32767

APPENDIX A4.4

INPUT DATA FILES
VAAL BARRAGE
SIMULATION: 1 JULY TO 15 NOVEMBER 1990

1. LONGITUDINAL PROFILE FILE: VAAL BARRAGE - MEASURED CONDUCTIVITY DATA

LONGITUDINAL PROFILE FILE FOR VAAL BARRAGE (17 june 1992)

Segment 2									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
85	85	101	102						
Segment 3									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
99	100	101	102						
Segment 4									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
100	100	100	105	105					
Segment 5									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
107	108	108	108	108					
Segment 6									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
108	108	108	108	108	108				
Segment 7									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
105	105	105	105	105	105				
Segment 8									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
104	104	104	104	104	104				
Segment 9									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
103	103	103	103	103	103				
Segment 10									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
102	102	102	102	102	103				
Segment 11									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
102	102	102	102	102	102	102			
Segment 12									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
101	101	101	101	101	101	101			
Segment 13									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
97	97	97	97	98	98	98	98		
Segment 14									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
94	94	94	95	95	95	95	95		
Segment 15									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
93	93	93	93	94	94	94	94		
Segment 16									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
92	92	92	92	92	92	92	92		
Segment 17									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
90	90	90	90	91	91	91	91		
Segment 18									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
89	89	89	90	90	90	90	90		
Segment 19									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
87	87	87	87	87	87	87	87	87	
Segment 20									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
86	86	86	86	86	86	86	87	88	
Segment 21									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
85	85	85	85	85	85	85	85	86	
Segment 22									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
80	80	80	80	80	80	80	80	80	81
Segment 23									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
80	80	80	80	80	80	80	80	80	81
Segment 24									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
79	79	79	79	79	80	80	80	80	80
Segment 25									
EC LPR	C1	C1	C1	C1	C1	C1	C1	C1	C1
79	79	79	79	79	79	79	80	80	80

2. CONTROL FILE FOR CEQUAL SIMULATION: VAAL BARRAGE

```
Vaal Barrage control file for CE-QUAL-W3

TITLE C ................................TITLE..................................
        Vaal Barrage : July to November 1990 simulation
        Daily: flow, wq and met. updates // new LPR file.
        Mecer 80486i+Lahey FORTRAN/Sim date:=04/6/92b with EC+P+algae

TIME CON  TMSTRT   TMEND
             1.5   137.5

DLT CON      NDT  MINDLT
               1    60.0

DLT DATE    DLTD    DLTD    DLTD    DLTD    DLTD    DLTD    DLTD    DLTD    DLTD
             1.5

DLT MAX   DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX  DLTMAX
         10800.0

DLT FRN     FDLT    FDLT    FDLT    FDLT    FDLT    FDLT    FDLT    FDLT    FDLT
             0.9

SURFACE       KT      IZ   DATUM
               3    0.74  1411.6

HEIGHT         H       H       H       H       H       H       H       H       H
               1       1       1       1       1       1       1       1       1
               1       1       1       1

ORIENT      PHI0    PHI0    PHI0    PHI0    PHI0    PHI0    PHI0    PHI0    PHI0
           0.100   0.100   0.170   5.930   5.750   5.410   4.880   3.660   3.840
           4.360   4.180   3.840   3.840   4.710   4.710   4.710   4.710   4.710
           4.010   3.140   3.140   5.580   5.580   5.580   4.710   4.710   4.710

BRANCH G      US      DS     UHS     DHS     DLX
BR01           2      26       0       0    2000

INIT CND   ITEMP  IICETH   WTYPE
            -1.0     0.0   FRESH

CALCULAT   VOLBC   PQINC   EVAPC    ICEC  PRCIPC   WINDC    QINC   QOUTC   HTEXC
             OFF      ON     OFF     OFF     OFF      ON      ON      ON      ON

WSC NUMB    NWSC
               1

WSC DATE    WSCD    WSCD    WSCD    WSCD    WSCD    WSCD    WSCD    WSCD    WSCD
             0.5

WSC COEF     WSC     WSC     WSC     WSC     WSC     WSC     WSC     WSC     WSC
             0.8

HYD COEF      AX     IDX   FRNDZ   CHEZY
            10.0     1.0    0.14    70.0

N OUTLET    NOUT    NOUT    NOUT    NOUT    NOUT    NOUT    NOUT    NOUT    NOUT
               1

O LAYER     KOUT    KOUT    KOUT    KOUT    KOUT    KOUT    KOUT    KOUT    KOUT
BR01          11

WDR COMP    NWDC
              ON

W SEGMNT     IWD     IWD     IWD     IWD     IWD     IWD     IWD     IWD     IWD
               4       8       9      12      16      22

W LAYER      KWD     KWD     KWD     KWD     KWD     KWD     KWD     KWD     KWD
               4       4       4       4       4       4

TRB COMP  NTRIBC
              ON

TRIB SEG   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB   ITRIB
               6       7      14      21      26

DST TRIB  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC  DTRIBC
             OFF       0

SNAPSHOT    FORM     HPR     HPR     HPR
            LONG      ON      ON      ON

SNRT SEG   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF   SPRSF
               2       3       6       9      11      16      19      21      26
```

```
LONG SEG   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF   SPRLF
               3       5       6       7       8       9      12      13      14
              15      16      21      22      23      24      25      26

SNP PRNT    SNPC    NSNP
              ON      26

SNP DATE    SNPD    SNPD    SNPD    SNPD    SNPD    SNPD    SNPD    SNPD    SNPD
             4.5    11.5    18.5    23.5    24.5    27.5    29.5    32.5    34.5
            38.5    45.5    52.5    59.5    67.5    81.5    82.5    92.5    95.5
           101.5   106.5   109.5   115.5   122.5   123.5   136.5   137.5

SNP FREQ    SNPF    SNPF    SNPF    SNPF    SNPF    SNPF    SNPF    SNPF    SNPF
           100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0
           100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0
           100.0   100.0   100.0   100.0   100.0   100.0   100.0   100.0

PST PRNT    PSTC    NPST  NPSTST
              ON      26      22

PST DATE    PSTD    PSTD    PSTD    PSTD    PSTD    PSTD    PSTD    PSTD    PSTD
             4.5    11.5    18.5    23.5    24.5    27.5    29.5    32.5    34.5
            38.5    45.5    52.5    59.5    67.5    81.5    82.5    92.5    95.5
           101.5   106.5   109.5   115.5   122.5   123.5   136.5   137.5

PST SEG   NPSTSG  NPSTSG  NPSTSG  NPSTSG  NPSTSG  NPSTSG  NPSTSG  NPSTSG  NPSTSG
               3       4       5       6       7       8       9      10      11
              12      13      14      15      16      17      18      20      21
              22      23      25      26

RESTART     RSOC    NRSO    RSIC
             OFF       4     OFF

RSO DATE    RSOD    RSOD    RSOD    RSOD    RSOD    RSOD    RSOD    RSOD    RSOD
             4.5    18.5    23.5    29.5

CST COMP  CCOMPC
              ON

CST ACT      ACC     ACC     ACC     ACC     ACC     ACC     ACC     ACC     ACC
              ON      ON     OFF      ON     OFF     OFF      ON     OFF      ON
             OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF
             OFF     OFF

CST ICON     CIC     CIC     CIC     CIC     CIC     CIC     CIC     CIC     CIC
            -2.0    -1.0     0.0    -1.0   2.022   0.867    -1.0   5.555    -1.0
            -1.0    -1.0    -1.0     0.0   10.00    30.0     7.0     0.0     0.0
             0.0     0.1

CST PRNT     CPR     CPR     CPR     CPR     CPR     CPR     CPR     CPR     CPR
              ON      ON     OFF      ON     OFF     OFF      ON     OFF      ON
             OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF
             OFF     OFF

CST UPDT  KFREQU  RFREQU
              12      24

CIN CON    INACC   INACC   INACC   INACC   INACC   INACC   INACC   INACC   INACC
              ON      ON      ON      ON      ON      ON      ON      ON      ON
              ON      ON     OFF     OFF     OFF     OFF     OFF     OFF     OFF
             OFF     OFF

CTR CON    TRACC   TRACC   TRACC   TRACC   TRACC   TRACC   TRACC   TRACC   TRACC
              ON      ON      ON      ON      ON      ON      ON      ON      ON
              ON      ON     OFF     OFF     OFF     OFF     OFF     OFF     OFF
             OFF     OFF

CDT CON    DTACC   DTACC   DTACC   DTACC   DTACC   DTACC   DTACC   DTACC   DTACC
             OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF
             OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF
             OFF     OFF

CPR CON    PRACC   PRACC   PRACC   PRACC   PRACC   PRACC   PRACC   PRACC   PRACC
             OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF
             OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF     OFF
             OFF     OFF

EX COEF    EXH20  EXINOR   EXORG    BETA
            0.75    0.15     0.3    0.45

COLIFORM  COLQ10   COLDK
            1.04     1.4

S SOLIDS   SSETL
             0.1

DOMDECAY   LABDK   LRFDK   REFDK    LDT1    LDT2
```

```
             0.12    0.01   0.001     2.0    20.0

ALGAE        AGROW   AMORT   AEXCR   ARESP   ASETL  ASATUR  ALGDET
             0.30    0.001   0.01    0.02    0.00    30.0    0.80

ALG TEMP     AGT1    AGT2    AGT3    AGT4
             10.0    26.0    30.0    35.0

DETRITUS     DETDK   DSETL   DDT1    DDT2
             0.06    0.50     4.0    30.0

PHOSPHOR    PO4REL   PARTP    AHSP
             0.007   0.02   0.006

AMMONIA     NH3REL   NH3DK   PARTN    AHSN  NH3DT1  NH3DT2
             0.18    0.05    0.05   0.080     2.0    32.0

NITRATE      NO3DK  NO3DT1  NO3DT2
             0.25     2.0    32.0

SEDIMENT     SEDDK    SDT1    SDT2    SDT3    SDT4  CO2REL
             0.06     0.0     5.0    35.0    40.0     0.1

S DEMAND      SOD     SOD     SOD     SOD     SOD     SOD     SOD     SOD     SOD
              0.3     0.3     0.3     0.3     0.3     0.3     0.3     0.3     0.3
              0.3     0.3     0.3     0.3     0.3     0.3     0.3     0.3     0.3
              0.3     0.3     0.3     0.3     0.3     0.3     0.3     0.3

IRON         FEREL  FESETL
              0.5     2.0

STOICHMT     O2NH3   O2DET  O2RESP   O2ALG   O2LAB    BIOP    BION    BIOC
             4.57     1.4     1.1     1.4     1.4   0.011    0.08    0.45

O2 LIMIT     O2LIM
             0.000
VPR FILE..............................VPRFN..................................
       VBVPR.NPT
LPR FILE..............................LPRFN..................................
       VBLPR.NPT
RSI FILE..............................RSIFN..................................
       VBRSI.NPT
MET FILE..............................METFN..................................
       VBMET.NPT
QWD FILE..............................QWDFN..................................
       VBQWD.NPT
QIN FILE..............................QINFN..................................
       VBQIN.NPT
TIN FILE..............................TINFN..................................
       VBTIN.NPT
QDT FILE..............................QDTFN..................................
      not used
TDT FILE..............................TDTFN..................................
      not used
PRE FILE..............................PREFN..................................
      not used
TPR FILE..............................TPRFN..................................
      not used
EUH FILE..............................EUPFN..................................
      not used
EDH FILE..............................EDNFN..................................
      not used
QOT FILE..............................QOTFN..................................
BR01   VBQOT.NPT
CIN FILE..............................CINFN..................................
BR01   VBCIN.NPT
CDT FILE..............................CDTFN..................................
BR01  not used
CPR FILE..............................CPRFN..................................
BR01  not used
TUH FILE..............................TUPFN..................................
BR01  not used
CUH FILE..............................CUPFN..................................
BR01  not used
TDH FILE..............................TDNFN..................................
BR01  not used
CDH FILE..............................CDNFN..................................
BR01  not used
QTR FILE..............................QTRFN..................................
       VBQTR.NPT
TTR FILE..............................TTRFN..................................
       VBTTR.NPT
CTR FILE..............................CTRFN..................................
       VBCTR.NPT
SNP FILE..............................SNPFN..................................
       VBSNAP.OPT
```

```
PST FILE...............................PSTFN...................................
        VBPOST.OPT

RSD FILE...............................RSDFN...................................
        VBRSD.OPT
```

3. VERTICAL PROFILE FILE: VAAL BARRAGE SIMULATION

```
CE-QUAL-W2 Vertical profiles for the VAAL BARRAGE 1990

TEMPERATURE    C1      C1      C1      C1      C1      C1      C1      C1      C1
               10      10      10      10      10     9.9     9.9     9.8     9.8
              9.8

SS             C1      C1      C1      C1      C1      C1      C1      C1      C1
             19.9      25      25      25      30      30      40      40      45
               50

TDS            C1      C1      C1      C1      C1      C1      C1      C1      C1
            568.0   568.0   568.0   568.0   568.0   570.0   570.0   572.0   574.0
            576.0

ALGAE          C1      C1      C1      C1      C1      C1      C1      C1      C1
              0.5     0.5     0.5     0.5     0.4     0.4     0.4     0.4     0.4
              0.4

PO4            C1      C1      C1      C1      C1      C1      C1      C1      C1
             0.24    0.24    0.24    0.24    0.24    0.34    0.34    0.34    0.40
             0.50

NH4            C1      C1      C1      C1      C1      C1      C1      C1      C1
             0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25    0.25
             0.25

NO3            C1      C1      C1      C1      C1      C1      C1      C1      C1
              3.5     3.6     3.6     3.6     3.6     3.6     3.6     3.6     3.6
              3.6

DO             C1      C1      C1      C1      C1      C1      C1      C1      C1
              6.6     6.6     6.6     6.6     6.6     6.7     6.8     6.9     7.0
              7.1
```

4. WATER QUALITY DATA FILE: VAAL BARRAGE CHEMICAL DATA FOR UPSTREAM BOUNDARY: LETHABO WEIR

water quality data for Lethabo Weir

JDAY	Tracer	Ssolid	Cifrm	Dsolid	L DOM	R Dom	Algae	Detrit	PO4	NH4	NO3
1.0	22.8	50.0	0.0	149.6	0.2	1.2	0.00	0.0	0.009	0.06	0.09
2.0	19.6	50.0	0.0	144.8	0.2	1.2	0.00	0.0	0.010	0.07	0.15
3.0	19.6	50.0	0.0	144.8	0.2	1.2	0.00	0.0	0.011	0.07	0.15
4.0	19.6	50.0	0.0	144.8	0.2	1.2	0.00	0.0	0.011	0.07	0.15
5.0	19.6	50.0	0.0	144.8	0.2	1.2	0.00	0.0	0.011	0.07	0.15
6.0	19.6	50.0	0.0	144.8	0.2	1.2	0.00	0.0	0.011	0.07	0.15
7.0	19.6	50.0	0.0	144.8	0.2	1.2	0.00	0.0	0.011	0.07	0.15
8.0	19.6	50.0	0.0	144.8	0.2	1.2	0.00	0.0	0.010	0.07	0.15
9.0	20.1	50.0	0.0	142.8	0.2	1.2	0.00	0.0	0.009	0.08	0.15
10.0	20.1	50.0	0.0	142.8	0.2	1.2	0.00	0.0	0.009	0.08	0.15
11.0	20.1	50.0	0.0	142.8	0.2	1.2	0.00	0.0	0.009	0.08	0.15
12.0	20.1	50.0	0.0	142.8	0.2	1.2	0.00	0.0	0.009	0.08	0.15
13.0	20.1	50.0	0.0	142.8	0.2	1.2	0.00	0.0	0.009	0.08	0.15
14.0	20.1	50.0	0.0	142.8	0.2	1.2	0.00	0.0	0.009	0.08	0.15
15.0	20.1	50.0	0.0	142.8	0.2	1.2	0.00	0.0	0.009	0.08	0.15
16.0	20.0	50.0	0.0	147.0	0.2	1.2	0.00	0.0	0.008	0.08	0.13
17.0	20.0	50.0	0.0	147.0	0.2	1.2	0.00	0.0	0.008	0.08	0.13
18.0	20.0	50.0	0.0	147.0	0.2	1.2	0.00	0.0	0.008	0.08	0.13
19.0	20.0	50.0	0.0	147.0	0.2	1.2	0.00	0.0	0.008	0.08	0.13
20.0	20.0	50.0	0.0	147.0	0.2	1.2	0.00	0.0	0.008	0.08	0.13
21.0	20.0	50.0	0.0	147.0	0.2	1.2	0.00	0.0	0.008	0.08	0.13
22.0	20.0	50.0	0.0	147.0	0.2	1.2	0.00	0.0	0.008	0.08	0.13
23.0	21.0	52.8	0.0	144.0	0.2	1.2	0.35	4.4	0.010	0.06	0.10
24.0	21.9	66.0	0.0	141.7	0.2	1.2	0.36	5.5	0.020	0.05	0.10
25.0	21.9	66.0	0.0	141.7	0.2	1.2	0.36	5.5	0.040	0.05	0.10
26.0	21.9	66.0	0.0	141.7	0.2	1.2	0.36	5.5	0.070	0.05	0.10
27.0	21.9	66.0	0.0	141.7	0.2	1.2	0.36	5.5	0.100	0.05	0.10
28.0	21.9	66.0	0.0	141.7	0.2	1.2	0.36	5.5	0.100	0.05	0.10
29.0	21.9	66.0	0.0	141.7	0.2	1.2	0.36	5.5	0.100	0.05	0.10
30.0	21.0	64.8	0.0	143.0	0.2	1.2	0.42	5.4	0.100	0.05	0.10
31.0	21.2	68.4	0.0	145.0	0.2	1.2	0.45	5.7	0.171	0.07	0.09
32.0	21.2	68.4	0.0	145.0	0.2	1.2	0.45	5.7	0.171	0.07	0.09
33.0	21.2	68.4	0.0	145.0	0.2	1.2	0.45	5.7	0.030	0.07	0.09
34.0	21.2	68.4	0.0	145.0	0.2	1.2	0.45	5.7	0.040	0.07	0.09
35.0	21.2	68.4	0.0	145.0	0.2	1.2	0.45	5.7	0.040	0.07	0.09
36.0	21.2	68.4	0.0	145.0	0.2	1.2	0.45	5.7	0.040	0.07	0.09
37.0	21.0	67.7	0.0	145.0	0.2	1.2	0.58	5.6	0.040	0.06	0.11
38.0	20.5	62.4	0.0	145.5	0.2	1.2	0.58	5.2	0.009	0.06	0.20
39.0	20.5	62.4	0.0	145.5	0.2	1.2	0.58	5.2	0.009	0.06	0.20
40.0	20.5	62.4	0.0	145.5	0.2	1.2	0.58	5.2	0.009	0.06	0.20
41.0	20.5	62.4	0.0	145.5	0.2	1.2	0.58	5.2	0.009	0.06	0.20
42.0	20.5	62.4	0.0	145.5	0.2	1.2	0.58	5.2	0.009	0.06	0.20
43.0	20.5	62.4	0.0	145.5	0.2	1.2	0.58	5.2	0.009	0.06	0.20
44.0	20.0	64.3	0.0	145.0	0.2	1.2	0.58	5.4	0.010	0.06	0.10
45.0	20.6	60.0	0.0	145.1	0.2	1.2	0.54	5.0	0.010	0.06	0.08
46.0	20.6	60.0	0.0	145.1	0.2	1.2	0.54	5.0	0.010	0.06	0.08
47.0	20.6	60.0	0.0	145.1	0.2	1.2	0.54	5.0	0.010	0.06	0.08
48.0	20.6	60.0	0.0	145.1	0.2	1.2	0.54	5.0	0.010	0.06	0.08
49.0	20.6	60.0	0.0	145.1	0.2	1.2	0.54	5.0	0.010	0.06	0.08
50.0	20.6	60.0	0.0	145.1	0.2	1.2	0.54	5.0	0.010	0.06	0.08
51.0	20.0	60.0	0.0	147.3	0.2	1.2	0.50	5.0	0.010	0.06	0.10
52.0	20.0	60.2	0.0	147.0	0.2	1.2	0.54	5.0	0.010	0.06	0.10
53.0	20.0	60.2	0.0	147.0	0.2	1.2	0.54	5.0	0.010	0.06	0.10
54.0	20.0	60.2	0.0	147.0	0.2	1.2	0.54	5.0	0.010	0.06	0.10
55.0	20.0	60.2	0.0	147.0	0.2	1.2	0.54	5.0	0.010	0.06	0.10
56.0	20.0	60.2	0.0	147.0	0.2	1.2	0.54	5.0	0.010	0.06	0.10
57.0	20.0	60.2	0.0	147.0	0.2	1.2	0.54	5.0	0.010	0.06	0.10
58.0	21.0	60.0	0.0	148.0	0.2	1.2	0.42	5.0	0.010	0.06	0.10
59.0	22.5	60.0	0.0	149.6	0.2	1.2	0.40	5.0	0.007	0.07	0.09
60.0	22.5	60.0	0.0	149.6	0.2	1.2	0.40	5.0	0.007	0.07	0.09
61.0	22.5	60.0	0.0	149.6	0.2	1.2	0.40	5.0	0.007	0.07	0.09
62.0	22.5	60.0	0.0	149.6	0.2	1.2	0.40	5.0	0.007	0.07	0.09
63.0	22.5	60.0	0.0	149.6	0.2	1.2	0.40	5.0	0.007	0.07	0.09
64.0	22.5	60.0	0.0	149.6	0.2	1.2	0.40	5.0	0.007	0.07	0.09
65.0	22.0	65.0	0.0	149.0	0.2	1.2	0.38	5.4	0.010	0.08	0.07
66.0	22.3	62.4	0.0	149.1	0.2	1.2	0.34	5.2	0.009	0.08	0.05
67.0	22.3	62.4	0.0	149.1	0.2	1.2	0.34	5.2	0.009	0.08	0.05
68.0	22.3	62.4	0.0	149.1	0.2	1.2	0.34	5.2	0.009	0.08	0.05
69.0	22.3	62.4	0.0	149.1	0.2	1.2	0.34	5.2	0.009	0.08	0.05
70.0	22.3	62.4	0.0	149.1	0.2	1.2	0.34	5.2	0.009	0.08	0.05
71.0	22.3	62.4	0.0	149.1	0.2	1.2	0.34	5.2	0.009	0.08	0.05
72.0	22.3	62.4	0.0	149.1	0.2	1.2	0.34	5.2	0.009	0.08	0.05
73.0	22.3	62.4	0.0	149.1	0.2	1.2	0.34	5.2	0.009	0.08	0.05
74.0	22.3	62.4	0.0	149.0	0.2	1.2	0.40	5.2	0.009	0.07	0.06
75.0	22.3	62.4	0.0	149.0	0.2	1.2	0.40	5.2	0.009	0.07	0.06
76.0	22.3	62.4	0.0	149.0	0.2	1.2	0.40	5.2	0.009	0.07	0.06
77.0	22.3	62.4	0.0	149.0	0.2	1.2	0.40	5.2	0.009	0.07	0.06
78.0	22.3	62.4	0.0	149.0	0.2	1.2	0.40	5.2	0.009	0.07	0.06

5. TRIBUTARY INFLOW HYDROGRAPH DATA: VAAL BARRAGE

Vaal barrage inflows: suikerb, klip,taai, leeu, & riet

JDAY	QTR	QTR	QTR	QTR	QTR	QTR	QTR	QTR	QTR
1.0	1.19	8.85	0.02	0.007	1.41				
2.0	1.19	8.60	0.02	0.007	1.41				
3.0	1.19	8.60	0.01	0.003	1.41				
4.0	1.19	8.60	0.00	0.001	1.41				
5.0	1.01	9.20	0.00	0.001	1.41				
6.0	1.01	9.20	0.00	0.001	1.41				
7.0	1.19	8.85	0.00	0.001	1.41				
8.0	1.19	8.85	0.00	0.001	1.41				
9.0	1.01	8.85	0.02	0.007	1.53				
10.0	1.01	9.20	0.02	0.007	1.65				
11.0	1.01	8.85	0.02	0.007	1.65				
12.0	1.01	8.93	0.02	0.007	1.65				
13.0	0.88	9.23	0.02	0.007	1.65				
14.0	0.88	9.13	0.02	0.007	1.65				
15.0	0.88	9.10	0.02	0.007	1.65				
16.0	0.88	9.08	0.05	0.017	1.65				
17.0	0.88	9.08	0.05	0.017	1.65				
18.0	0.88	8.00	0.05	0.017	1.41				
19.0	0.88	8.00	0.05	0.017	1.41				
20.0	0.88	8.00	0.05	0.017	1.41				
21.0	0.88	9.08	0.05	0.017	1.41				
22.0	0.81	8.00	0.05	0.017	1.41				
23.0	0.81	8.00	0.05	0.017	1.41				
24.0	0.81	8.00	0.05	0.017	1.41				
25.0	0.81	8.00	0.05	0.017	1.41				
26.0	0.81	9.08	0.05	0.017	1.41				
27.0	0.85	9.08	0.05	0.017	1.41				
28.0	0.85	9.60	0.05	0.017	1.41				
29.0	0.80	9.31	0.05	0.017	1.65				
30.0	0.79	9.08	0.08	0.027	1.41				
31.0	0.82	9.08	0.08	0.027	1.41				
32.0	0.82	9.08	0.08	0.027	1.53				
33.0	0.82	9.08	0.08	0.027	1.41				
34.0	0.82	9.60	0.08	0.027	1.65				
35.0	0.82	9.08	0.08	0.027	1.41				
36.0	0.76	9.08	0.08	0.027	1.41				
37.0	0.76	9.08	0.05	0.017	1.41				
38.0	0.76	8.50	0.05	0.017	1.41				
39.0	0.76	8.50	0.05	0.017	1.53				
40.0	0.76	8.50	0.05	0.017	1.41				
41.0	0.82	8.50	0.04	0.013	1.65				
42.0	0.82	8.50	0.04	0.013	1.41				
43.0	0.76	8.50	0.06	0.020	1.41				
44.0	0.82	8.50	0.02	0.007	1.41				
45.0	0.82	7.98	0.08	0.027	1.41				
46.0	0.76	7.98	0.13	0.043	1.41				
47.0	0.71	8.00	0.13	0.043	1.41				
48.0	0.71	9.31	0.15	0.050	1.41				
49.0	0.65	9.31	0.20	0.067	1.41				
50.0	0.60	9.31	0.23	0.077	1.41				
51.0	0.58	8.00	0.08	0.027	1.41				
52.0	0.60	7.98	0.08	0.027	1.65				
53.0	0.60	7.98	0.08	0.027	1.53				
54.0	0.55	7.98	0.08	0.027	1.65				
55.0	0.58	7.98	0.08	0.027	1.41				
56.0	0.55	7.98	0.08	0.027	1.41				
57.0	0.55	8.00	0.08	0.027	1.41				
58.0	0.60	9.08	0.02	0.007	1.41				
59.0	0.60	8.00	0.02	0.007	1.41				
60.0	0.55	8.00	0.02	0.007	1.41				
61.0	0.51	7.98	0.02	0.007	1.18				
62.0	0.51	8.00	0.02	0.007	1.41				
63.0	0.46	7.98	0.02	0.007	1.41				
64.0	0.46	8.83	0.02	0.007	1.41				
65.0	0.46	8.00	0.00	0.001	1.41				
66.0	0.46	8.00	0.00	0.001	1.65				
67.0	0.46	9.08	0.00	0.001	1.65				
68.0	0.41	10.20	0.00	0.001	1.41				
69.0	0.41	9.08	0.00	0.001	1.41				
70.0	0.46	9.08	0.00	0.001	1.41				
71.0	0.46	9.60	0.00	0.001	1.41				
72.0	0.46	9.08	0.00	0.001	1.65				
73.0	0.51	9.08	0.00	0.001	1.41				
74.0	0.51	7.98	0.00	0.001	1.41				
75.0	0.46	7.98	0.00	0.001	1.18				
76.0	0.46	7.98	0.00	0.001	1.18				
77.0	0.41	7.08	0.00	0.001	1.18				
78.0	0.37	8.00	0.00	0.001	1.18				
79.0	0.37	7.98	0.00	0.001	1.18				
80.0	0.60	7.20	0.00	0.001	0.96				

6. WATER QUALITY DATA FOR ALL TRIBUTARY INFLOWS: VAAL BARRAGE

WQ data for all tributary inflows to the Barrage 25 MAY 92

JDAY	Tracer	Ssolid	Clfrm	Dsolid	L DOM	R Dom	Algae	Detrit	PO4	NH4	NO3
1.0	72.8	14.0	0.0	554.1	1.26	0.28	3.0	1.4	0.01	0.08	0.01
1.0	106.1	12.8	0.0	702.8	0.86	1.14	0.4	1.3	0.17	0.07	6.07
1.0	66.9	25.0	0.0	435.0	0.80	1.20	0.1	1.0	0.04	0.08	0.06
1.0	66.9	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	1.40	2.00	8.00
1.0	110.2	12.0	0.0	838.4	0.12	1.20	0.6	1.2	0.01	3.97	8.86
2.0	72.8	14.0	0.0	554.1	1.26	0.28	3.0	1.4	0.01	0.08	0.01
2.0	106.1	12.8	0.0	702.8	0.86	1.14	0.4	1.3	0.17	0.07	6.07
2.0	66.9	25.0	0.0	435.0	0.80	1.20	0.1	1.0	0.04	0.08	0.06
2.0	66.9	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	1.40	2.00	8.00
2.0	110.2	12.0	0.0	838.4	0.12	1.20	0.6	1.2	0.01	3.97	8.86
3.0	72.8	14.0	0.0	554.1	1.26	0.28	3.0	1.4	0.01	0.08	0.01
3.0	106.1	12.8	0.0	704.0	0.86	1.14	0.4	1.3	0.17	0.07	6.07
3.0	66.9	25.0	0.0	435.0	0.80	1.20	0.1	1.0	0.04	0.08	0.06
3.0	66.9	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	0.70	2.00	8.00
3.0	110.2	12.0	0.0	838.4	0.12	1.20	0.6	1.2	0.01	3.97	8.86
4.0	72.8	14.0	0.0	554.1	1.26	0.28	3.0	1.4	0.01	0.08	0.01
4.0	106.1	13.0	0.0	710.0	0.86	1.14	0.4	1.3	0.17	0.07	6.07
4.0	66.9	25.0	0.0	435.0	0.80	1.20	0.1	1.0	0.04	0.08	0.06
4.0	66.9	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	0.70	2.00	8.00
4.0	110.2	12.0	0.0	838.4	0.12	1.20	0.6	1.2	0.01	3.97	8.86
5.0	85.6	15.0	0.0	554.5	1.26	0.28	3.0	1.5	0.01	0.07	0.12
5.0	105.0	13.2	0.0	720.0	0.86	1.14	0.4	1.3	0.22	0.19	6.47
5.0	68.7	25.0	0.0	480.5	0.80	1.20	0.1	1.0	0.03	0.08	0.07
5.0	68.7	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	0.70	2.00	8.00
5.0	114.0	12.0	0.0	803.7	0.12	1.20	0.5	1.2	0.02	1.78	8.57
6.0	85.6	15.0	0.0	554.5	1.26	0.28	3.0	1.5	0.01	0.07	0.12
6.0	105.0	13.2	0.0	720.0	0.86	1.14	0.4	1.3	0.22	0.19	6.47
6.0	68.7	25.0	0.0	480.5	0.80	1.20	0.1	1.0	0.03	0.08	0.07
6.0	68.7	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	0.70	2.00	8.00
6.0	114.0	12.0	0.0	803.7	0.12	1.20	0.5	1.2	0.02	1.78	8.57
7.0	85.6	15.0	0.0	554.5	1.26	0.28	3.0	1.5	0.01	0.07	0.12
7.0	105.0	13.2	0.0	720.0	0.86	1.14	0.4	1.3	0.22	0.19	6.47
7.0	68.7	25.0	0.0	480.5	0.80	1.20	0.1	1.0	0.03	0.08	0.07
7.0	68.7	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	0.70	2.00	8.00
7.0	114.0	12.0	0.0	803.7	0.12	1.20	0.5	1.2	0.02	1.78	8.57
8.0	85.6	15.0	0.0	554.5	1.26	0.28	3.0	1.5	0.01	0.07	0.12
8.0	105.0	13.2	0.0	720.0	0.86	1.14	0.4	1.3	0.22	0.19	6.47
8.0	68.7	25.0	0.0	480.5	0.80	1.20	0.1	1.0	0.03	0.08	0.07
8.0	68.7	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	0.70	2.00	8.00
8.0	114.0	12.0	0.0	803.7	0.12	1.20	0.5	1.2	0.02	1.78	8.57
9.0	85.6	15.0	0.0	554.5	1.26	0.28	3.0	1.5	0.01	0.07	0.12
9.0	105.0	13.2	0.0	720.0	0.86	1.14	0.4	1.3	0.22	0.19	6.47
9.0	68.7	25.0	0.0	480.5	0.80	1.20	0.1	1.0	0.03	0.08	0.07
9.0	68.7	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	0.70	2.00	8.00
9.0	114.0	12.0	0.0	803.7	0.12	1.20	0.5	1.2	0.02	1.78	8.57
10.0	85.6	15.0	0.0	554.5	1.26	0.28	3.0	1.5	0.01	0.07	0.12
10.0	105.0	13.2	0.0	720.0	0.86	1.14	0.4	1.3	0.22	0.19	6.47
10.0	68.7	25.0	0.0	480.5	0.80	1.20	0.1	1.0	0.03	0.08	0.07
10.0	68.7	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	3.20	2.00	8.00
10.0	114.0	12.0	0.0	803.7	0.12	1.20	0.5	1.2	0.02	1.78	8.57
11.0	85.6	15.0	0.0	554.5	1.26	0.28	3.0	1.5	0.01	0.07	0.12
11.0	105.0	13.2	0.0	730.0	0.86	1.14	0.4	1.3	0.22	0.19	6.47
11.0	68.7	25.0	0.0	480.5	0.80	1.20	0.1	1.0	0.03	0.08	0.07
11.0	68.7	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	0.80	2.00	8.00
11.0	114.0	12.0	0.0	803.7	0.12	1.20	0.5	1.2	0.02	1.78	8.57
12.0	95.3	17.0	0.0	551.6	1.26	0.28	3.0	1.7	0.01	0.05	0.12
12.0	126.0	13.4	0.0	751.9	0.86	1.14	0.4	1.3	0.30	0.19	6.33
12.0	84.4	25.0	0.0	512.7	0.80	1.20	0.1	1.0	0.03	0.06	0.09
12.0	84.4	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	1.40	2.00	8.00
12.0	142.0	14.0	0.0	845.1	0.12	1.20	0.4	1.4	0.03	2.46	7.74
13.0	95.3	17.0	0.0	551.6	1.26	0.28	3.0	1.7	0.01	0.05	0.12
13.0	126.0	13.4	0.0	751.9	0.86	1.14	0.4	1.3	0.30	0.19	6.33
13.0	84.4	25.0	0.0	512.7	0.80	1.20	0.1	1.0	0.03	0.06	0.09
13.0	84.4	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	1.10	2.00	8.00
13.0	142.0	14.0	0.0	845.1	0.12	1.20	0.4	1.4	0.03	2.46	7.74
14.0	95.3	17.0	0.0	551.6	1.26	0.28	3.0	1.7	0.01	0.05	0.12
14.0	126.0	13.4	0.0	751.9	0.86	1.14	0.4	1.3	0.30	0.19	6.33
14.0	84.4	25.0	0.0	512.7	0.80	1.20	0.1	1.0	0.03	0.06	0.09
14.0	84.4	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	1.10	2.00	8.00
14.0	142.0	14.0	0.0	845.1	0.12	1.20	0.4	1.4	0.03	2.46	7.74
15.0	95.3	17.0	0.0	551.6	1.26	0.28	3.0	1.7	0.01	0.05	0.12
15.0	126.0	13.4	0.0	751.9	0.86	1.14	0.4	1.3	0.30	0.19	6.33
15.0	84.4	25.0	0.0	512.7	0.80	1.20	0.1	1.0	0.03	0.06	0.09
15.0	84.4	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	1.30	2.00	8.00
15.0	142.0	14.0	0.0	845.1	0.12	1.20	0.4	1.4	0.03	2.46	7.74
16.0	95.3	17.0	0.0	551.6	1.26	0.28	3.0	1.7	0.01	0.05	0.12
16.0	126.0	13.4	0.0	751.9	0.86	1.14	0.4	1.3	0.30	0.19	6.33
16.0	84.4	25.0	0.0	512.7	0.80	1.20	0.1	1.0	0.03	0.06	0.09
16.0	84.4	35.0	0.0	1076.0	0.80	1.20	2.0	3.5	1.10	2.00	8.00
16.0	142.0	14.0	0.0	845.1	0.12	1.20	0.4	1.4	0.03	2.46	7.74

7. METEOROLOGICAL DATA : VAAL BARRAGE

Met data for Vaal Barrage version 24 may 92

JDAY	ET	TD	WINDSP	PHI	CSHE	SRO
1.0	7.76	-8.5	0.0	0.00	3.05E-06	3.97E-05
2.0	4.84	-6.6	3.9	6.28	4.50E-06	2.44E-05
3.0	9.09	-0.1	4.2	6.28	4.91E-06	3.84E-05
4.0	9.85	1.2	3.6	6.28	4.48E-06	3.65E-05
5.0	13.79	0.7	0.0	0.00	3.18E-06	5.26E-05
6.0	4.67	-8.7	1.8	1.57	3.33E-06	2.51E-05
7.0	13.04	-0.3	1.8	4.71	3.48E-06	5.62E-05
8.0	4.60	-11.2	0.9	6.28	3.06E-06	3.07E-05
9.0	5.97	-5.9	3.0	6.28	3.91E-06	3.03E-05
10.0	9.75	-6.0	0.0	0.00	3.06E-06	4.78E-05
11.0	9.14	-5.9	0.0	0.00	3.06E-06	4.38E-05
12.0	14.46	3.2	3.0	6.28	4.12E-06	6.54E-05
13.0	9.10	-5.9	1.8	4.01	3.37E-06	4.72E-05
14.0	2.22	-16.1	0.0	0.00	2.90E-06	3.04E-05
15.0	15.54	-0.2	0.0	0.00	3.15E-06	6.79E-05
16.0	14.57	0.2	0.0	0.00	3.16E-06	5.99E-05
17.0	11.72	-0.3	2.4	0.87	3.73E-06	5.05E-05
18.0	11.33	-1.7	0.9	6.28	3.22E-06	4.53E-05
19.0	11.28	-5.1	0.0	0.00	3.09E-06	5.35E-05
20.0	4.61	-12.9	0.0	0.00	2.96E-06	3.48E-05
21.0	9.32	-2.7	0.0	0.00	3.12E-06	3.50E-05
22.0	15.35	0.2	0.0	0.00	3.17E-06	6.46E-05
23.0	14.36	-1.3	0.9	4.01	3.23E-06	6.36E-05
24.0	9.86	-6.4	0.0	0.00	3.07E-06	4.79E-05
25.0	7.37	-9.6	0.0	0.00	3.02E-06	4.18E-05
26.0	9.60	-6.5	1.2	0.87	3.20E-06	4.91E-05
27.0	6.32	-10.2	0.0	0.00	3.00E-06	3.76E-05
28.0	9.19	-2.1	2.4	1.57	3.69E-06	3.81E-05
29.0	13.12	2.8	2.4	6.28	3.79E-06	5.06E-05
30.0	15.87	-1.3	0.0	0.00	3.15E-06	7.17E-05
31.0	11.88	-6.0	0.0	0.00	3.08E-06	5.92E-05
32.0	6.12	-11.9	0.0	0.00	2.98E-06	4.05E-05
33.0	8.67	-8.3	1.5	1.57	3.24E-06	4.94E-05
34.0	12.29	0.0	3.6	4.71	4.45E-06	6.35E-05
35.0	16.45	1.2	1.2	1.57	3.34E-06	7.10E-05
36.0	13.26	1.5	3.6	0.87	4.51E-06	6.44E-05
37.0	18.36	1.0	0.0	0.00	3.20E-06	7.96E-05
38.0	18.34	3.1	1.8	1.57	3.58E-06	8.00E-05
39.0	15.71	-1.3	0.0	0.00	3.19E-06	6.73E-05
40.0	13.31	-3.7	0.0	0.00	3.15E-06	5.84E-05
41.0	8.75	-10.0	0.9	6.28	3.12E-06	4.89E-05
42.0	12.77	-1.7	3.0	4.71	4.07E-06	6.31E-05
43.0	14.73	4.9	0.0	0.00	3.29E-06	4.21E-05
44.0	11.38	-2.2	3.0	1.57	4.06E-06	5.30E-05
45.0	10.56	-10.2	0.0	0.00	3.05E-06	5.92E-05
46.0	13.42	-6.5	0.0	0.00	3.11E-06	6.68E-05
47.0	9.48	-11.5	0.0	0.00	3.03E-06	5.62E-05
48.0	12.73	-1.8	1.5	0.87	3.40E-06	5.27E-05
49.0	10.17	-5.5	3.0	5.41	3.98E-06	5.57E-05
50.0	15.01	-4.8	1.2	4.71	3.27E-06	7.54E-05
51.0	14.23	-3.7	1.5	3.14	3.37E-06	6.84E-05
52.0	10.35	-2.5	4.5	1.57	5.16E-06	5.77E-05
53.0	15.31	-1.4	2.7	6.28	3.91E-06	7.88E-05
54.0	13.56	-6.8	0.0	0.00	3.11E-06	6.79E-05
55.0	10.59	-10.0	0.0	0.00	3.06E-06	5.82E-05
56.0	11.81	-9.4	0.0	0.00	3.07E-06	6.42E-05
57.0	19.84	-0.3	0.0	0.00	3.22E-06	8.98E-05
58.0	10.15	-11.6	0.0	0.00	3.04E-06	5.92E-05
59.0	9.35	-11.6	0.0	0.00	3.04E-06	5.46E-05
60.0	10.55	-7.1	2.1	1.57	3.52E-06	5.64E-05
61.0	15.65	4.9	3.6	6.28	4.65E-06	6.65E-05
62.0	6.01	-17.7	0.0	0.00	2.94E-06	5.10E-05
63.0	19.93	-1.9	0.0	0.00	3.19E-06	9.47E-05
64.0	11.21	0.7	0.0	0.00	3.24E-06	3.01E-05
65.0	10.82	8.0	1.5	6.28	3.60E-06	4.49E-06
66.0	15.65	3.1	4.2	1.57	5.09E-06	8.10E-05
67.0	18.31	6.4	2.7	1.57	4.11E-06	7.27E-05
68.0	19.24	3.2	1.5	4.71	3.53E-06	7.90E-05
69.0	23.55	3.8	0.0	0.00	3.32E-06	9.98E-05
70.0	13.48	0.9	4.8	6.28	5.64E-06	6.96E-05
71.0	19.13	0.0	1.8	1.57	3.60E-06	8.83E-05
72.0	24.09	4.5	1.2	1.57	3.50E-06	1.04E-04
73.0	16.49	-0.3	3.0	6.28	4.20E-06	7.90E-05
74.0	15.49	-2.8	2.4	6.28	3.82E-06	7.33E-05
75.0	9.92	-7.1	3.3	0.87	4.23E-06	5.19E-05
76.0	21.63	3.4	1.8	6.28	3.68E-06	9.38E-05
77.0	6.44	-9.0	3.4	6.28	4.26E-06	3.04E-05
78.0	8.14	-4.0	4.2	6.28	4.95E-06	2.99E-05
79.0	11.85	-6.9	1.8	4.71	3.47E-06	5.82E-05
80.0	16.93	-5.2	1.2	4.01	3.32E-06	8.42E-05
81.0	10.06	3.2	6.0	1.57	7.07E-06	2.17E-05

8. BATHYMETRIC DATA : VAAL BARRAGE

```
    Bathymetric file for the Vaal Barrage
Segment 1
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.
Segment 2
      0.    185.    175.    145.    112.     87.      0.      0.      0.      0.
      0.      0.      0.
Segment 3
      0.    176.    170.    154.    121.     94.      0.      0.      0.      0.
      0.      0.      0.
Segment 4
      0.    175.    158.    145.    136.    120.    105.      0.      0.      0.
      0.      0.      0.
Segment 5
      0.    175.    165.    145.    133.    105.     86.      0.      0.      0.
      0.      0.      0.
Segment 6
      0.    195.    175.    155.    135.    121.     86.     40.      0.      0.
      0.      0.      0.
Segment 7
      0.    165.    155.    135.    118.     93.     87.     40.      0.      0.
      0.      0.      0.
Segment 8
      0.    175.    165.    145.    123.     90.     87.     85.      0.      0.
      0.      0.      0.
Segment 9
      0.    233.    215.    187.    155.    135.    115.     95.      0.      0.
      0.      0.      0.
Segment 10
      0.    225     199     181     167     159     135     111       0.      0.
      0.      0.      0.
Segment 11
      0.    221     195     183     167     152     132     124      50       0.
      0.      0.      0.
Segment 12
      0.    227.    194.    175.    165.    155.    145.    127.     30.      0.
      0.      0.      0.
Segment 13
      0.    225.    197.    187.    175.    165.    141.    110.     80.     40.
      0.      0.      0.
Segment 14
      0.    210.    190.    170.    165.    145.    123.    100.     90.     53.
      0.      0.      0.
Segment 15
      0.    199.    190.    180.    176.    160.    150.    135.    115.     75.
      0.      0.      0.
Segment 16
      0.    211.    198.    185.    177.    155.    145.    130.    120.     65.
      0.      0.      0.
Segment 17
      0.    221.    196.    174.    167.    155.    145.    135.    124.    116.
      0.      0.      0.
Segment 18
      0.    221.    211.    183.    164.    158.    140.    135.    129.    111.
      0.      0.      0.
Segment 19
      0.    227.    185.    180.    165.    155.    145.    138.    123.     99.
     40.      0.      0.
Segment 20
      0.    190.    177.    170.    165.    155.    134.    129.    120.    114.
     60.      0.      0.
Segment 21
      0.    220.    190.    180.    160.    145.    135.    125.    117.    110.
     95.      0.      0.
Segment 22
      0.    285.    275.    255.    233.    189.    177.    165.    145.    115.
    103.     90.      0.
Segment 23
      0.    285     275.    266.    235.    211.    187.    163.    143.    134.
    106.     90.      0.
Segment 24
      0.    310.    299.    288.    267.    254.    213.    190.    178.    150.
    130.     90.      0.
Segment 25
      0.    398.    389.    376.    345.    289.    267.    245.    235.    189.
    111.     40.      0.
Segment 26
      0.    411.    395.    385.    362.    350.    340.    295.    270.    250.
    123.     80.      0.
Segment 27
      0.      0.      0.      0.      0.      0.      0.      0.      0.      0.
      0.      0.      0.
```

9. WITHDRAWAL HYDROGRAPH DATA: VAAL BARRAGE

withdrawals from the vaal barrage - p3,ver,p1,p2,iscor,sasol

JDAY	QWD	QWD	QWD	QWD	QWD	QWD	QWD	QWD	QWD
1.0	4.00	0.04	0.52	0.21	0.47	0.42			
2.0	4.00	0.04	0.21	0.06	0.47	0.42			
3.0	3.97	0.04	0.25	0.18	0.47	0.42			
4.0	4.01	0.04	1.13	0.11	0.47	0.42			
5.0	4.02	0.04	1.11	0.37	0.47	0.42			
6.0	4.13	0.04	1.10	0.00	0.47	0.42			
7.0	4.18	0.04	1.08	0.00	0.47	0.42			
8.0	4.17	0.04	0.35	0.13	0.47	0.42			
9.0	4.16	0.04	0.25	0.00	0.47	0.42			
10.0	4.20	0.04	0.23	0.00	0.47	0.42			
11.0	4.29	0.04	0.23	0.00	0.47	0.42			
12.0	4.59	0.04	0.23	0.00	0.47	0.42			
13.0	3.96	0.04	0.52	0.00	0.47	0.42			
14.0	4.21	0.04	0.52	0.00	0.47	0.42			
15.0	4.28	0.04	0.47	0.00	0.47	0.42			
16.0	4.28	0.04	0.52	0.00	0.47	0.42			
17.0	4.39	0.04	0.81	0.00	0.47	0.42			
18.0	4.33	0.04	0.81	0.00	0.47	0.42			
19.0	1.81	0.04	0.81	0.00	0.47	0.42			
20.0	0.00	0.04	0.81	0.00	0.47	0.42			
21.0	0.00	0.04	0.81	0.00	0.47	0.42			
22.0	0.00	0.04	0.81	0.00	0.47	0.42			
23.0	0.00	0.04	0.81	0.00	0.47	0.42			
24.0	0.00	0.04	0.81	0.00	0.47	0.42			
25.0	0.00	0.04	0.81	0.00	0.47	0.42			
26.0	0.00	0.04	0.93	0.00	0.47	0.42			
27.0	0.00	0.04	0.98	0.00	0.47	0.42			
28.0	0.00	0.04	1.39	0.00	0.47	0.42			
29.0	0.00	0.04	1.05	0.00	0.47	0.42			
30.0	0.00	0.04	2.08	0.00	0.47	0.42			
31.0	0.00	0.04	0.46	0.00	0.47	0.42			
32.0	0.00	0.03	0.00	0.00	0.43	0.51			
33.0	0.00	0.03	0.00	0.00	0.43	0.51			
34.0	0.00	0.03	0.00	0.00	0.43	0.51			
35.0	0.00	0.03	0.00	0.00	0.43	0.51			
36.0	0.00	0.03	0.00	0.00	0.43	0.51			
37.0	0.00	0.03	0.00	0.00	0.43	0.51			
38.0	0.00	0.03	0.00	0.00	0.43	0.51			
39.0	0.00	0.03	0.00	0.00	0.43	0.51			
40.0	0.00	0.03	0.00	0.00	0.43	0.51			
41.0	0.00	0.03	0.00	0.00	0.43	0.51			
42.0	0.00	0.03	0.00	0.00	0.43	0.51			
43.0	0.00	0.03	0.00	0.00	0.43	0.51			
44.0	0.00	0.03	0.00	0.00	0.43	0.51			
45.0	0.00	0.03	0.00	0.00	0.43	0.51			
46.0	0.00	0.03	0.00	0.00	0.43	0.51			
47.0	0.00	0.03	0.00	0.00	0.43	0.51			
48.0	0.00	0.03	0.00	0.00	0.43	0.51			
49.0	0.00	0.03	0.00	0.00	0.43	0.51			
50.0	0.00	0.03	0.00	0.00	0.43	0.51			
51.0	0.00	0.03	0.00	0.00	0.43	0.51			
52.0	0.00	0.03	0.00	0.00	0.43	0.51			
53.0	0.00	0.03	0.00	0.00	0.43	0.51			
54.0	0.00	0.03	0.00	0.00	0.43	0.51			
55.0	0.00	0.03	0.00	0.00	0.43	0.51			
56.0	0.00	0.03	0.00	0.69	0.43	0.51			
57.0	0.00	0.03	0.00	1.39	0.43	0.51			
58.0	0.00	0.03	0.00	1.39	0.43	0.51			
59.0	0.00	0.03	0.00	1.39	0.43	0.51			
60.0	0.00	0.03	0.00	1.39	0.43	0.51			
61.0	0.00	0.03	0.00	0.69	0.43	0.51			
62.0	0.00	0.03	0.00	0.12	0.43	0.51			
63.0	0.00	0.05	0.00	0.00	0.44	0.49			
64.0	0.00	0.05	0.00	0.00	0.44	0.49			
65.0	0.00	0.05	0.00	0.00	0.44	0.49			
66.0	0.00	0.05	0.00	0.00	0.44	0.49			
67.0	0.00	0.05	0.00	0.00	0.44	0.49			
68.0	0.00	0.05	0.00	0.00	0.44	0.49			
69.0	0.00	0.05	0.00	0.00	0.44	0.49			
70.0	0.00	0.05	0.00	0.00	0.44	0.49			
71.0	0.00	0.05	0.00	0.00	0.44	0.49			
72.0	0.00	0.05	0.00	0.00	0.44	0.49			
73.0	0.00	0.05	0.00	0.00	0.44	0.49			
74.0	0.00	0.05	0.00	0.00	0.44	0.49			
75.0	0.00	0.05	0.00	0.00	0.44	0.49			
76.0	0.00	0.05	0.00	0.00	0.44	0.49			
77.0	0.00	0.05	0.00	0.00	0.44	0.49			
78.0	0.00	0.05	0.00	0.00	0.44	0.49			
79.0	0.00	0.05	0.00	0.00	0.44	0.49			

10. PRE-PROCESSOR OUTPUT FILE: VAAL BARRAGE

```
CE-QUAL-W2 - V3.0 - February 1992
Vaal Barrage : July to November 1990 simulation
Delivy: flow, wq and met. updates // new LPR file.
Mocer 80486i+Lahey FORTRAN/Sim date:=04/6/92b with EC+P+algae
Levers:=13_1m deep/wind:=0.8/Ssettl:=0.1/AGROW:=.3/PARTP:=.02

 Time Control
*____ _______

   Steping time              [TMSTRT] =    1.50 Julian day
   Ending time               [TMEND] =  137.50 Julian day
   # Timestep intervals       [NDLT] =       1
   Timestep day (Julian day)  [DLTD] =    1.50
   Maximum timestep         [DLTMAX] =10800.00
   Fraction of timestep       [DLTF] =    0.90

 Initial Conditions
*_______ __________

   Temperature      [IT1] = Downstream vertical profile
   Water type     [WTYPE] = FRESH water
   Ice thickness [IICETH] =    0.0 m

   Calculations
*  ____________

     Evaporation    [EVAPC] = OFF
     Ice cover      [ICEC] = OFF
     Precipitation [PRCIPC] = OFF
     Volume balance [VOLBC] = OFF
     Wind          [WINDC] =  ON
     Inflow         [QINC] =  ON
     Outflow       [QOUTC] =  ON
     Heat exchange [HTEXCH] =  ON

   Meteorlogical Parameters
*  _____________ __________

*
     Wind shading date        [WSCD] =   0.50
*
     Wind shading coefficient  [WSC] =   0.80
     Axis orientation [PHI0]
       Branch  1 =   0.00 rads

   Hydraulic Coefficients
*  _________ ____________

     Chezy coefficient                   [CHEZY] =     70.0 m**0.5/sec
     Longitudinal eddy viscosity            [AX] =     10.0 m**2/sec
     Longitudinal eddy diffusivity          [DX] =      1.0 m**2/sec
     Minimum vertical eddy viscosity [AZMIN] = 1.40E-08 m**2/sec


1Output Control
*______ _______

   Form    [FORM] =  LONG

   Snapshot [SNC] =  ON
     Horizontal velocity [U]          =  ON
     Vertical velocity [W]            =  ON
     Temperature [T2]                 =  ON

     Number of time intervals [NSNP] =     26
*
     Date  (Julian day)      [SNPD] =   4.50  11.50  18.50  23.50  24.50  27.50
*
     Date  (Julian day)      [SNPD] =  29.50  32.50  34.50  38.50  45.50  52.50
*
     Date  (Julian day)      [SNPD] =  59.50  67.50  81.50  82.50  92.50  95.50
*
     Date  (Julian day)      [SNPD] = 101.50 106.50 109.50 115.50 122.50 123.50
*
     Date  (Julian day)      [SNPD] = 136.50 137.50
*
     Frequency  (days)       [SNPF] = 100.00 100.00 100.00 100.00 100.00 100.00
*
     Frequency  (days)       [SNPF] = 100.00 100.00 100.00 100.00 100.00 100.00
*
     Frequency  (days)       [SNPF] = 100.00 100.00 100.00 100.00 100.00 100.00
*
     Frequency  (days)       [SNPF] = 100.00 100.00 100.00 100.00 100.00 100.00
*
```

```
    Frequency  (days)         [SNPF] = 100.00 100.00

  Profile plot [PRFC] =  ON
    Number of profiles       [NPST] =      26
    Number of stations     [NPSTST] =      22
+
    Segment location       [PSTSEG] =       3      4      5      6      7      8
+
    Segment location       [PSTSEG] =       9     10     11     12     13     14
+
    Segment location       [PSTSEG] =      15     16     17     18     20     21
+
    Segment location       [PSTSEG] =      22     23     25     26
+
    Date  (Julian day)        [PSTD] =   4.50  11.50  18.50  23.50  24.50  27.50
+
    Date  (Julian day)        [PSTD] =  29.50  32.50  34.50  38.50  45.50  52.50
+
    Date  (Julian day)        [PSTD] =  59.50  67.50  81.50  82.50  92.50  95.50
+
    Date  (Julian day)        [PSTD] = 101.50 106.50 109.50 115.50 122.50 123.50
+
    Date  (Julian day)        [PSTD] = 136.50 137.50

  Restart  [RSOC] = OFF
    Number of restarts [NRSO] =       4
+
    Date (Julian day)  [RSOD] =   4.50  18.50  23.50  29.50
1Inflow - Outflow
+______   _______

  Number of outlets            [NOUT] =  1
+
  Branch  1 Location at layer [KOUT] = 11
  Number of withdrawals         [NWP] =  6
    at segment [IWD] =  4  8  9 12 16 22
+
    and layer  [KWD] =  4  4  4  4  4  4
  Number of tributaries       [NTP] =  5
+
    at segment [ITRIB] =  6  7 14 21 26
  Distributed tributaries [DTRIBC]
    Branch  1 = OFF

 Input Filenames
+_____ _________

  Control                  = VBCON.NPT
  Bathymetry               = VBBTH.NPT
  Vertical profiles        = VBVPR.NPT
  Longitudinal profiles = VBLPR.NPT
  Restart                  = VBRSI.NPT
  Meteorlogic              = VBMET.NPT
  Withdrawal               = VBQWD.NPT

  Branch 1
+ ______
    Inflow                                         = VBQIN.NPT
    Inflow temperature                             = VBTIN.NPT
    Inflow concentrations                          = VBCIN.NPT
    Outflow                                        = VBQOT.NPT
    Distr tributary inflows                        = not used
    Distr tributary temperatures                   = not used
    Distr tributary inflow concentrations = not used
    Precipitation                                  = not used
    Precipitation temperatures                     = not used
    Precipitation concentrations                   = not used
    Upstream head                                  = not used
    Upstream head temperatures                     = not used
    Upstream head concentrations                   = not used
    Downstream head                                = not used
    Downstream head temperatures                   = not used
    Downstream head concentrations                 = not used
  Tributary 1

    Inflow                 = VBQTR.NPT
    Inflow temperature     = VBTTR.NPT
    Inflow concentration = VBCTR.NPT


  Tributary 2

    Inflow                 = VBQTR.NPT
    Inflow temperature     = VBTTR.NPT
    Inflow concentration = VBCTR.NPT
```

```
Tributary 3

  Inflow                  = VBQTR.NPT
  Inflow temperature      = VBTTR.NPT
  Inflow concentration    = VBCTR.NPT

Tributary 4

  Inflow                  = VBQTR.NPT
  Inflow temperature      = VBTTR.NPT
  Inflow concentration    = VBCTR.NPT

Tributary 5

  Inflow                  = VBQTR.NPT
  Inflow temperature      = VBTTR.NPT
  Inflow concentration    = VBCTR.NPT


 Output Filenames
*------ --------

   Error        = VBERR.OPT
   Snapshot     = VBSNAP.OPT
   Restart      = VBRSO.OPT
   Time-series  = VBPOST.OPT
   Profile      =
   Vector plot  =
1Constituents [CCOMP] =  ON
*-----------
```

Constituent [CNAME]	Computation [ACC]	Initial Concentration [CIC] (g/m**3)	Printout [CPR]
Tracer	ON	-2.000	ON
Suspended solids	ON	-1.000	ON
Coliform	OFF	0.000	OFF
Dissolved solids	ON	-1.000	ON
Labile DOM	OFF	2.022	OFF
Refractory DOM	OFF	0.867	OFF
Algae	ON	-1.000	ON
Detritus	OFF	5.555	OFF
Phosphorous	ON	-1.000	ON
Ammonia	OFF	-1.000	OFF
Nitrate-Nitrite	OFF	-1.000	OFF
Dissolved oxygen	OFF	-1.000	OFF
Sediment	OFF	0.000	OFF
Inorganic carbon	OFF	10.000	OFF
Alkalinity	OFF	30.000	OFF
pH	OFF	7.000	OFF
Carbon dioxide	OFF	0.000	OFF
Bicarbonate	OFF	0.000	OFF
Carbonate	OFF	0.000	OFF
Iron	OFF	0.100	OFF

Constituent Rates

Constituent		Rate
Suspended solids	Settling	[SSETL] = 0.100 m/day
Coliform	Decay	[COLDK] = 1.400 /day
Labile DOM	Decay	[LABDK] = 0.120 /day
	to refractory	[LRFDK] = 0.010 /day
Refractory DOM	Decay	[RFRDK] = 0.001 /day
Algae	Growth	[AGROW] = 0.300 /day
	Mortality	[AMORT] = 0.001 /day
	Excretion	[AEXCR] = 0.010 /day
	Respiration	[ARESP] = 0.020 /day
	Settling	[ASETL] = 0.000 m/day
Detritus	Decay	[DETDK] = 0.060 /day
	Settling	[DSETL] = 0.500 m/day
Phosphorous	Release	[PO4REL] = 0.007 g/m**2/day
Ammonia	Decay	[NO3DK] = 0.050 /day
	Release	[NH3REL] = 0.180 g/m**2/day
Nitrate-Nitrite	Decay	[NO3DK] = 0.250 /day
Sediment	Decay	[SEDDK] = 0.060 /day
Iron	Settling	[FESETL] = 2.000 m/day
	Release	[FEREL] = 0.500 g/m**2/day

1 Lower Temperature Bounds

```
+   _____ ___________ ______

      Constituent   Rate        Lower         Max Lower
+     ___________   ____       _______        _________
                               (deg C)         (deg C)

      Labile DOM    Decay    LDT1   = 2.0    LDT2   = 20.0
      Algae         Growth   AGT1   =10.0    AGT2   = 26.0
      Detritus      Decay    DDT1   = 4.0    DDT2   = 30.0
      Ammonia       Decay    NH3DT1 = 2.0    NH3DT2 = 32.0
      Nitrate       Decay    NO3DT1 = 2.0    NO3DT2 = 32.0
      Sediment      Decay    SDT1   = 0.0    SDT2   =  5.0

    Upper Temperature Bounds
+   _____ ___________ ______

      Constituent   Rate        Upper         Max Upper
+     ___________   ____       _______        _________
                               (deg C)         (deg C)

      Algae         Growth   AGT3 = 30.0     AGT4 = 35.0
      Sediment      Decay    SDT3 = 35.0     SDT4 = 40.0

    Stoichiometric Equivalence
+   ______________ ___________

      Oxygen
+     ______

        Ammonia     [O2NH3] = 4.57
        Detritus    [O2DET] = 1.40
        Respiration [O2RESP] = 1.10
        Algal growth [O2ALG] = 1.40
        Labile DOM  [O2LAB] = 1.40

      Organics
+     ________

        Phosphorous [BIOP] = 0.011
        Nitrogen    [BION] = 0.080
        Carbon      [BIOC] = 0.450

    Half Saturation
+   ____ __________

      Phosphorous [AHSP] = 0.006 g/m**3
      Nitrogen    [AHSN] = 0.080 g/m**3

    Light
+   _____

      Attenuation
+     ___________

        Surface layer      [BETA] = 0.45
        Water             [EXH2O] = 0.75 /m
        Inorganic solids [EXINOR] = 0.15 m**2/g
        Organic solids    [EXORG] = 0.30 m**2/g

      Saturation Intensity
+     __________ _________

        Algae [ASATUR] =  30.0 W/m**2

1   Diffusion
+   _________

      Oxygen          [DMO2] = 2.040E-09 m**2/g
      Carbon dioxide [DMCO2] = 1.630E-09 m**2/g

    Partitioning Coefficient
+   ____________ ___________

      Phosphorous [PARTP] = 0.020 m**3/g
      Nitrogen    [PARTN] = 0.050 m**3/g

    Miscellaneous Constants
+   _____________ _________

      Aerobic oxygen limit          [O2LIM] = 0.00 g/m**3
      Coliform Q10                 [COLQ10] = 1.04
      Fraction algae to detritus   [ALGDET] = 0.80
      Sediment release of CO2      [CO2REL] = 0.10

  Geometry
+ ________
```

Overall Grid
*

Total segments [IMP] = 27 Total layers [KMP] = 13
Total branches [NB] = 1 Bottom elevation [DATUM] =1411.60 m
Surface layer [KT] = 3

Vertical Spacing [H]
*

Layer	1	2	3	4	5	6	7	8	9	10	11	12
Height (m)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0

Layer	13
Height (m)	1.0

Branch 1
*

Upstream segment [US] = 2 Downstream segment [DS] = 26
Upstream head segment [UHS] = 0 Downstream head segment [DHS] = 0
Segment length [DLX] = 2000.0 m

1Bathymetry [B] m
*

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1																	
2		185.	176.	175.	175.	195.	165.	175.	235.	225.	221.	227.	225.	210.	199.	211.	221.
3		175.	170.	158.	165.	175.	155.	165.	215.	199.	195.	194.	197.	190.	190.	198.	196.
* [KT]																	
4		145.	154.	145.	145.	155.	135.	145.	187.	181.	183.	175.	187.	170.	180.	185.	174.
5		112.	121.	136.	133.	135.	118.	123.	155.	167.	167.	165.	175.	165.	176.	177.	167.
6		87.	94.	120.	105.	121.	93.	90.	135.	159.	152.	155.	165.	145.	160.	155.	155.
7				105.	86.	86.	87.	87.	115.	135.	132.	145.	141.	123.	150.	145.	145.
8						40.	40.	85.	95.	111.	124.	127.	110.	100.	135.	130.	135.
9											50.	30.	80.	90.	115.	120.	124.
10													40.	53.	75.	65.	116.
11																	
12																	
13																	

1Bathymetry [B] m
*

0	18	19	20	21	22	23	24	25	26	27
1										
2	221.	227.	190.	220.	285.	285.	310.	398.	411.	
3	211.	185.	177.	190.	275.	275.	299.	389.	395.	
* [KT]										
4	183.	180.	170.	180.	255.	266.	288.	376.	385.	
5	164.	165.	165.	160.	233.	235.	267.	345.	362.	
6	158.	155.	155.	145.	189.	211.	254.	289.	350.	
7	140.	145.	134.	135.	177.	187.	213.	267.	340.	
8	135.	138.	129.	125.	165.	163.	190.	245.	295.	
9	129.	123.	120.	117.	145.	143.	178.	235.	270.	
10	111.	99.	114.	110.	115.	134.	150.	189.	250.	
11		40.	60.	95.	103.	106.	130.	111.	123.	
12					90.	90.	90.	40.	80.	
13										

1Initial Grid Volume [VOLG] = 51771160. m**3

Grid Volume-Area-Elevation Table
*

Layer	Elevation (m)	Area (1.0E6 m**2)	Volume (1.0E6 m**3)	Active Cells
2	1422.60	11.534	71.198	212
3	1421.60	10.666	59.664	187
* [KT]				
4	1420.60	9.858	48.998	162
5	1419.60	8.976	39.140	137
6	1418.60	7.994	30.164	112
7	1417.60	6.840	22.170	87
8	1416.60	5.634	15.330	64
9	1415.60	4.138	9.696	43
10	1414.60	3.242	5.558	27
11	1413.60	1.536	2.316	13
12	1412.60	0.780	0.780	5

Water Surface [Z1] (m)
*

3	5	6	7	8	9	12	13	14	15	16	21	22	23	24	25	26
0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400	0.7400

Temperature [T2] deg C

	3	5	6	7	8	9	12	13	14	15	16	21	22	23	24	25	26
3	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
4	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
5	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
6	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
7		10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00	10.00
8			9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90
9							9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90	9.90
10								9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80	9.80
11												9.80	9.80	9.80	9.80	9.80	9.80
12													9.80	9.80	9.80	9.80	9.80

Tracer g/m**3

	3	5	6	7	8	9	12	13	14	15	16	21	22	23	24	25	26
3	99.00	107.00	108.00	105.00	104.00	103.00	101.00	97.00	94.00	93.00	92.00	85.00	80.00	80.00	79.00	79.00	79.00
4	100.00	108.00	108.00	105.00	104.00	103.00	101.00	97.00	94.00	93.00	92.00	85.00	80.00	80.00	79.00	79.00	79.00
5	101.00	108.00	108.00	105.00	104.00	103.00	101.00	97.00	94.00	93.00	92.00	85.00	80.00	80.00	79.00	79.00	79.00
6	102.00	108.00	108.00	105.00	104.00	103.00	101.00	97.00	95.00	93.00	92.00	85.00	80.00	80.00	79.00	79.00	79.00
7		108.00	108.00	105.00	104.00	103.00	101.00	98.00	95.00	94.00	92.00	85.00	80.00	80.00	79.00	79.00	79.00
8			108.00	105.00	104.00	103.00	101.00	98.00	95.00	94.00	92.00	85.00	80.00	80.00	80.00	79.00	79.00
9							101.00	98.00	95.00	94.00	92.00	85.00	80.00	80.00	80.00	79.00	79.00
10								98.00	95.00	94.00	92.00	85.00	80.00	80.00	80.00	80.00	80.00
11												86.00	80.00	80.00	80.00	80.00	80.00
12													81.00	81.00	80.00	80.00	80.00

Suspended solids g/m**3

	3	5	6	7	8	9	12	13	14	15	16	21	22	23	24	25	26
3	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90	19.90
4	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
5	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
6	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00	25.00
7		30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
8			30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00	30.00
9							40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
10								40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00	40.00
11												45.00	45.00	45.00	45.00	45.00	45.00
12													50.00	50.00	50.00	50.00	50.00

Dissolved solids g/m**3

	3	5	6	7	8	9	12	13	14	15	16	21	22	23	24	25	26
3	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00
4	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00
5	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00
6	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00
7		568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00	568.00
8			570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00
9							570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00	570.00
10								572.00	572.00	572.00	572.00	572.00	572.00	572.00	572.00	572.00	572.00
11												574.00	574.00	574.00	574.00	574.00	574.00
12													576.00	576.00	576.00	576.00	576.00

Algae g/m**3

	3	5	6	7	8	9	12	13	14	15	16	21	22	23	24	25	26
3	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
4	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
5	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
6	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50
7		0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
8			0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
9							0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
10								0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40	0.40
11												0.40	0.40	0.40	0.40	0.40	0.40
12													0.40	0.40	0.40	0.40	0.40

Phosphorous mg/m**3

	3	5	6	7	8	9	12	13	14	15	16	21	22	23	24	25	26
3	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00
4	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00
5	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00
6	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00
7		240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00	240.00
8			340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00
9							340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00
10								340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00	340.00
11												400.00	400.00	400.00	400.00	400.00	400.00
12													500.00	500.00	500.00	500.00	500.00

11. Example of data files provided by Rand Water Board and DWA&F for the Vaal Barrage.

Example of water quality data provided by the Rand Water Board.

Sample Point: Vaal River (1st Week) Date: 5 09 90

Analysis	SAMPLING POINTS										Det.
	0	5	10	15	20	24	30	37	40	45	LVC	Limit
TOP												
Temperature	16	12	16	12	12	15	12	15	11,5	15		
Conductivity	56	77	36	72	72	72	66	56	52	24		
DO (lab.)	11,6	10,6	12,2	12,2	9,7	10,2	9,2	7,9	7,1	8,4		
Chlorophyll a	24	27	53	55	57	36	28	17	17	10		
Phaeophytin a	40	47	92	95	99	58	47	30	29	18		
Total chlorophyll	64	75	145	150	156	92	75	47	45	28		
Secchi (cm)	130	120	100	90	70	25	60	50	40	25		
BOTTOM												
Temperature	16	12	14,5	12	12	15	12	15,5	11,5	15		
Conductivity	85	78	85	71	71	72	66	58	52	23		
DO (lab.)	8,5	10,5	11,6	11,2	10,2	10,2	8,3	7,8	–	9,6		
Chlorophyll a	23		21			37		17		10		
Phaeophytin a	38		35			66		29		18		
Total chlorophyll	61		56			103		45		28		

CZM03 3222540152802405VAAL RIV AT [illegible]

CZM04 3212840152801405[illegible] RIVER AT UTRECHT

Station	year	mo	Day	Date	G.plate		EC	pH	Na	Mg	Ca	F	Cl	NO3	SO4	PO4	T.ALK	Si	K	NH4	Temp.
CZM04	90	6	28	90-06-28	0.500M	0 1	72.8	8.02	80.1	24.1	55.1	0.22	114.7	0.01	157.8	0.009	104.9	0.62	9.35	0.08	13
CZM04	90	7	5	90-07-05	0.500M	0 1	85.6	8.14	84.1	24.6	40.5	0.26	113.4	0.12	162	0.011	110.5	0.79	9.15	0.07	10
CZM04	90	7	12	90-07-12	0.500M	0 1	90.3	8.54	83.2	25.8	48.4	0.33	109.9	0.12	166.8	0.011	107	0.4	9.55	0.05	11
CZM04	90	7	19	90-07-19	0.450M	0 1	95.4	8.03	82.4	28.7	53.2	0.42	100.1	0.08	162.8	0.007	113.7	0.42	10.06	0.08	12
CZM04	90	7	26	90-07-26	0.280M	0 1	88.7	8.56	95.3	28.2	64.9	0.29	121.7	0.39	188.7	0.012	121.8	0.17	11.28	0.05	13
CZM04	90	8	2	90-08-02	0.400M	0 1	84.2	7.73	89.2	27.1	53.3	0.24	116.4	0.05	165.9	0.012	119.5	0.63	10.54	0.11	14
CZM04	90	8	9	90-08-09	0.380M	0 1	87.6	8.44	94.2	25.8	61.4	0.27	120.3	0.07	178.4	0.008	122.8	0.45	11.15	0.05	16
CZM04	90	8	16	90-08-16	0.400M	0 1	85.1	8.33	98.1	25.2	60	0.22	130.3	0.1	174.7	0.014	126.9	0.3	11.11	0.03	14
CZM04	90	8	23	90-08-23	0.280M	0 1	88.2	8.14	99.7	25.6	53.8	0.29	133.9	0.06	178	0.018	111.9	0.4	10.97	0.08	16
CZM04	90	8	30	90-08-30	0.180M	0 1	95.2	8.42	105.7	30	59.6	0.33	135	0.11	183.2	0.01	120.6	0.6	11.88	0.07	16
CZM04	90	9	6	90-09-06	0.100M	0 1	97.7	8.21	108.7	31.7	59.1	0.27	144.8	0.02	192.3	0.005	121.3	0.65	11.44	0.08	17
CZM04	90	9	13	90-09-13	0.100M	0 1	103.5	8.17	113.7	32.7	62	0.28	148.2	0.08	200.3	0.014	141.3	0.59	12.14	0.07	20
CZM04	90	10	18	90-10-18	0.159M	0 1	102.2	8.1	122	32.5	68.1	0.33	167.7	0.04	195.1		147.6	2.42	12.42		22
CZM04	90	10	25	90-10-25	0.055M	0 1	104.5	8.12	124.2	34.7	66.3	0.32	164.2	0.02	193.9		155	2.42	12.58		24
CZM04	90	11	1	90-11-01	0.035M	0 1	103.4	8.16	126.6	35.6	66.6	0.33	168.7	0.02	197.7		158.1	2.53	12.64		25
CZM04	90	11	8	90-11-08	0.010M	0 1	112.1	8.42	129.2	37.1	68	0.38	173.6	0.11	215.1	0.001	159.8	3.04	12.77	0.07	24

CZM05 3222643452743006RIETSPRUIT AT KAALPLAATS

Station	year	mo	Day	Date	G.plate		EC	pH	Na	Mg	Ca	F	Cl	NO3	SO4	PO4	T.ALK	Si	K	NH4	Temp.
CZM05	90	6	28	90-06-28	0.342M	0 1	110.2	8.18	75.3	31	131.4	0.89	102.6	8.86	288.1	0.011	76.6	3.29	14.26	3.97	14
CZM05	90	7	5	90-07-05	0.213M	0 1	114	7.94	73	29.5	122.8	0.81	94.8	8.57	272.9	0.021	82.9	3.59	13.23	1.78	12
CZM05	90	7	12	90-07-12	0.320M	0 1	142	7.57	78.3	32	123	1.48	100.8	7.74	294.5	0.034	86.7	3.00	14.73	2.46	14
CZM05	90	7	19	90-07-19	0.310M	0 1	113.5	7.89	79.9	34.6	122.2	1.12	109.4	7.65	342.2	0.407	95.1	3.61	15.40	7.66	12
CZM05	90	7	26	90-07-26	0.290M	0 1	109.8	7.94	75.6	34.3	141	1.08	107.5	7.3	431	0.015	87.1	2.8	15.70	2.52	14
CZM05	90	8	2	90-08-02	0.310M	0 1	105	7.62	80.2	28.8	113	1.23	107.1	7.05	240.8	0.21	94.3	3.29	13.95	1.24	12
CZM05	90	8	9	90-08-09	0.305M	0 1	97.2	8.28	73	31.1	120.4	1.12	103.7	6.09	332.4	0.178	93	3.56	13.24	1.25	13
CZM05	90	8	16	90-08-16	0.290M	0 1	94	7.86	63.7	30	116.2	1.04	83.2	6.39	381	0.083	78.2	2.83	11.67	3.49	11
CZM05	90	8	23	90-08-23	0.297M	0 1	94.4	7.82	69	29.4	111.7	1.32	94.4	6.87	330.8	0.027	77.2	2.92	12.19	0.95	13
CZM05	90	8	30	90-08-30	0.270M	0 1	103	7.94	65.7	31.2	114.3	1.25	80.2	5.38	378.2	0.468	81.1	3.00	12.84	2.29	19
CZM05	90	9	6	90-09-06	0.282M	0 1	94.9	7.9	75	28	104.3	1.26	91.9	4.72	321.9	0.077	85.4	3.36	13.86	0.81	18
CZM05	90	9	13	90-09-13	0.270M	0 1	103.7	7.91	71.7	33.6	122.2	1.33	98	4.15	405	0.104	76.2	4.19	14.06	0.84	20
CZM05	90	10	5	90-10-05	0.270M	0 1	111.2	8.25	80.2	21.5	125	1.61	113.3	3.2	359.4		98	5.35	14.03		21
CZM05	90	10	11	90-10-11	0.320M	0 1	99.2	7.29	78.2	29.5	133.1	1.62	114.8	7.7	354.6		73.9	5.28	13.22		19
CZM05	90	10	18	90-10-18	0.264M	0 1	100.1	7.88	77.5	30.5	131.5	1.08	112.3	4.67	389.4		81.2	5.51	12.98		21
CZM05	90	10	25	90-10-25	0.223M	0 1	99.2	7.17	68	30.5	113.3	1.29	78.6	4.37	365.5		82.8	5.32	14.22		25
CZM05	90	11	1	90-11-01	0.220M	0 1	99.2	7.7	73.2	21.3	121	1.7	116	4.75	344		88.8	5.24	12.64		25
CZM05	90	11	8	90-11-08	0.216M	0 1	116.7	7.91	71	32.8	121.2	1.06	88.5	3.26	383.9	0.823	90.8	5.77	11.81	3.02	22
CZM05	90	11	15	90-11-15	0.280M	0 1	109.5	8.12	71.9	35.0	172.5	1.55	90.1	4.87	407.9	1.351	86.9	6.15	13.12	2.88	25
CZM05	90	11	22	90-11-22	0.211M	0 1	126	7.9	74.5	31	120.9	1.71	108.4	5.67	346.9	0.586	98.6	5.76	13.93	0.63	25
CZM05	90	11	29	90-11-29	0.230M	0 1	107.5	7.05	88.3	30.8	120.1	1.47	96.7	4.38	365.1	0.775	85.3	6.04	11.86	0.03	26
CZM05	90	12	6	90-12-06	0.231M	0 1	100.3	7.12	65.7	26.7	104.6	1.30	105.3	6.93	293.7	1.465	76.8	6.82	12.13	0.04	25
CZM05	90	12	13	90-12-13	0.218M	0 1	78	7.06	63	21.5	76.7	1.14	79.8	7.42	215.8	1.814	88.4	7.49	12.82	0.04	26

CZM14 3222640302755030TAAIBOS SPRUIT AT VERDUN

Station	year	mo	Day	Date	G.plate		EC	pH	Na	Mg	Ca	F	Cl	NO3	SO4	PO4	T.ALK	Si	K	NH4	Temp.
CZM14	90	6	14	90-06-14	0.010M	0 1	66.9	7.71	103.4	9.5	19	0.64	88.4	0.06	25.6	0.041	175.2	7.56	3.39	0.08	15
CZM14	90	7	5	90-07-05	0.007M	0 1	68.7	8.22	110.8	12.2	22.6	0.50	94.5	0.07	28.2	0.03	199.5	6.57	3.61	0.08	10
CZM14	90	7	12	90-07-12	0.001M	0 1	84.4	8.37	112.4	13.7	23.6	0.72	97.1	0.08	44.2	0.033	208.9	6.16	3.71	0.06	12
CZM14	90	8	9	90-08-09	0.005M	0 1	76	8.46	131.9	16.1	30.8	0.34	110.5	0.07	31.4	0.012	244.5	5.01	6	0.09	14
CZM14	90	8	16	90-08-16	0.010M	0 1	79.1	8.3	138.6	15.5	28.6	0.62	119	0.2	32.6	0.019	254.2	4.74	5.64	0.05	14
CZM14	90	8	23	90-08-23	0.010M	0 1	80.5	8.11	145	16	29.5	0.6	124.8	0.07	35	0.048	282.4	4.57	5.74	0.06	17
CZM14	90	10	25	90-10-25	0.001M	0 1	58.7	8.42	90.7	16.4	33.3	0.69	64	0.05	44.9		228.9	5.89	5.86		26
CZM14	90	11	8	90-11-08	0.001M	0 1	57.2	8.58	82.7	19.1	32.8	0.55	42.9	0.08	39.3	0.037	219.4	6.28	5.28	0.03	24
CZM14	90	11	15	90-11-15	0.005M	0 1	48.3	8.46	52.7	19.4	32.8	0.61	37.6	0.05	32.1	0.01	209.7	6.23	5.82	0.04	25
CZM14	90	11	22	90-11-22	0.001M	0 1	44.4	7.86	39.4	16.8	29.2	0.54	24.1	0.03	30.5	0.007	177.2	8.2	4.50	0.03	24
CZM14	90	11	29	90-11-29	0.001M	0 1	40.2	7.58	36.3	14.3	24.9	0.48	24.5	0.03	32.3	0.006	148.5	5.92	4.6	0.03	24
CZM14	90	12	6	90-12-06	0.010M	0 1	28	8.33	23.7	10.7	19.2	0.51	15.9	0.12	21.3	0.036	114.4	4.75	3.44	0.09	23
CZM14	90	12	13	90-12-13	0.010M	0 1	41.5	8.13	26.3	12.5	22.5	0.43	18.2	0.03	23.6	0.015	129.5	5.29	2.80	0.03	26

CZM15 3222836300757450KLIP RIVER AT WALDRIFT (VEREENIGING)

Station	year	mo	Day	Date	G.plate		EC	pH	Na	Mg	Ca	F	Cl	NO3	SO4	PO4	T.ALK	Si	K	NH4	Temp.
CZM15	90	6	28	90-06-28	0.850M	0 1	126.1	8.02	83.8	30.9	88	0.34	97.3	6.07	258.2	0.168	115.2	4.39	17.31	0.07	13
CZM15	90	7	5	90-07-05	0.800M	0 1	105.4	8.03	82.8	30.8	84.4	0.22	100.6	0.47	285.7	0.216	120.4	4.31	17.79	0.19	11
CZM15	90	7	12	90-07-12	0.850M	0 1	126.3	7.90	89.5	33.7	82.4	0.41	103.3	6.23	296.5	0.303	114.8	3.88	17.44	0.18	13
CZM15	90	7	19	90-07-19	0.835M	0 1	117.8	7.88	86.8	34.7	87.9	0.54	101.3	6.07	258.7	0.392	118.9	2.74	17.34	0.1	12
CZM15	90	7	26	90-07-26	0.819M	0 1	91.3	8.51	64.8	30.4	93.2	0.38	98.1	5.53	293.8	0.328	121.3	3.12	17.21	0.09	13
CZM15	90	8	2	90-08-02	0.840M	0 1	90.1	8.02	82.4	30.6	77.7	0.4	94.5	5.34	254.7	0.361	125.7	3.98	17.24	0.15	13
CZM15	90	8	9	90-08-09	0.840M	0 1	91.3	7.24	81.8	31.2	85.9	0.28	93	4.81	247.3	0.453	120.7	4.08	17.28	0.11	15
CZM15	90	8	16	90-08-16	0.820M	0 1	91.2	8.12	81.7	30.7	83.5	0.3	94.9	4.78	276.2	0.337	123.7	3.88	18.31	0.1	14
CZM15	90	8	23	90-08-23	0.770M	0 1	88.9	7.98	82.3	30.1	81.1	0.28	97.9	5.45	288.1	0.222	114.4	3.37	17.07	0.08	20
CZM15	90	8	30	90-08-30	0.740M	0 1	90.7	8.42	83.2	27.8	78.1	0.42	94.2	4.9	225.1	0.388	125.1	4.38	17.84	0.16	17
CZM15	90	9	6	90-09-06	0.820M	0 1	94	8.03	80.5	28.2	74.8	0.29	93.2	4.89	215.8	0.449	117.5	4.94	17.72	0.12	17
CZM15	90	9	13	90-09-13	0.720M	0 1	95	8.66	86.8	31.4	84.9	0.23	101.5	4.31	253.4	0.568	121.8	5.05	18.55	0.14	20
CZM15	90	10	11	90-10-11	1.020M	0 1	108.9	7.44	89.6	28.5	79.6	0.45	95.7	4.16	271.7	0.628	125.9	7.2	20.27	0.04	20
CZM15	90	10	18	90-10-18	0.730M	0 1	97.3	7.79	78.7	30.7	95.1	0.45	80.6	3.38	304.2		117.3	6.36	17.09		21
CZM15	90	10	25	90-10-25	0.620M	0 1	86.7	8.04	81	25	72.7	0.33	87.6	4.32	204.2		138.4	6.23	18.75		23
CZM15	90	11	1	90-11-01	0.600M	0 1	78.1	7.94	77.4	21.1	60.3	0.3	80.3	2.9	152.8		149.4	6.45	18.63		24
CZM15	90	11	8	90-11-08	0.700M	0 1	80.4	8.17	82.3	26	74.7	0.29	88	3.48	248.4	0.635	124.7	6.86	17.42	0.14	26
CZM15	90	11	15	90-11-15	0.550M	0 1	102.3	8.1	82.2	22.9	59.5	0.24	89	4.09	178.7	1.133	137.7	7.46	17.42	0.05	24
CZM15	90	11	22	90-11-22	0.560M	0 1	77.4	7.53	80.8	21.3	55	0.23	82.2	3.8	141.7	0.998	147.5	7.49	19.44	0.03	25
CZM15	90	11	29	90-11-29	0.780M	0 1	90.3	7.48	79.8	22.2	59.7	0.24	80.8	4.32	189.4	1.21	133.3	6.89	18.01	0.03	24

APPENDIX A4.5

OUTPUT DATA
INANDA DAM
SIMULATION: JANUARY TO DECEMBER 1990

```
1DeGray Reservoir 1980 simulation
 Daily meteorologic updates
 Everex 80386 25MHz using Lahey FORTRAN and Weitek coprocessor
 1 hr 12 min CPU time for 251 days of simulation

 Time Parameters
*____ __________

   Date                      [JDAY] =     77 days 12.36 hours
   Elapsed time            [ELTMJD] =     13 days  0.36 hours
   Timestep                   [DLT] =   2440 sec
   Minimum timestep        [MINDLT] =   1550 sec
   Average timestep         [AVDLT] =   2493 sec
   Number of iterations       [NIT] =    451
   Number of violations        [NV] =      1

 Meteorological Parameters
*______________ __________

   Equilibrium temperature [ET] =     14.10 deg C
   Dewpoint temperature    [TD] =      7.20 deg C
   Wind speed          [WINDSP] =      4.56 m/sec
   Wind direction         [PHI] =      2.00 rad
   Wind sheading          [WSC] =      0.70
   Surface heat exchange [CSHE] = 5.60E-06 m/sec
   Short wave radiation   [SRO] = 4.15E-05 C-m/sec

 Inflow
*______

   Branch  1
     Inflow       [QIN] =   53.42 m**3/sec
     Temperature  [TIN] =   11.20 deg C

*
 Outflow
*_______

   Outlets
*  _______

     Layer                [KOUT] =      8       9      10      11      12      13      14      15
*
     Outflow (m**3/sec)  [QOUT] =    0.00    0.00    0.00    0.04    0.08    0.14    0.08    0.04
*

1Constituent Inflow Concentrations
*___________ ______ ______________

   Branch  1
     Suspended solids    =   5.000 g/m**3
     Dissolved solids    =  60.000 g/m**3
     Labile DOM          =   5.333 g/m**3
     Refractory DOM      =   7.778 g/m**3
     Algae               =   0.000 g/m**3
     Detritus            =   0.200 g/m**3
     Phosphorous         =   0.000 g/m**3
     Ammonia             =   0.070 g/m**3
     Nitrate-Nitrite     =   0.000 g/m**3
     Dissolved oxygen    =   8.600 g/m**3
     Iron                =   0.100 g/m**3

 Geometry
*________

   Surface layer [KT] =        8
   Elevation   [ELKT] =   123.87 m

   Current left segment [IUC]
*  _______ ____ _______

     Branch  1 =  2

 Volume Balance
*______ _______

   Branch  1
     Spatial change   [VOLSBR] =     1726.4 m**3
     Temporal change  [VOLTBR] =     1726.4 m**3
     Ratio            [VRATIOB] =    1.0000
   Grid
     Spatial change    [VOLSG] =     1726.4 m**3
     Temporal change   [VOLTG] =     1726.4 m**3
     Ratio           [VRTIOG] =      1.0000


   Water Surface [Z1] (m)
*  _____ _______
```

2	4	7	10	12	13	14	15	18	19	20	22	24	26	27	29	31
-1.5188	-1.5191	-1.5193	-1.5196	-1.5198	-1.5199	-1.5201	-1.5203	-1.5206	-1.5207	-1.5208	-1.5211	-1.5214	-1.5216	-1.5218	-1.5222	-1.5226

```
1DeGray Reservoir 1980 simulation
 Daily meteorologic updates
 Everex 80386 25MHz using Lahey FORTRAN and Weitek coprocessor
 1 hr 12 min CPU time for 251 days of simulation

 Date =   77 days 12.36 hours
```

Horizontal velocity (U) m/sec

	2	4	7	10	12	13	14	15	18	19	20	22	24	26	27	29	31
8	0.1162	0.0756	0.0499	0.0492	0.0411	0.0390	0.0385	0.0456	0.0421	0.0406	0.0444	0.0434	0.0551	0.0558	0.0481	0.0422	0.0000
9	0.3868	0.0305	0.0120	0.0206	0.0161	0.0126	0.0138	0.0186	0.0150	0.0161	0.0189	0.0204	0.0351	0.0310	0.0269	0.0241	0.0005
10		-0.0188	-0.0159	-0.0212	-0.0218	-0.0209	-0.0202	-0.0259	-0.0213	-0.0190	-0.0165	-0.0100	0.0009	-0.0089	-0.0073	-0.0016	0.0000
11			-0.0306	-0.0354	-0.0341	-0.0319	-0.0333	-0.0401	-0.0327	-0.0295	-0.0277	-0.0221	-0.0232	-0.0278	-0.0329	-0.0171	0.0000
12			-0.0332	-0.0408	-0.0393	-0.0368	-0.0381	-0.0449	-0.0355	-0.0315	-0.0295	-0.0272	-0.0356	-0.0357	-0.0315	-0.0278	0.0001
13			-0.0255	-0.0326	-0.0364	-0.0338	-0.0316	-0.0401	-0.0310	-0.0251	-0.0313	-0.0280	-0.0357	-0.0348	-0.0276	-0.0259	0.0001
14				-0.0246	-0.0270	-0.0213	-0.0219	-0.0313	-0.0245	-0.0171	-0.0154	-0.0105	-0.0241	-0.0261	-0.0199	-0.0175	0.0001
15				-0.0152	-0.0131	-0.0119	-0.0121	-0.0207	-0.0186	-0.0104	-0.0081	-0.0043	-0.0107	-0.0125	-0.0085	-0.0000	0.0000
16					-0.0080	-0.0033	-0.0032	-0.0100	-0.0179	-0.0086	-0.0069	-0.0036	-0.0011	0.0005	0.0010	-0.0006	0.0000
17					-0.0011	0.0041	0.0048	0.0005	-0.0111	-0.0108	-0.0102	-0.0054	-0.0010	0.0056	0.0049	0.0029	0.0000
18							0.0059	0.0094	-0.0123	-0.0163	-0.0158	-0.0084	-0.0048	0.0019	0.0031	0.0033	0.0000
19								0.0075	-0.0192	-0.0228	-0.0209	-0.0116	-0.0104	-0.0065	-0.0033	0.0017	0.0000
20									-0.0221	-0.0252	-0.0224	-0.0148	-0.0161	-0.0169	-0.0104	-0.0013	0.0000
21										-0.0229	-0.0214	-0.0179	-0.0206	-0.0226	-0.0170	-0.0045	0.0000
22											-0.0200	-0.0210	-0.0244	-0.0294	-0.0226	-0.0070	0.0000
23												-0.0228	-0.0277	-0.0347	-0.0267	-0.0087	0.0000
24												-0.0219	-0.0296	-0.0379	-0.0292	-0.0097	0.0000
25												-0.0173	-0.0297	-0.0385	-0.0299	-0.0101	0.0000
26													-0.0277	-0.0378	-0.0293	-0.0102	0.0000
27													-0.0228	-0.0314	-0.0244	-0.0084	0.0000
28													-0.0179	-0.0270	-0.0218	-0.0073	0.0000
29														-0.0224	-0.0213	-0.0048	0.0000
30														-0.0174	-0.0162	-0.0029	0.0000
31															-0.0112	0.0002	0.0000

32	0.0032	0.0000
33	0.0063	0.0000
34	0.0073	0.0000
35		0.0000

1DeGray Reservoir 1980 simulation
Daily meteorologic updates
Everex 80386 25MHz using Lahey FORTRAN and Weitek coprocessor
1 hr 12 min CPU time for 251 days of simulation

Date = 77 days 12.36 hours

Vertical velocity [W] mm/sec

	2	4	7	10	12	13	14	15	18	19	20	22	24	26	27	29	31
8	-0.0245	-0.0626	-0.0241	-0.0445	-0.0202	-0.0330	-0.0091	0.0131	-0.0245	-0.0511	-0.0416	-0.0198	0.0513	-0.0047	0.0123	0.0623	0.1551
9	0.0000	-0.0543	-0.0381	-0.0550	-0.0284	-0.0274	-0.0138	0.0174	-0.0470	-0.0727	-0.0590	-0.0262	0.0470	-0.0002	0.0162	0.0817	0.2123
10		0.0000	-0.0399	-0.0444	-0.0247	-0.0165	-0.0163	0.0160	-0.0499	-0.0773	-0.0602	-0.0285	0.0534	0.0162	0.0175	0.0761	0.2210
11			-0.0409	-0.0333	-0.0179	-0.0347	-0.0183	0.0061	-0.0533	-0.0705	-0.0559	-0.0263	0.0341	0.0243	0.0190	0.0634	0.1955
12			-0.0368	-0.0257	-0.0138	-0.0253	-0.0161	-0.0075	-0.0565	-0.0565	-0.0481	-0.0179	0.0102	0.0246	0.0271	0.0483	0.1440
13			0.0000	-0.0213	-0.0095	-0.0091	-0.0090	-0.0139	-0.0584	-0.0450	-0.0412	-0.0122	-0.0018	0.0193	0.0290	0.0404	0.0865
14				-0.0126	-0.0047	0.0053	-0.0015	-0.0128	-0.0647	-0.0456	-0.0392	-0.0113	-0.0037	0.0163	0.0295	0.0376	0.0451
15				0.0000	-0.0020	0.0129	0.0044	-0.0084	-0.0803	-0.0592	-0.0441	-0.0125	-0.0009	0.0142	0.0292	0.0427	0.0256
16					-0.0019	0.0109	0.0090	0.0045	-0.0930	-0.0685	-0.0473	-0.0142	-0.0067	0.0122	0.0330	0.0525	0.0220
17					0.0000	0.0000	0.0105	0.0162	-0.0881	-0.0473	-0.0489	-0.0178	-0.0176	0.0108	0.0397	0.3637	0.0252
18							0.0000	0.0111	-0.0703	-0.0439	-0.0573	-0.0239	-0.0316	0.0073	0.0436	0.3734	0.0295
19								0.0000	-0.0423	-0.0629	-0.0625	-0.0312	-0.0476	0.0015	0.0413	0.0759	0.0322
20									0.0000	-0.0486	-0.0523	-0.0421	-0.0644	-0.0065	0.0408	0.0725	0.0322
21										0.0000	-0.0429	-0.0596	-0.0787	-0.0158	0.0370	0.0673	0.0291
22											0.0000	-0.0768	-0.0878	-0.0249	0.0318	0.0636	0.0230
23												-0.0802	-0.0896	-0.0319	0.0244	0.0634	0.0152
24												-0.0442	-0.0821	-0.0358	0.0154	0.0630	0.0073
25												0.0000	-0.0691	-0.0364	0.0068	0.0600	0.0000
26													-0.0519	-0.0334	0.0000	0.0542	-0.0064
27													-0.0382	-0.0299	-0.0066	0.0477	-0.0115
28													0.0000	-0.0314	-0.0160	0.0443	-0.0148
29														-0.0307	-0.0220	0.0402	-0.0165
30														0.0000	-0.0230	0.0340	-0.0171
31															0.0000	0.0291	-0.0170
32																0.0255	-0.0147
33																0.0154	-0.0098
34																0.0000	-0.0044
35																	0.0000

1DeGray Reservoir 1980 simulation
Daily meteorologic updates
Everex 80386 25MHz using Lahey FORTRAN and Weitek coprocessor
1 hr 12 min CPU time for 251 days of simulation

Date = 77 days 12.36 hours

Temperature [T2] deg C

	2	4	7	10	12	13	14	15	18	19	20	22	24	26	27	29	31
8	11.23	11.14	9.94	9.62	9.43	9.38	9.48	9.61	9.60	9.58	9.62	9.79	10.04	10.19	10.24	10.38	10.51
9	11.21	10.26	8.59	8.75	8.81	8.64	8.97	9.22	9.16	9.17	9.23	9.40	9.83	9.88	9.92	10.23	10.46
10		8.20	8.18	8.43	8.58	8.66	8.76	8.91	9.00	9.05	9.10	9.26	9.67	9.59	9.71	10.10	10.42
11			8.08	8.39	8.55	8.63	8.71	8.82	8.98	9.03	9.09	9.21	9.50	9.54	9.64	9.98	10.37
12			7.98	8.31	8.52	8.59	8.67	8.78	8.95	9.00	9.05	9.20	9.39	9.51	9.57	9.84	10.27
13			7.83	8.12	8.40	8.48	8.56	8.68	8.88	8.91	8.97	9.10	9.26	9.45	9.51	9.68	10.07
14				7.90	8.20	8.29	8.36	8.46	8.76	8.76	8.81	8.92	9.01	9.29	9.37	9.48	9.75
15				7.70	7.98	8.11	8.16	8.23	8.61	8.57	8.60	8.69	8.71	8.85	8.93	9.04	9.24
16					7.79	7.91	7.99	8.05	8.42	8.36	8.39	8.46	8.49	8.43	8.42	8.53	8.65
17					7.66	7.71	7.81	7.91	8.22	8.17	8.19	8.24	8.28	8.19	8.13	8.16	8.23
18							7.74	7.81	8.02	7.99	7.97	8.02	8.06	7.99	7.93	7.92	7.95
19								7.72	7.89	7.84	7.77	7.80	7.81	7.80	7.75	7.75	7.77
20									7.91	7.74	7.62	7.58	7.56	7.61	7.60	7.61	7.64
21										7.62	7.47	7.37	7.38	7.45	7.46	7.50	7.53
22											7.28	7.21	7.24	7.31	7.34	7.39	7.44
23												7.12	7.12	7.20	7.24	7.31	7.36
24												7.06	7.02	7.10	7.16	7.24	7.28
25												7.04	6.95	7.02	7.08	7.17	7.21
26													6.88	6.94	7.00	7.11	7.14
27													6.83	6.85	6.90	7.04	7.06
28													6.79	6.77	6.81	6.96	6.97
29														6.71	6.74	6.87	6.88
30														6.68	6.68	6.79	6.80
31															6.65	6.70	6.72
32																6.63	6.65
33																6.58	6.59
34																6.54	6.55
35																	6.52

1DeGray Reservoir 1980 simulation
Daily meteorologic updates
Everex 80386 25MHz using Lahey FORTRAN and Weitek coprocessor
1 hr 12 min CPU time for 251 days of simulation

Date = 77 days 12.36 hours

Suspended solids g/m**3

	2	4	7	10	12	13	14	15	18	19	20	22	24	26	27	29	31
8	8.58	7.36	3.32	1.42	0.63	0.45	0.34	0.28	0.21	0.20	0.18	0.15	0.11	0.10	0.09	0.07	0.06
9	8.94	6.81	2.39	1.01	0.56	0.45	0.37	0.31	0.25	0.25	0.23	0.18	0.13	0.12	0.11	0.08	0.07
10		3.17	1.25	0.67	0.49	0.43	0.38	0.33	0.28	0.27	0.25	0.20	0.14	0.14	0.13	0.09	0.07
11			0.93	0.60	0.48	0.41	0.39	0.35	0.29	0.28	0.26	0.22	0.16	0.15	0.13	0.10	0.07
12			0.80	0.57	0.47	0.41	0.40	0.36	0.30	0.29	0.27	0.23	0.18	0.16	0.15	0.11	0.08
13			0.78	0.58	0.47	0.44	0.41	0.37	0.31	0.30	0.28	0.24	0.19	0.17	0.16	0.12	0.09
14				0.61	0.50	0.46	0.43	0.39	0.33	0.32	0.30	0.26	0.21	0.18	0.17	0.14	0.11
15				0.67	0.54	0.50	0.47	0.43	0.35	0.35	0.33	0.29	0.24	0.21	0.19	0.17	0.14
16					0.60	0.55	0.51	0.48	0.38	0.39	0.37	0.32	0.27	0.25	0.24	0.22	0.19
17					0.66	0.62	0.57	0.53	0.43	0.44	0.42	0.36	0.31	0.30	0.30	0.27	0.24
18							0.62	0.57	0.49	0.49	0.48	0.42	0.37	0.36	0.37	0.34	0.30
19								0.62	0.54	0.55	0.55	0.50	0.47	0.44	0.45	0.40	0.36
20									0.55	0.60	0.64	0.63	0.61	0.55	0.54	0.48	0.42
21										0.67	0.74	0.79	0.76	0.67	0.64	0.56	0.48
22											0.82	0.93	0.88	0.79	0.74	0.64	0.55
23												1.02	0.99	0.89	0.83	0.72	0.61
24												1.09	1.08	0.98	0.92	0.79	0.69
25												1.12	1.15	1.06	1.00	0.86	0.76
26													1.22	1.14	1.07	0.93	0.85
27													1.28	1.22	1.16	1.01	0.93
28													1.32	1.30	1.25	1.09	1.03
29														1.37	1.32	1.17	1.12
30														1.41	1.39	1.25	1.20
31															1.44	1.33	1.28
32																1.43	1.36
33																1.49	1.43
34																1.55	1.50
35																	1.56

1DeGray Reservoir 1980 simulation
Daily meteorologic updates
Everex 80386 25MHz using Lahey FORTRAN and Weitek coprocessor
1 hr 12 min CPU time for 251 days of simulation

Date = 77 days 12.36 hours

Figure A4.5.1

Depth profile plots showing the simulated and measured water temperature in Inanda Dam at Segment 25, located at the dam wall.

DAYS 60 to 80

KEY:
Measured: ⊙
Simulated: —

Variable: Temperature

Units: Degree C

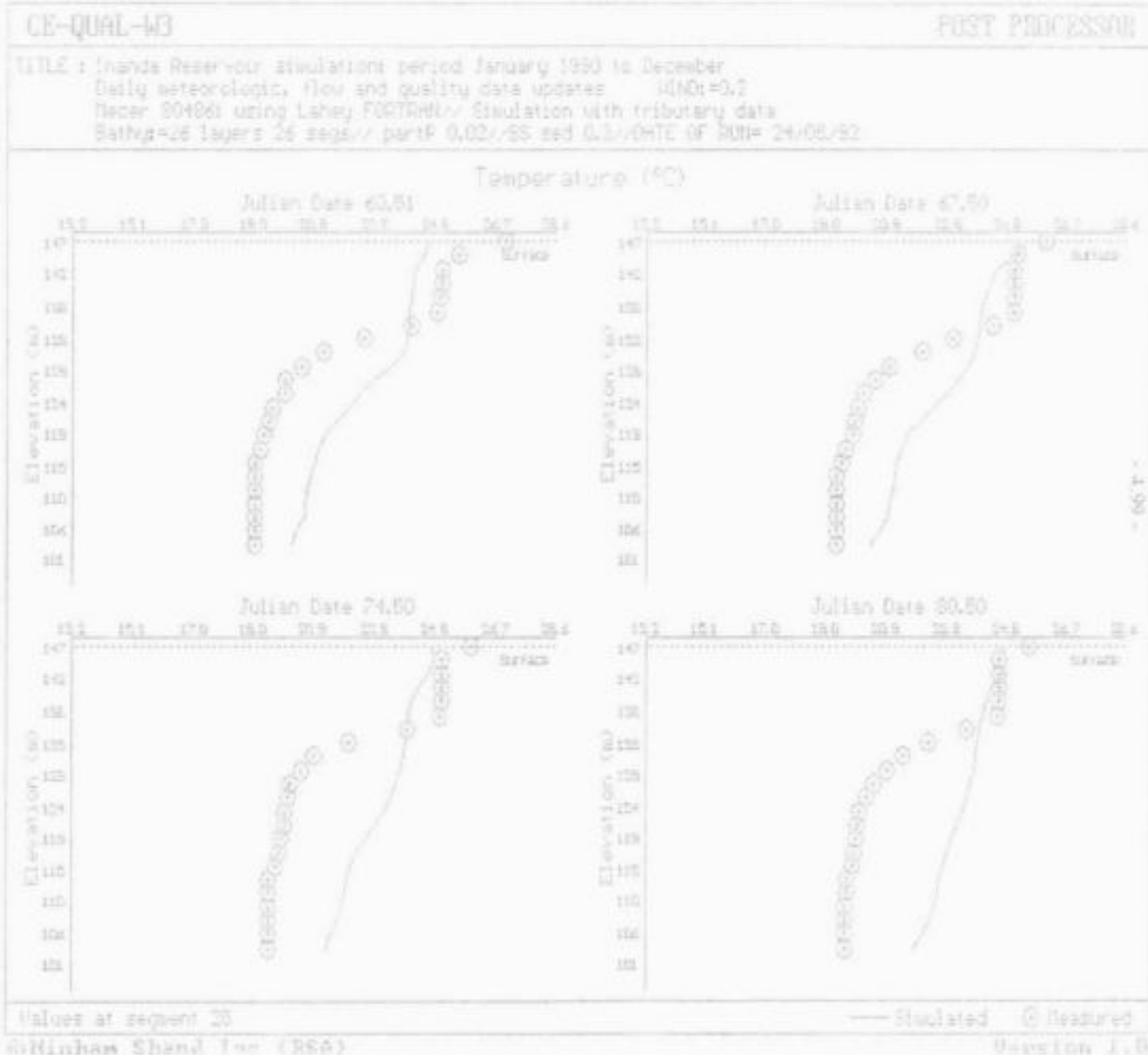

Figure A4.5.2

Depth profile plots showing the simulated and measured water temperature in Inanda Dam at Segment 25, located at the dam wall.

DAYS 143 to 172

KEY:
Measured: ⊙
Simulated: ---

Variable:Temperature

Units: Degree C

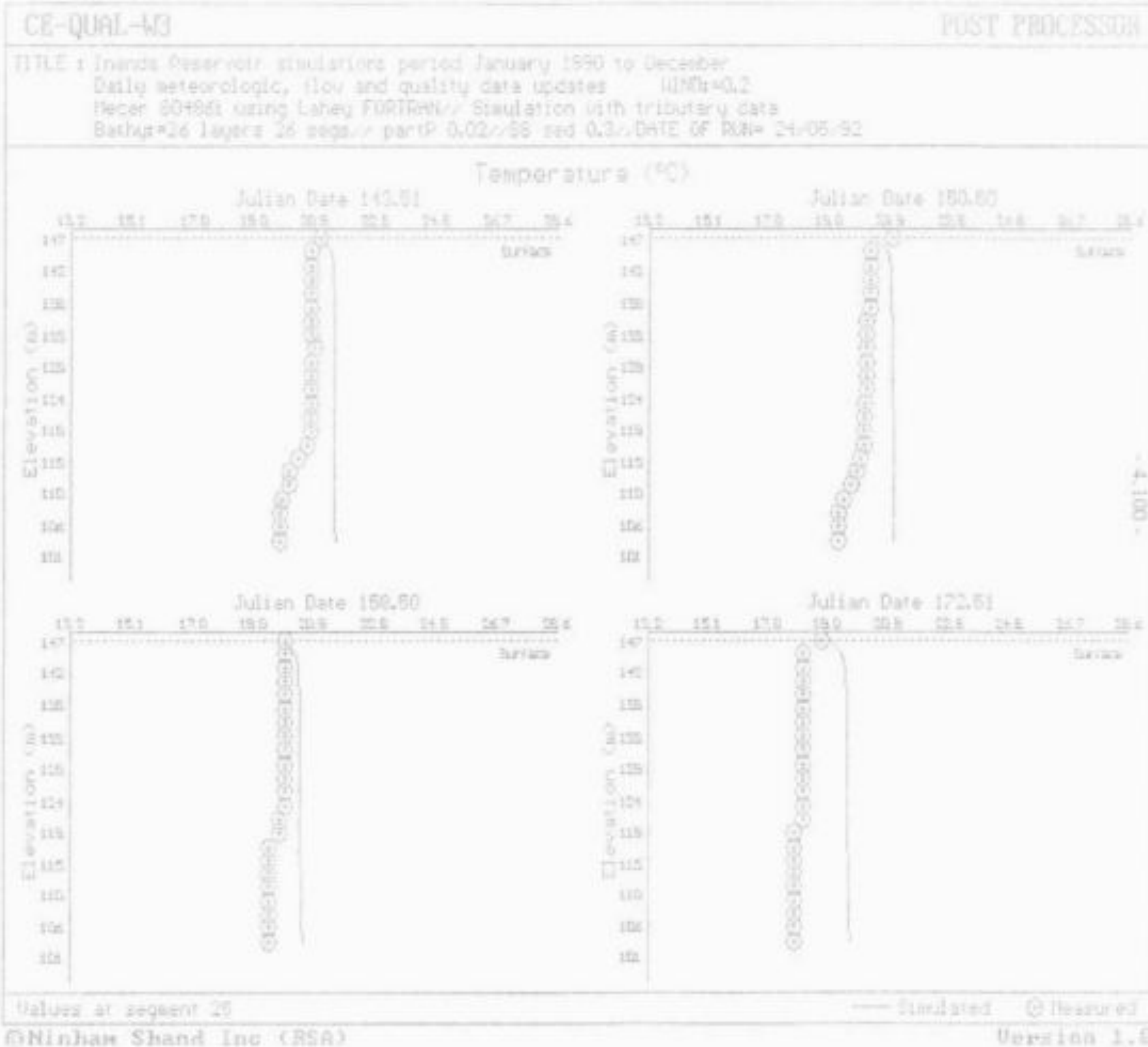

Figure A4.5.3

Two-dimensional plot showing the simulated water temperature in Inanda Dam at Segments 2 to 25.

DAY NUMBER: 4

Variable: Temperature

Units: Degree C.

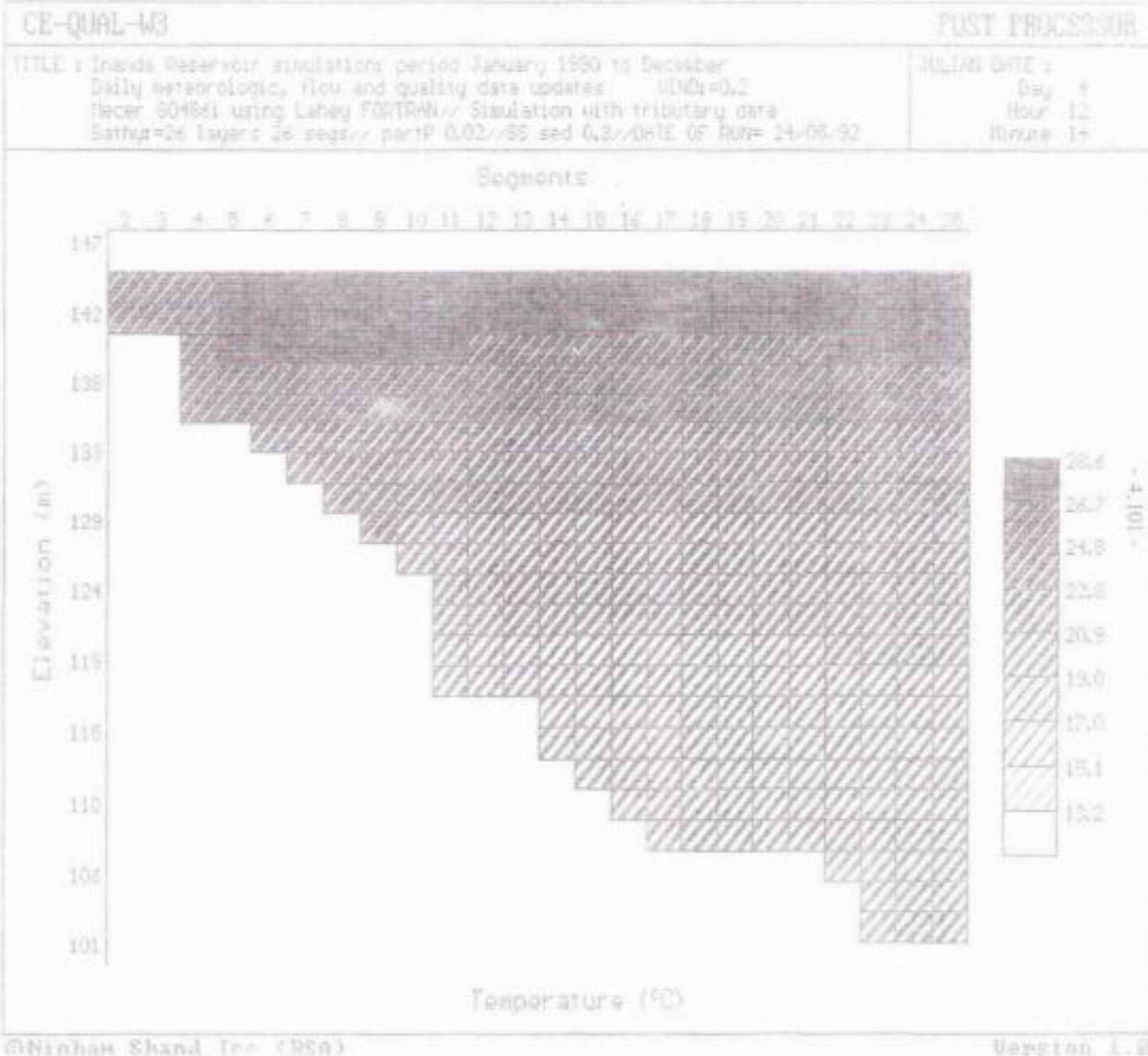

Figure A4.5.4

Two-dimensional plot showing the simulated water temperature in Inanda Dam at Segments 2 to 25.

DAY NUMBER: 200

Variable: Temperature

Units: Degree C.

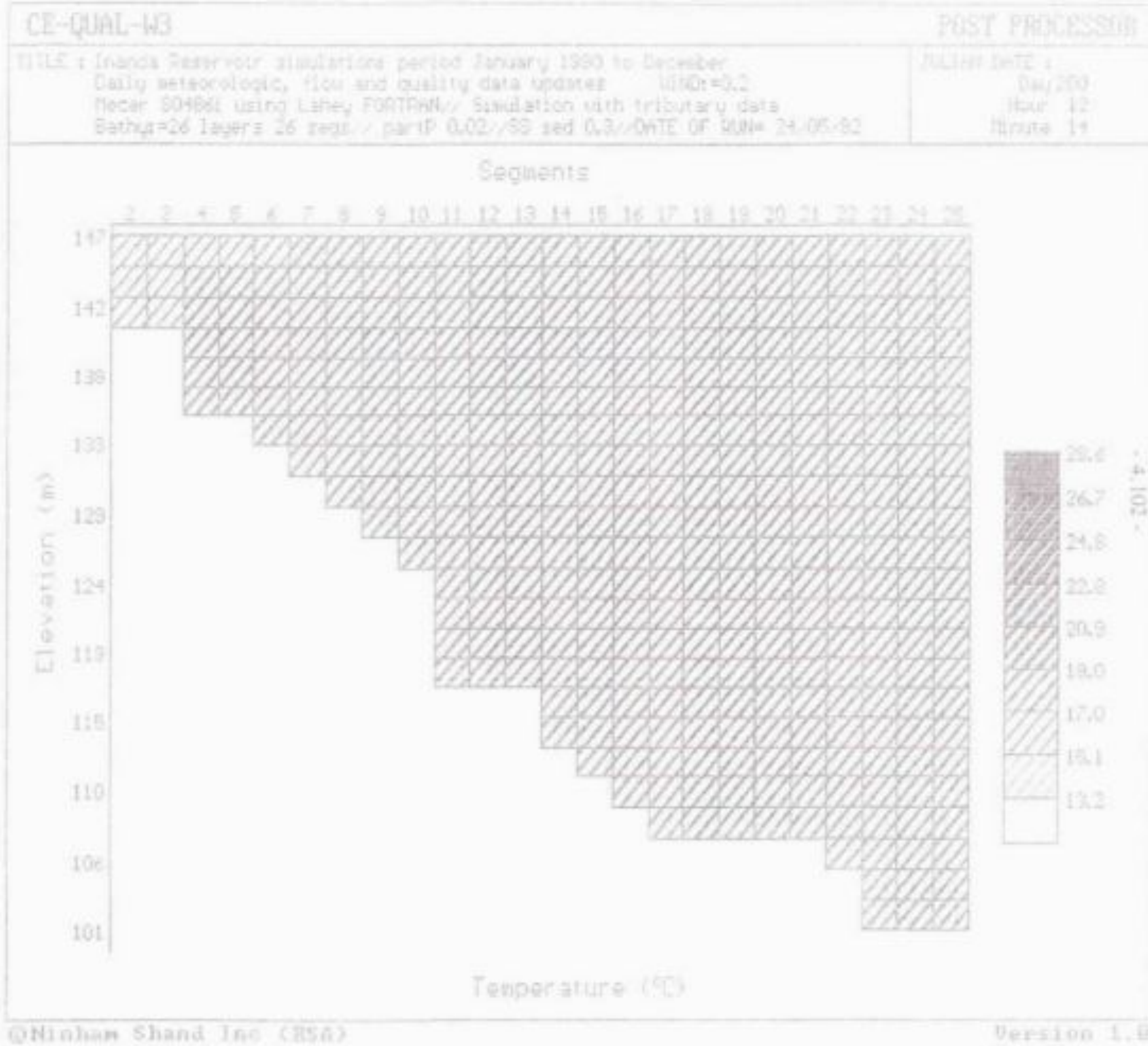

Figure A4.5.5

Depth profile plots showing the simulated and measured dissolved oxygen in Inanda Dam at Segment 25, located at the dam wall.

DAYS 4 to 25

KEY:
Measured: ⊙
Simulated: —

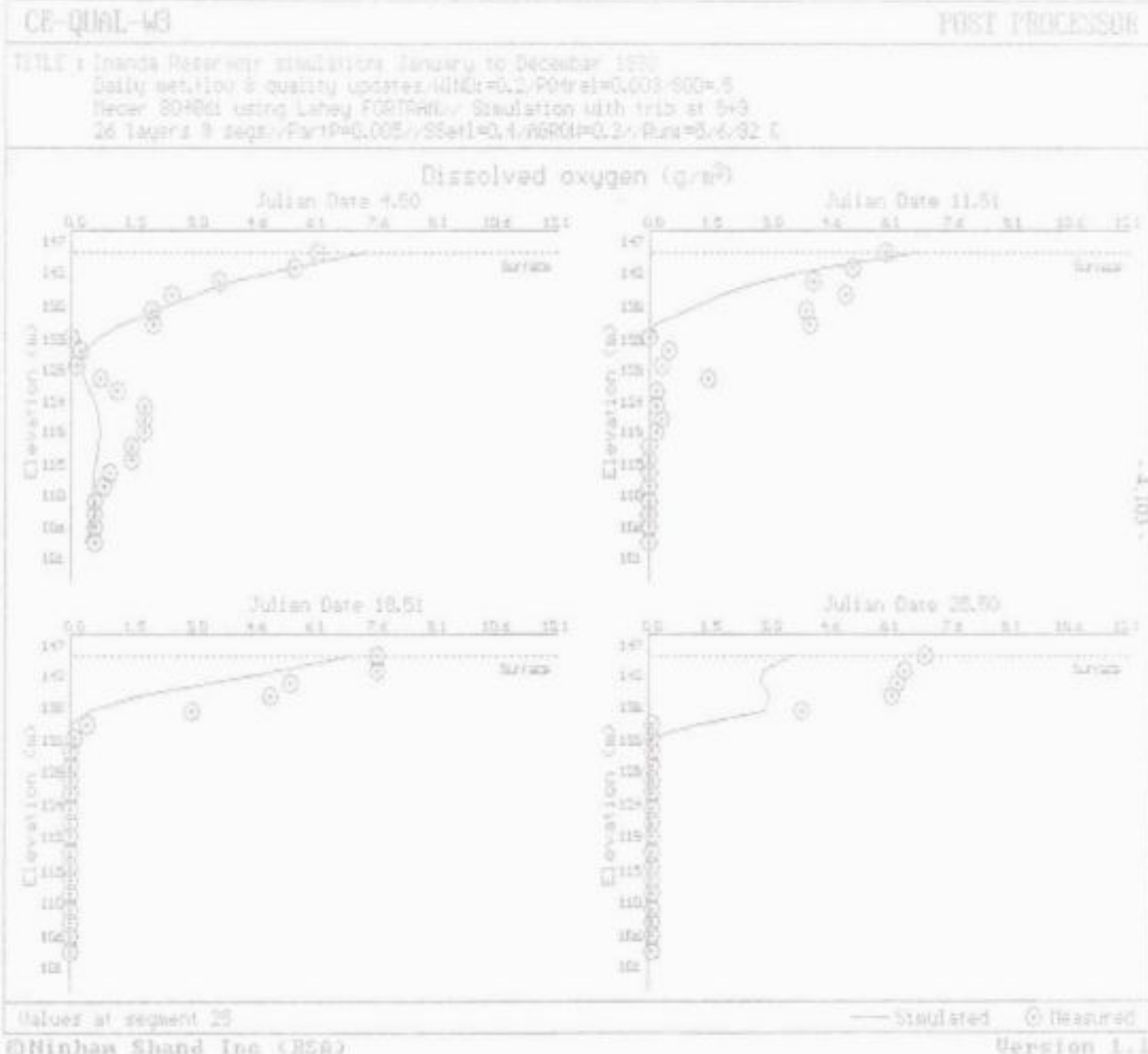

Figure A4.5.6

Depth profile plots showing the simulated and measured dissolved oxygen in Inanda Dam at Segment 25, located at the dam wall.

DAYS 25 to 46

KEY:
Measured: ⊙
Simulated: —

Variable:
Dissolved oxygen

Units: mg/l

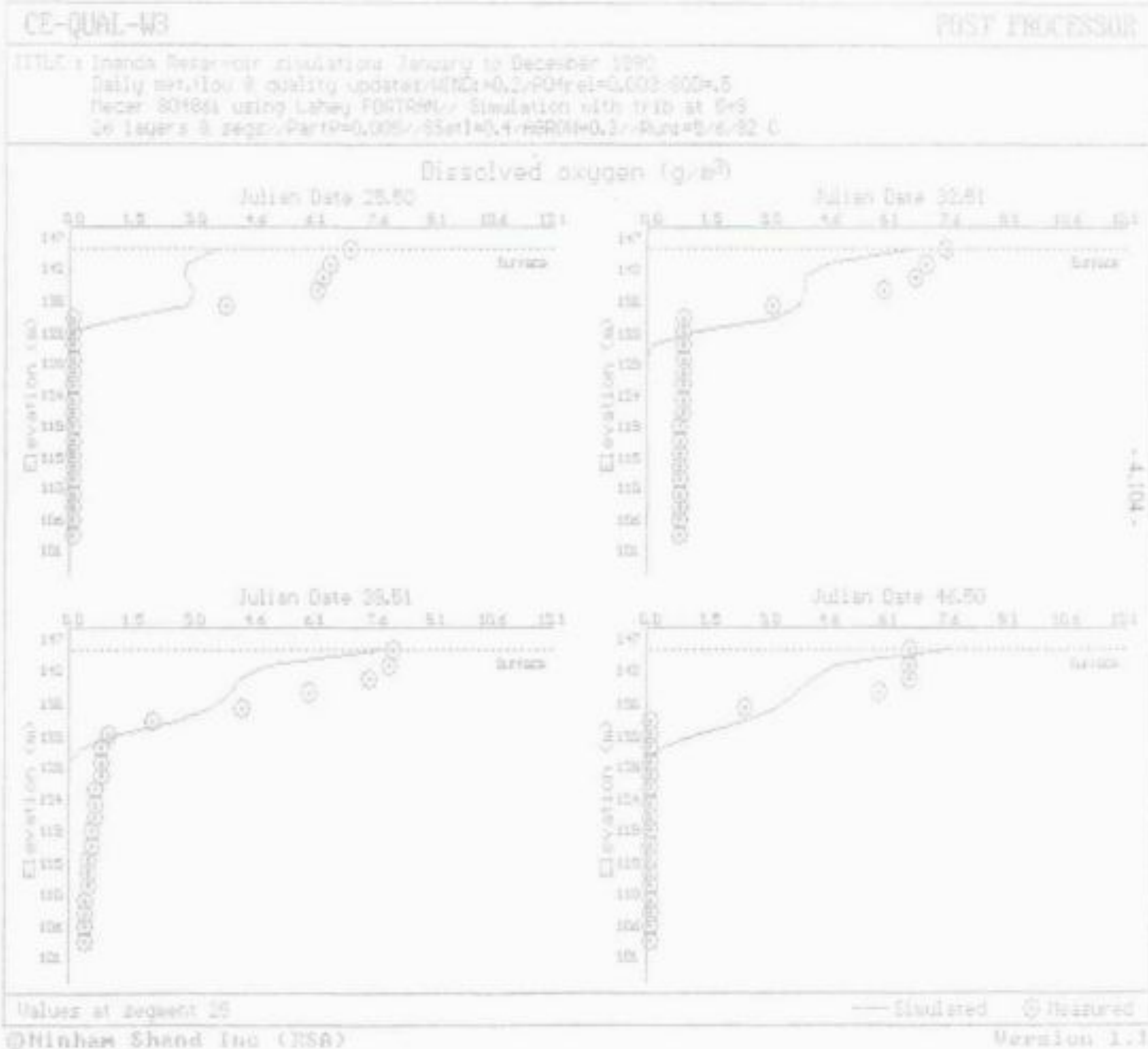

Figure A4.5.7

Two-dimensional plot showing the simulated and measured dissolved oxygen in Inanda Dam at Segments 2 to 25.

DAY NUMBER: 32

KEY:
Inflow: ▾

Variable:
Dissolved oxygen

Units: mg/l

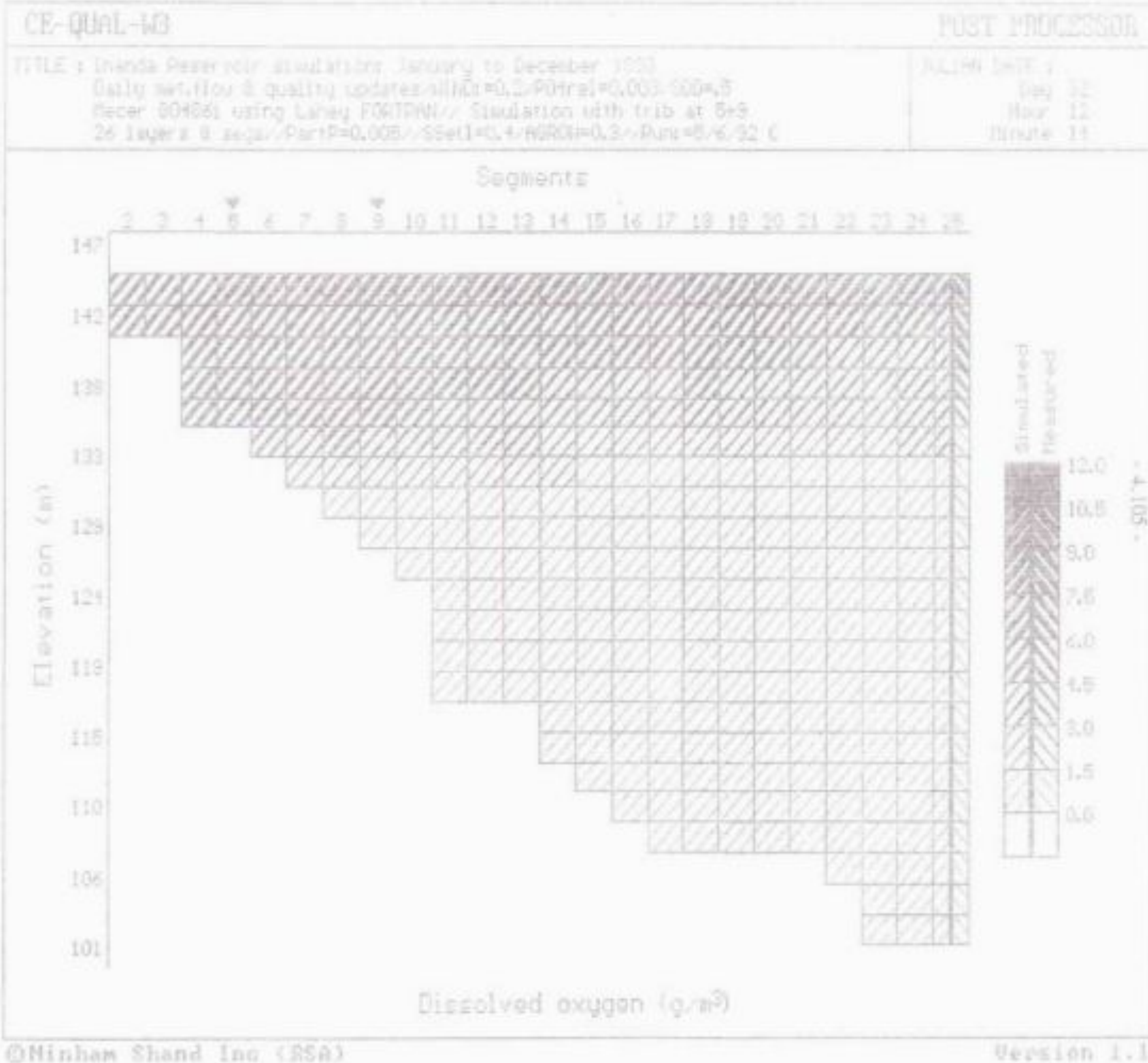

Figure A4.5.8

Two-dimensional plot showing the simulated and measured dissolved oxygen in Inanda Dam at Segments 2 to 25.

DAY NUMBER: 88

KEY:
Inflow: ▾

Variable:
Dissolved oxygen

Units: mg/l

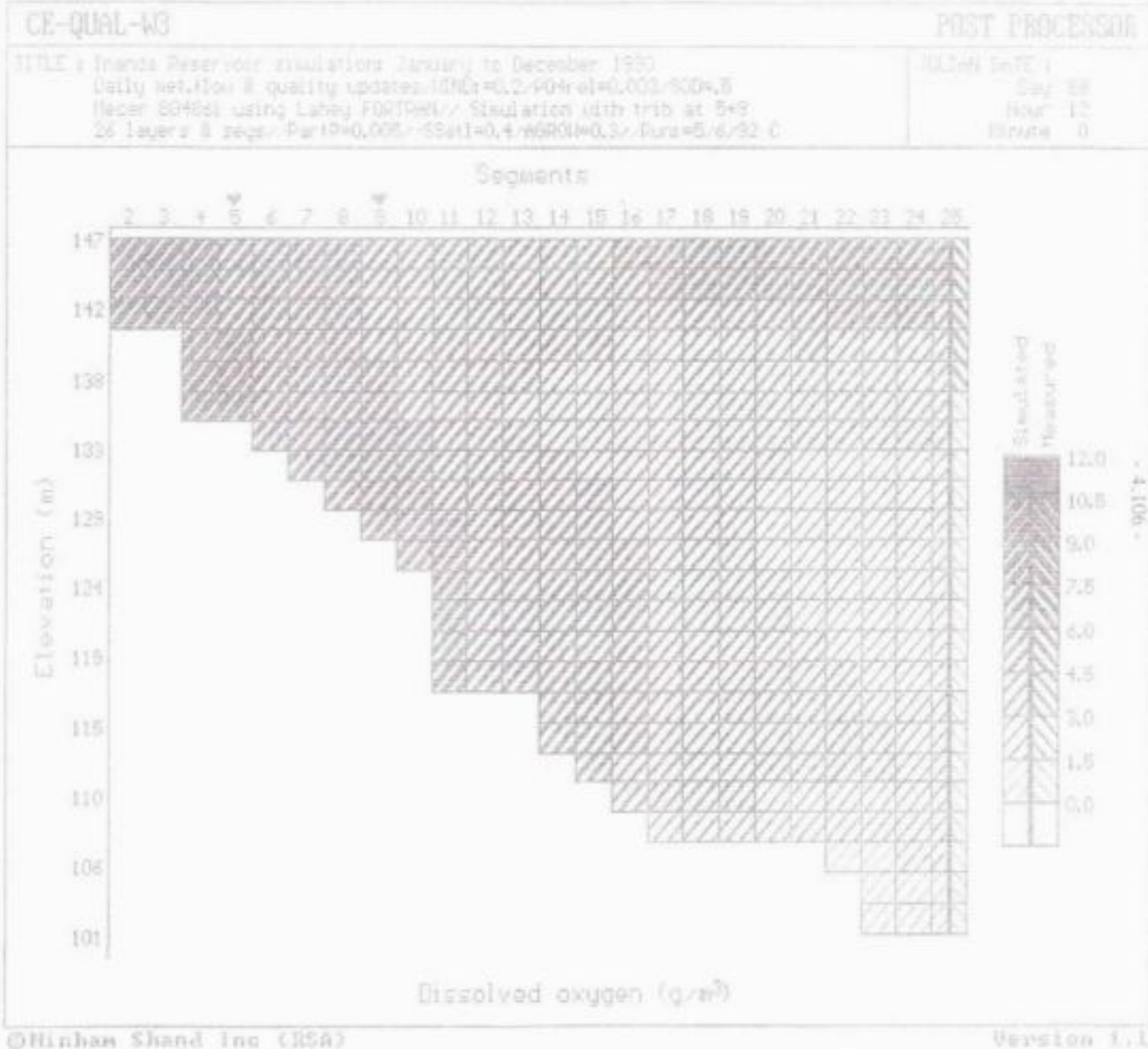

Figure A4.5.9

Two-dimensional plot showing the simulated movement of water within Inanda Dam at Segments 2 to 25.

DAY NUMBER: 4

SCALE:
Vertical: mm/s
Horizontal: m/s

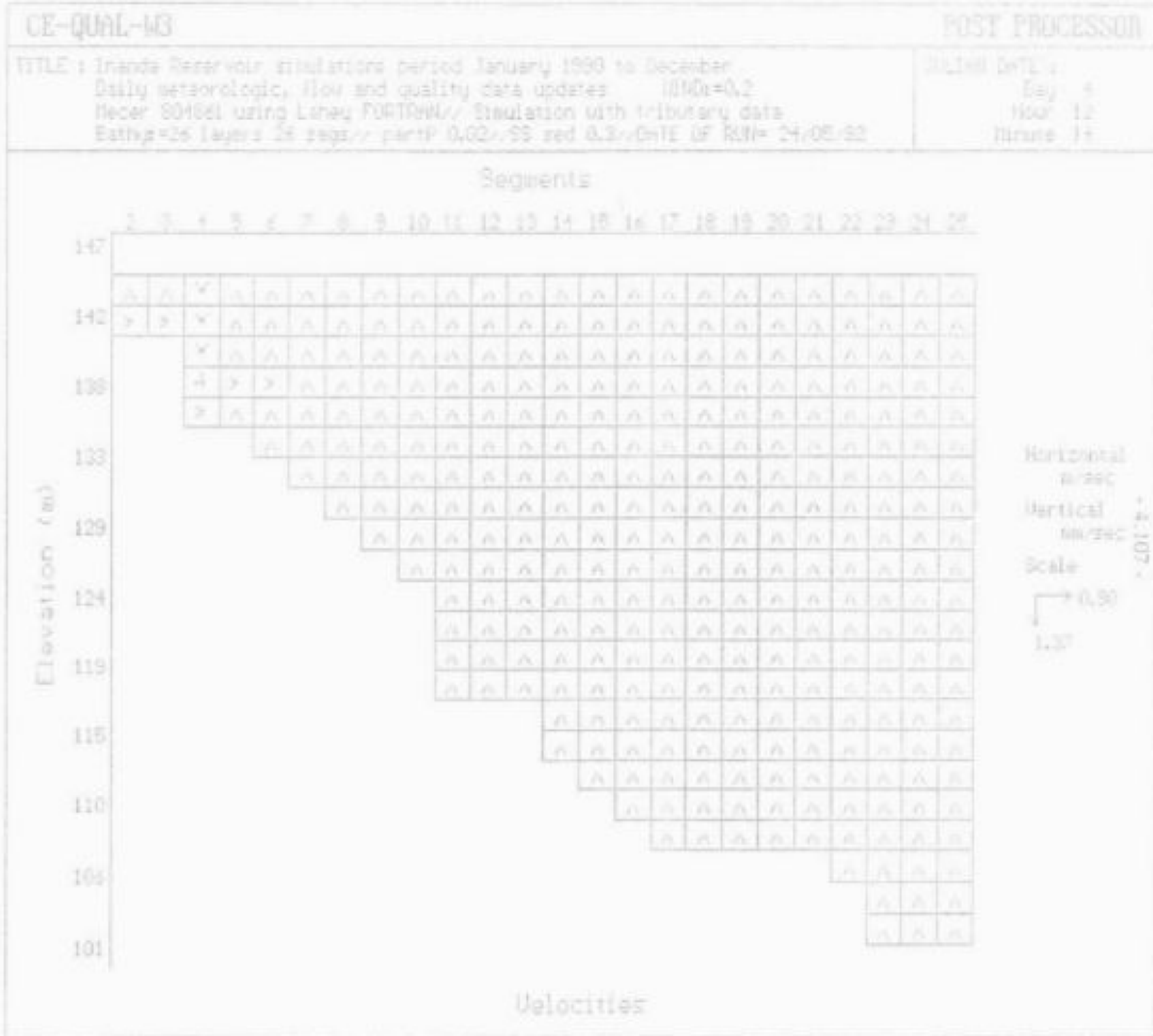

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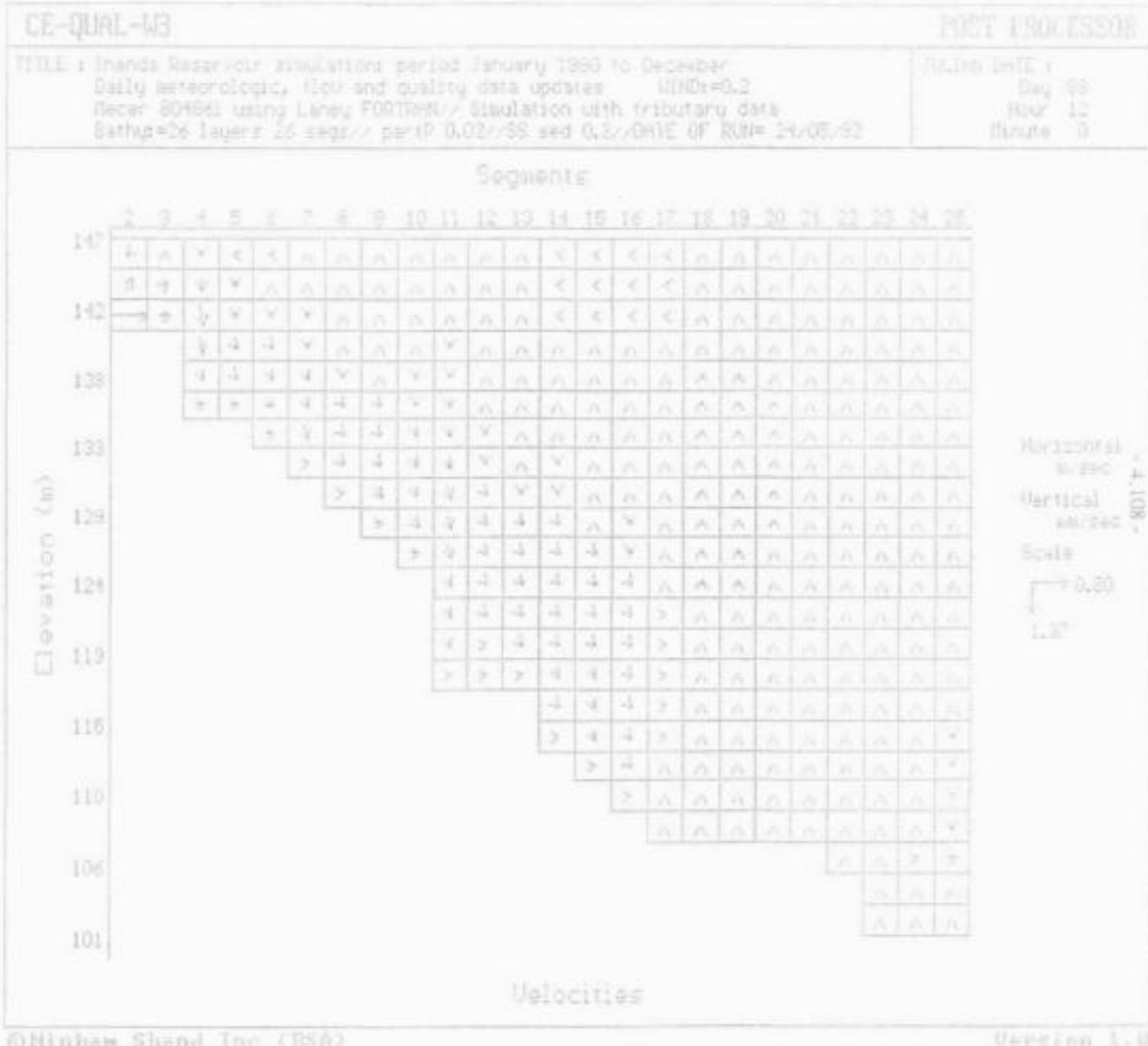
Figure A4.5.10

Two-dimensional plot showing the simulated movement of water within Inanda Dam at Segments 2 to 25.

DAY NUMBER: 88

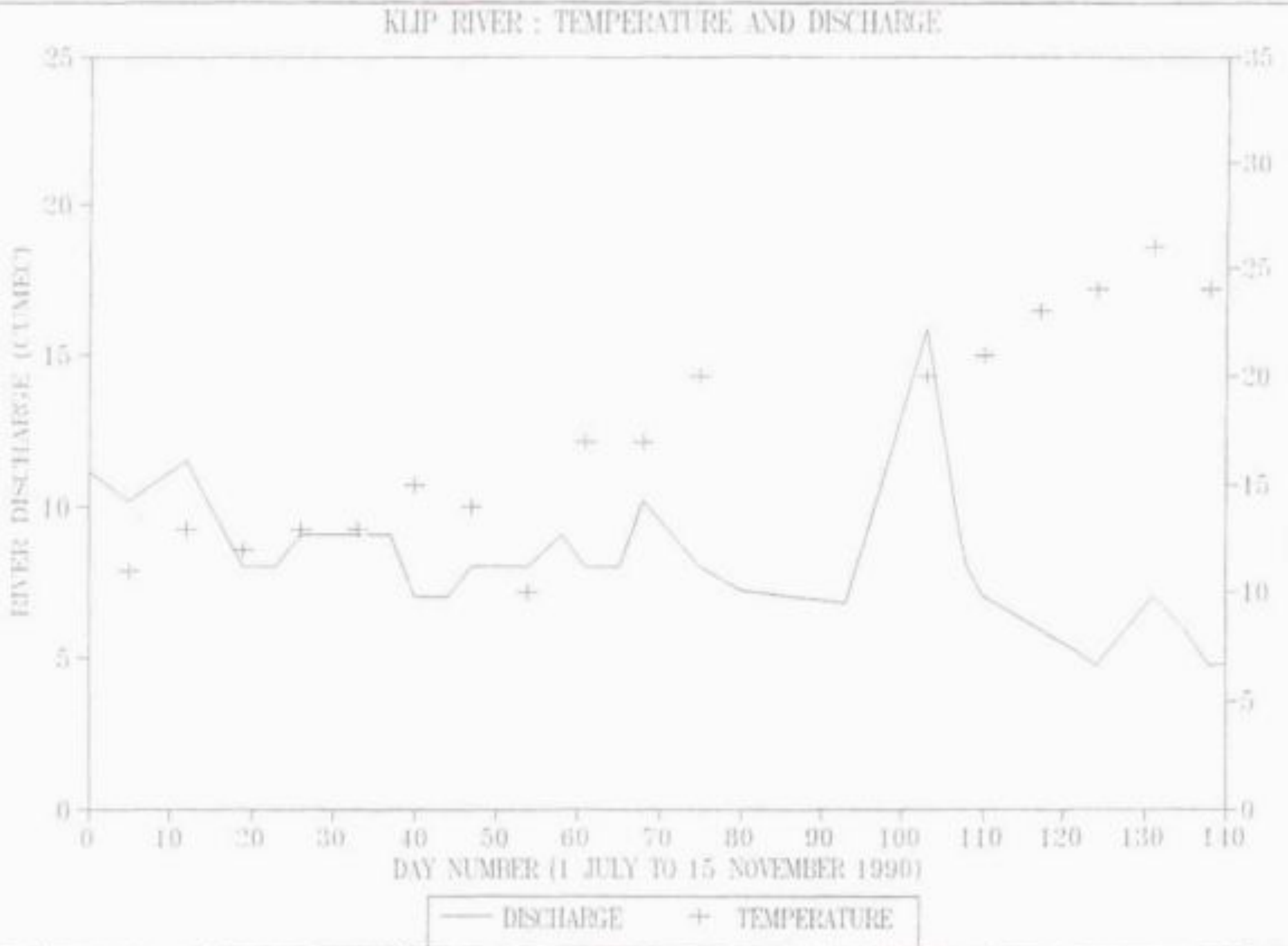
SCALE:
Vertical: mm/s
Horizontal: m/s



APPENDIX A4.6

OUTPUT DATA
VAAL BARRAGE SIMULATION

Figure Number:	Title:

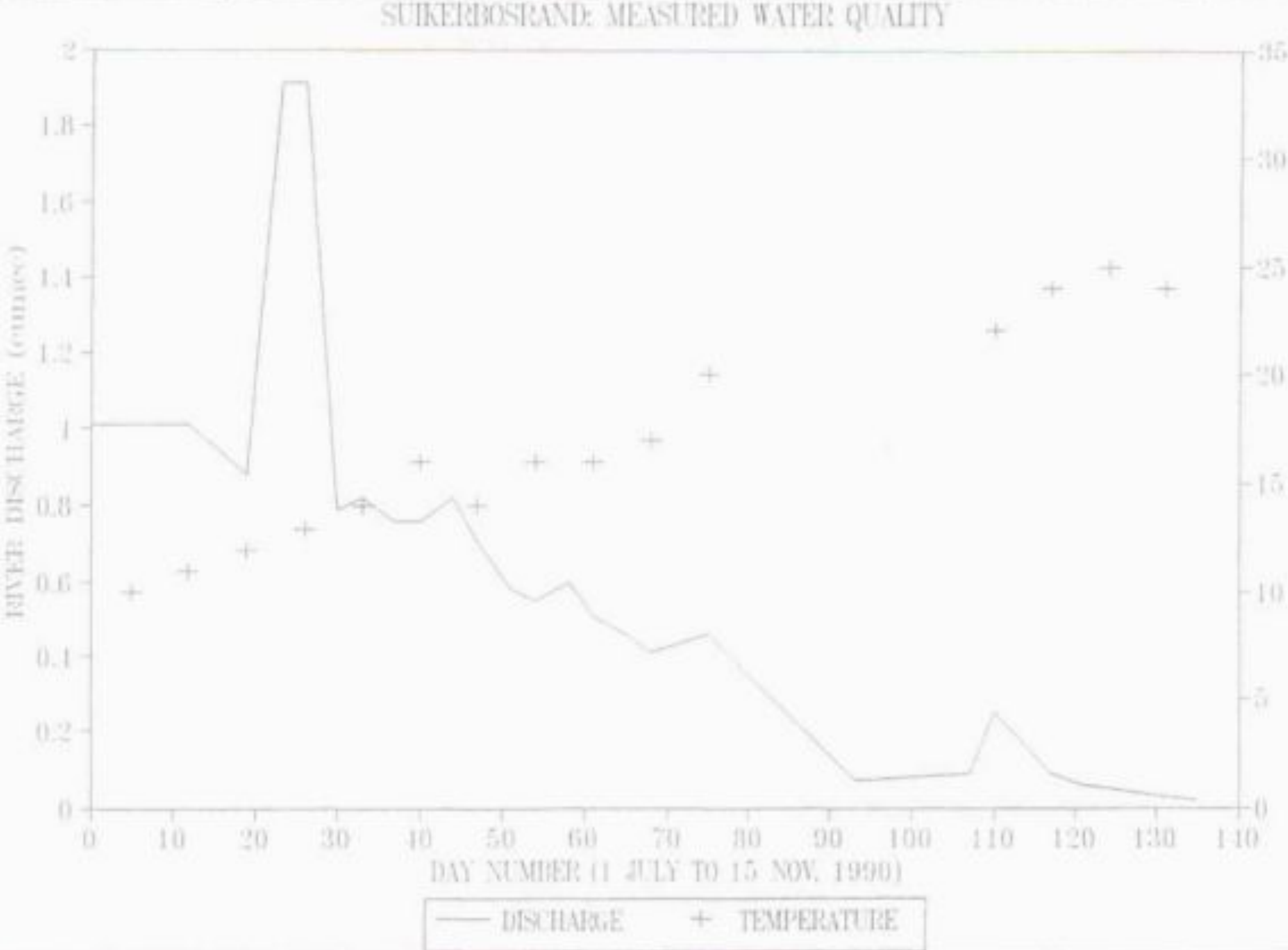


UNIVERSITY OF CAPE TOWN

WATER RESEARCH COMMISSION

FIGURE A4.6.1

Measured water temperature and discharge hydrograph for the Klip River.



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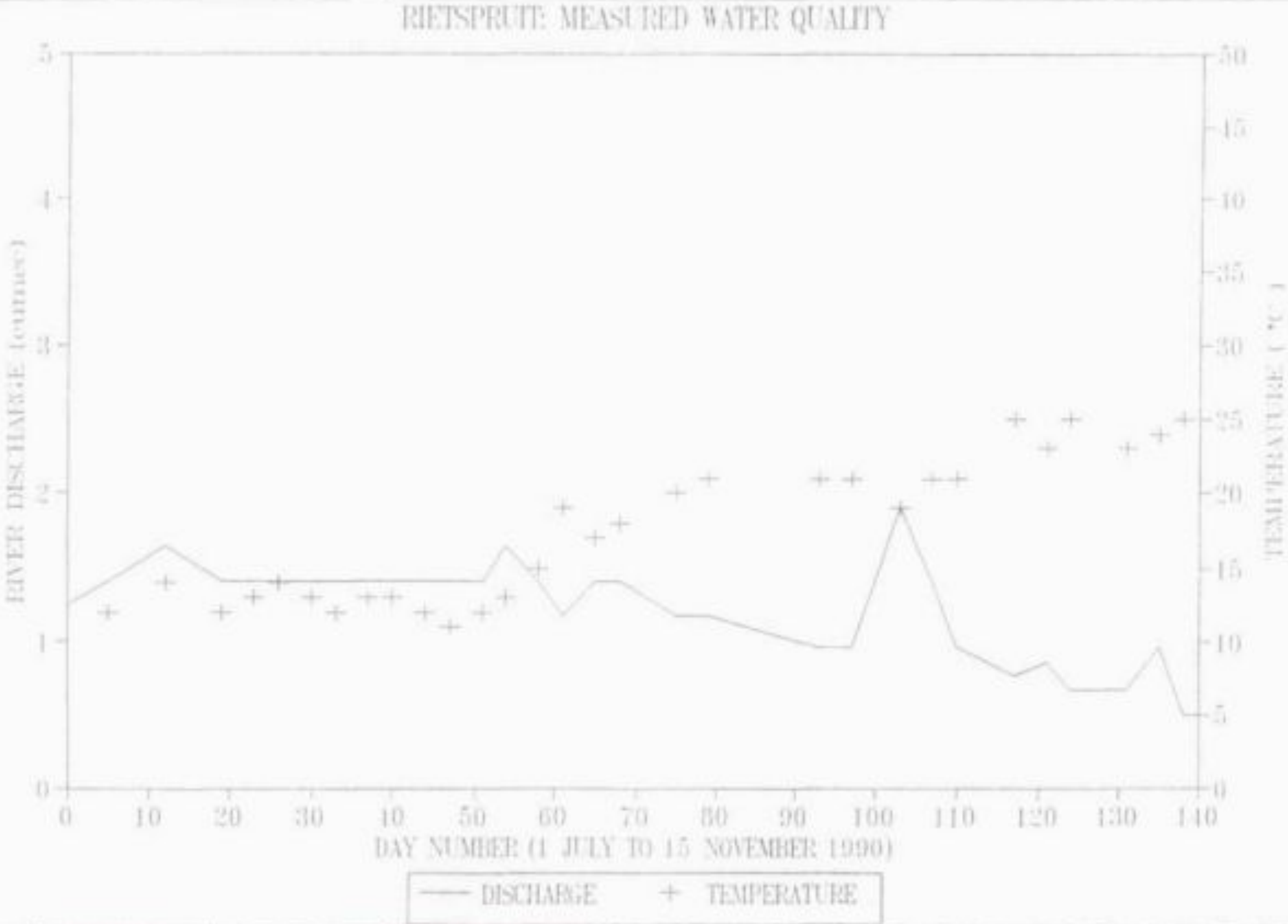
WATER RESEARCH COMMISSION

Measured water temperature and discharge hydrograph for the Suikerbosrand River.

FIGURE A4.6.2



UNIVERSITY OF CAPE TOWN

WATER RESEARCH COMMISSION

Measured water temperature and discharge hydrograph for the Rietspruit.

FIGURE A4.6.3

Figure A4.6.4

Simulated and measured temperature of the surface water at Segment 3 in the Vaal Barrage.

Segment 3 is located at the upstream boundary at Lethabo Weir.

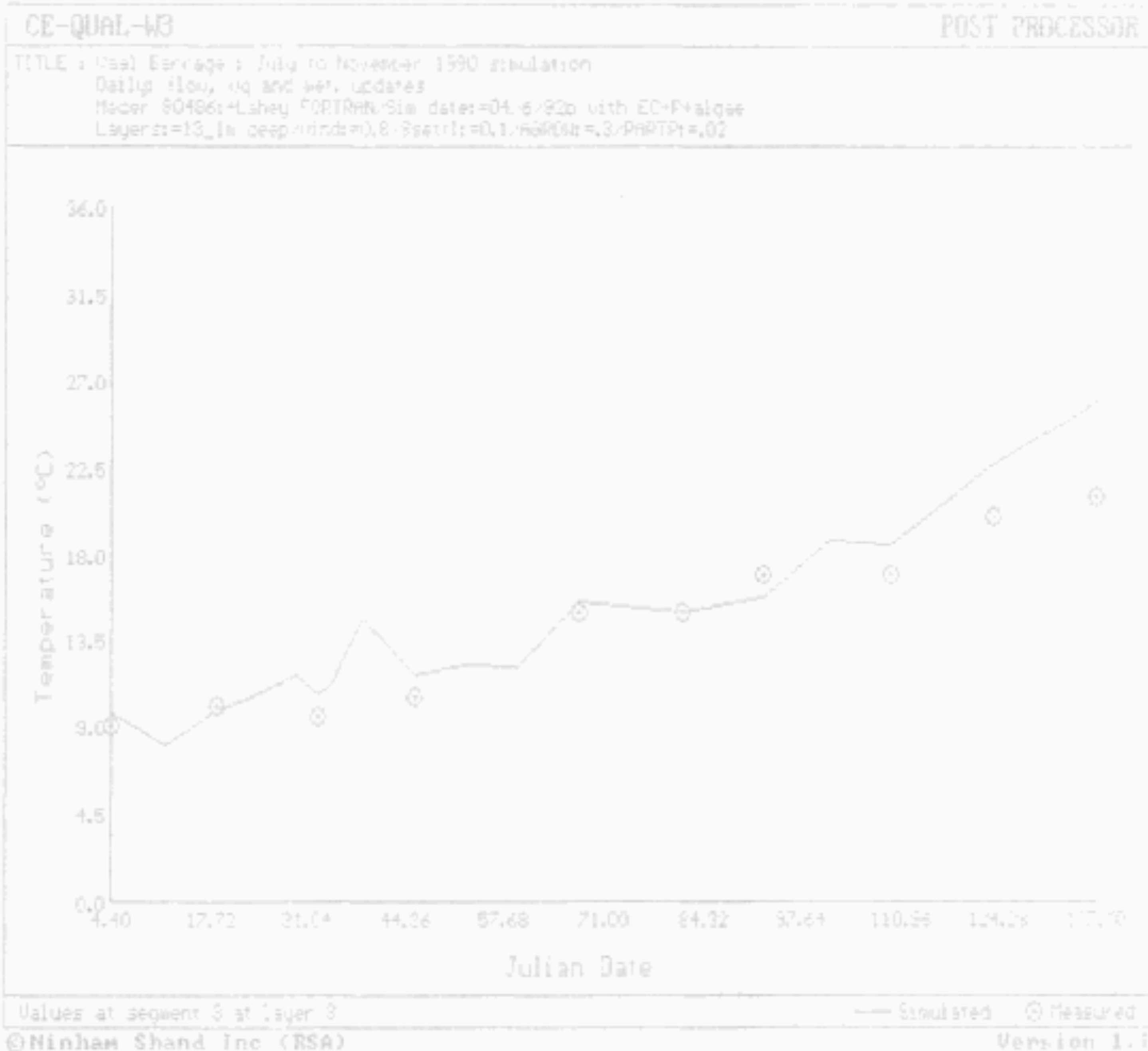


Figure A4.6.5

Simulated and measured temperature of the surface water at Segment 7 in the Vaal Barrage.

Segment 7 is located at the confluence with the Klip River.

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Figure A4.6.6

Simulated and measured temperature of the surface water at Segment 14 in the Vaal Barrage.

Segment 14 is located at the confluence with the Taaibos Spruit.

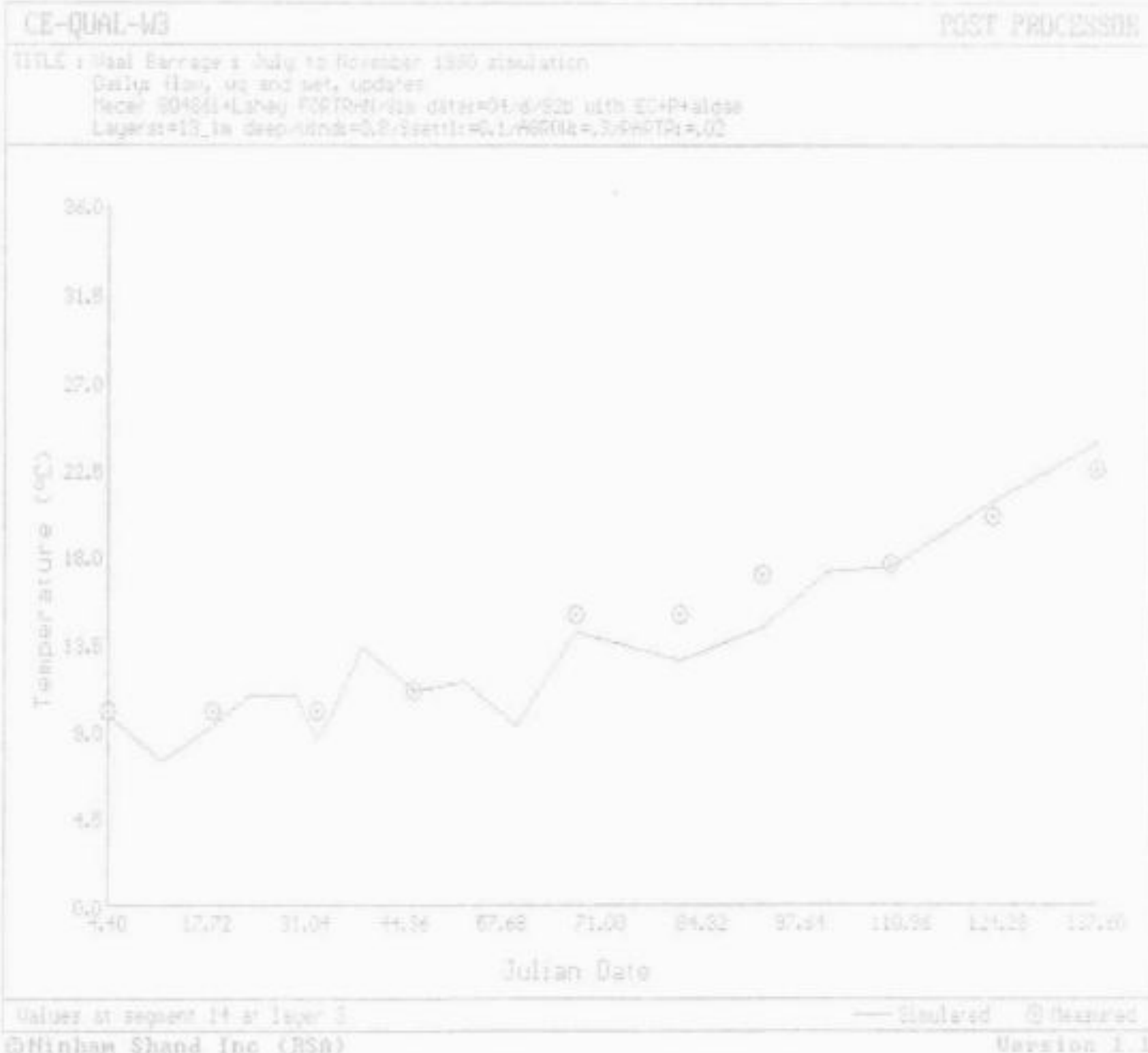
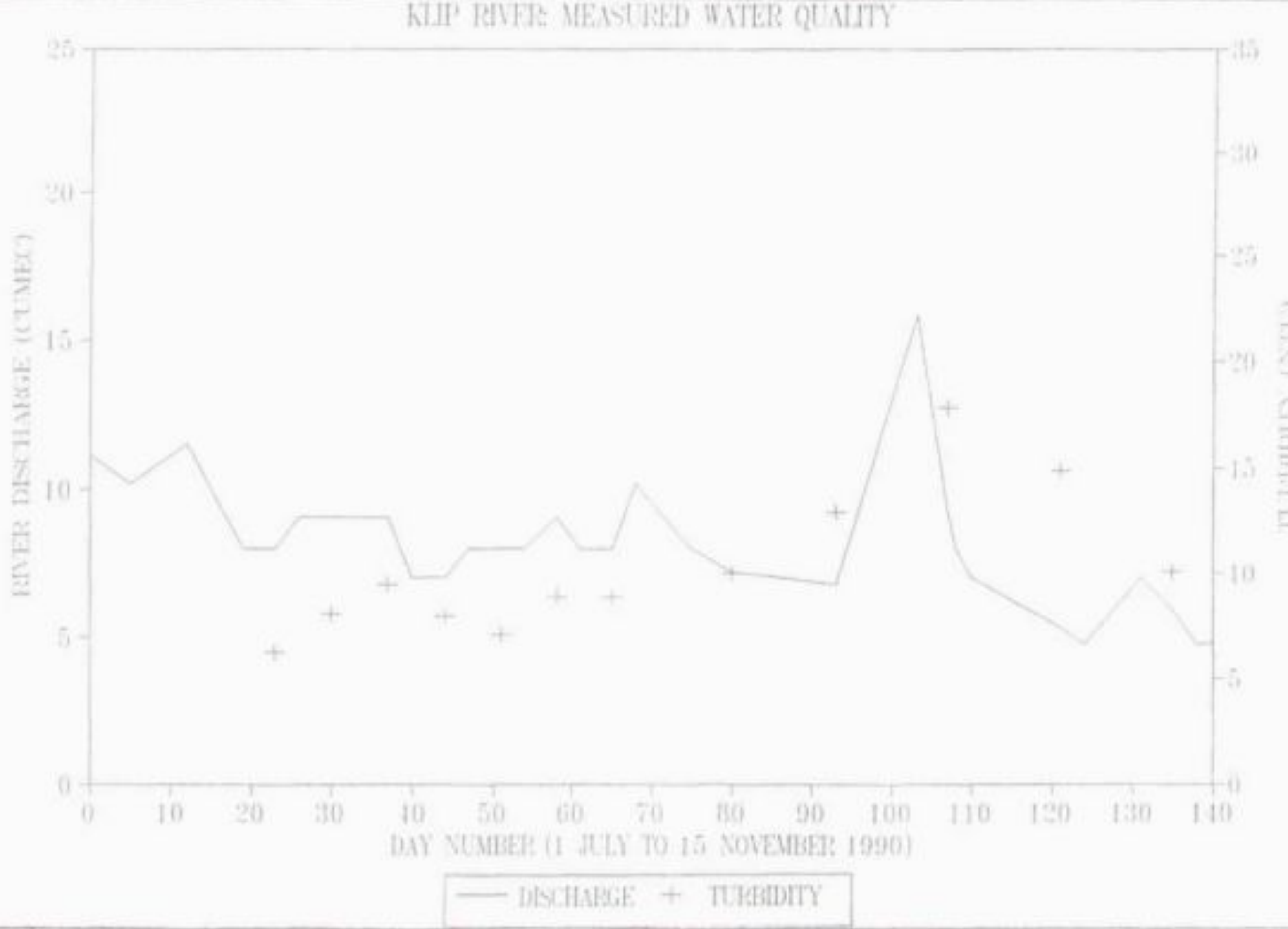


Figure A4.6.7

Simulated and measured temperature of the surface water at Segment 26 in the Vaal Barrage.

Segment 26 is located at the Vaal Barrage.

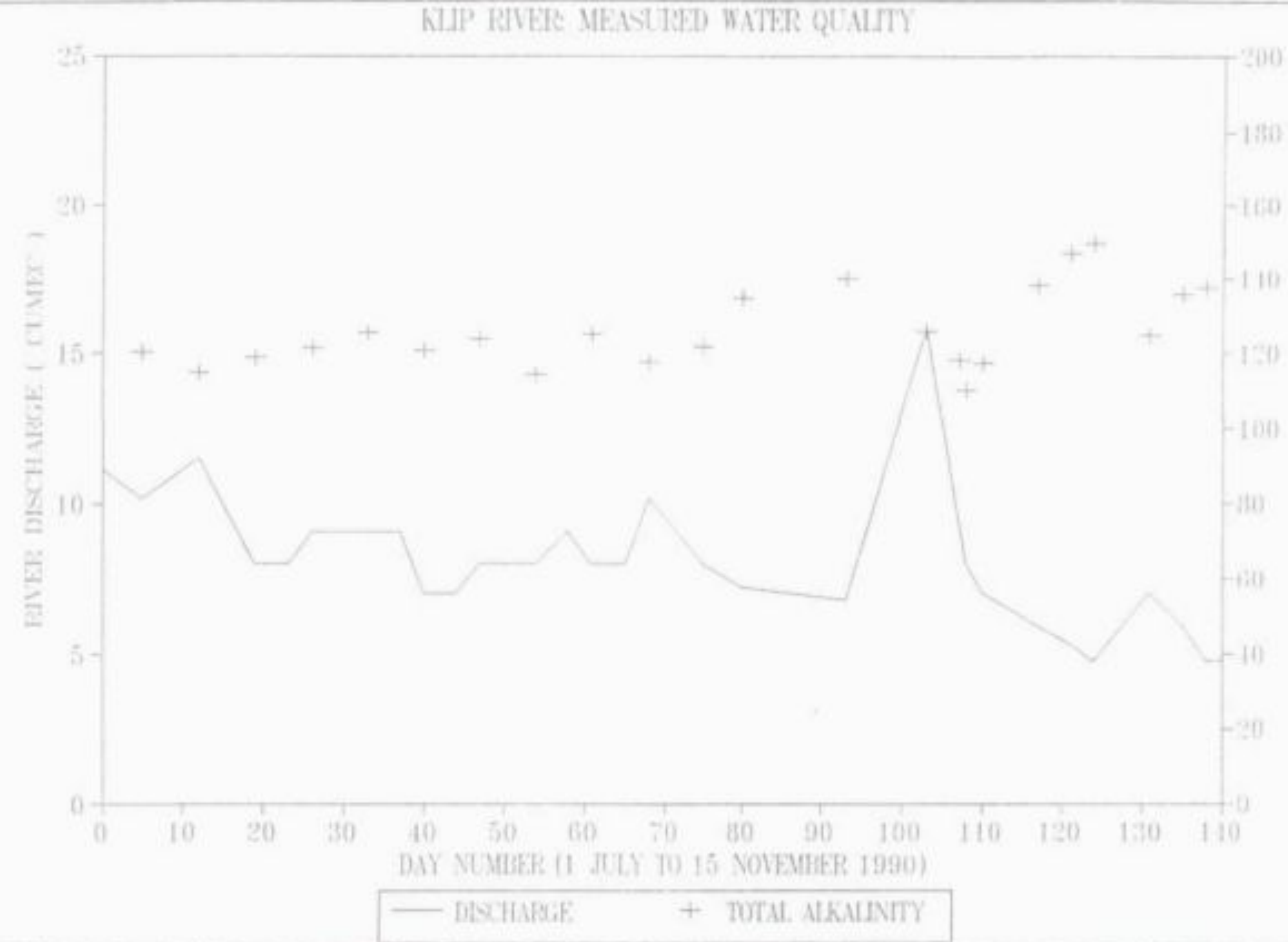


UNIVERSITY OF CAPE TOWN

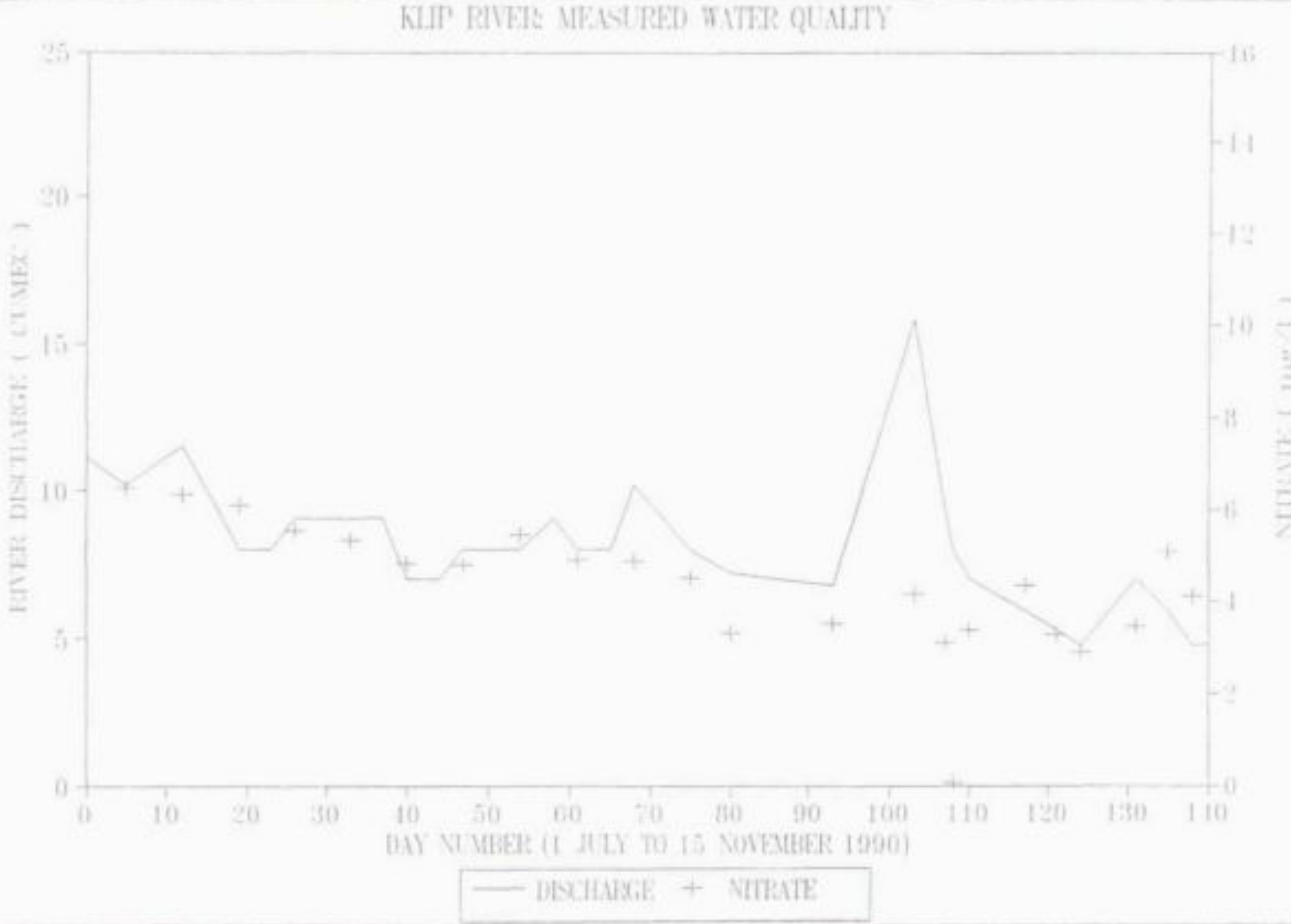
WATER RESEARCH COMMISSION

Measured turbidity and discharge hydrograph for the Klip River.

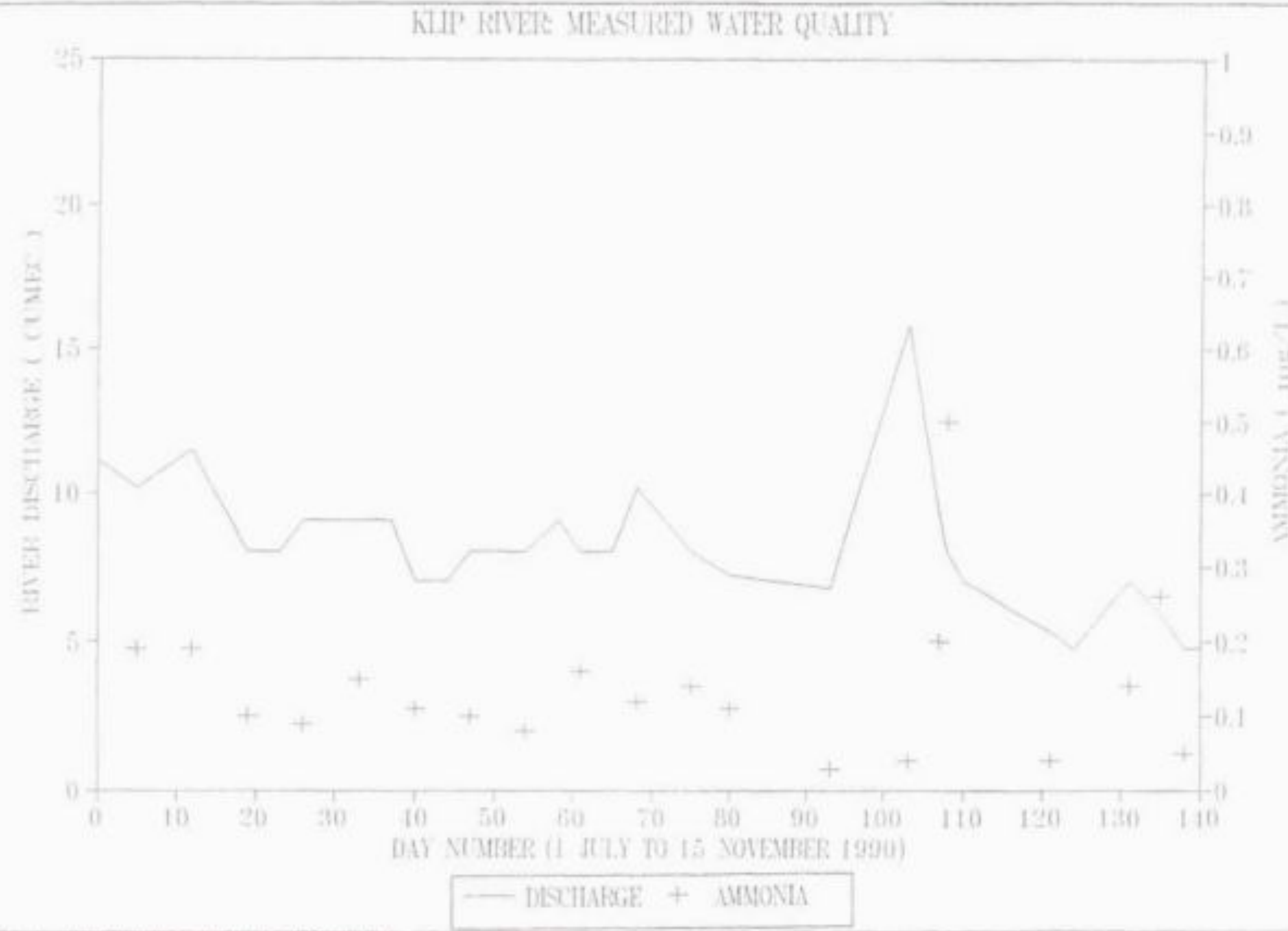
FIGURE A4.6.3



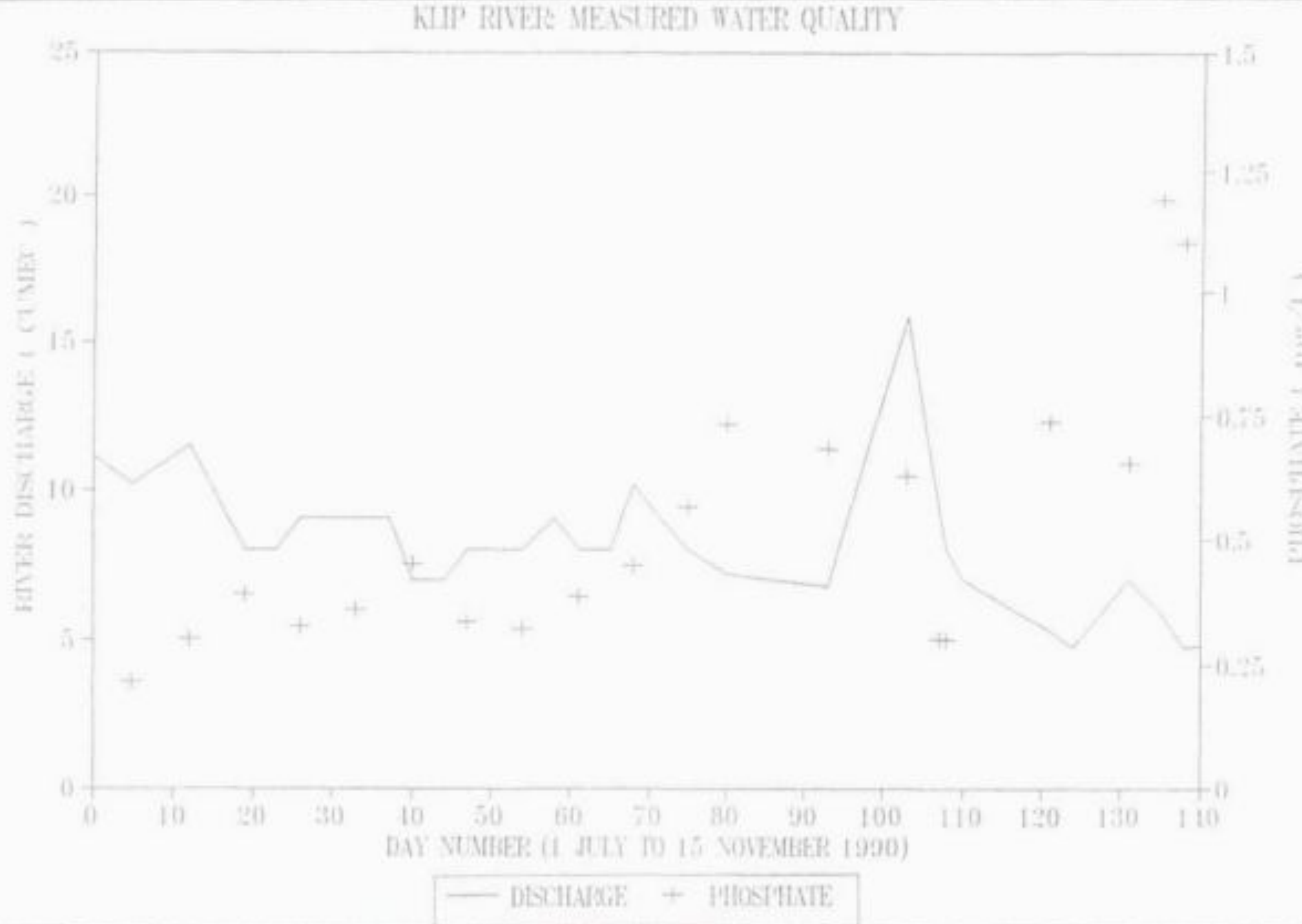
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured total alkalinity and discharge hydrograph for the Klip River.	FIGURE A4.6.9



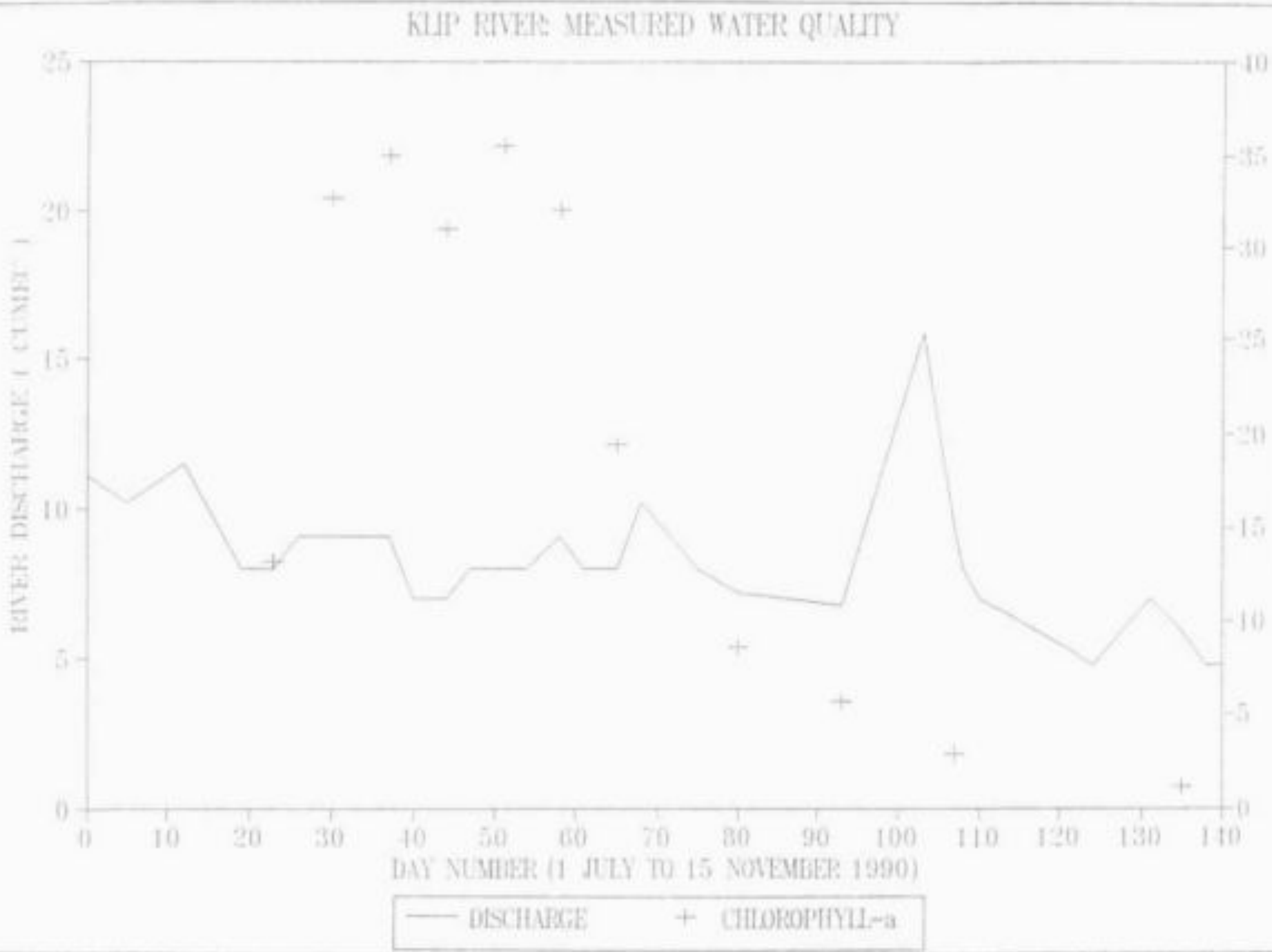
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured nitrate and discharge hydrograph for the Klip River.	FIGURE A4.6.10



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured ammonia and discharge hydrograph for the Klip River.	FIGURE A4.6.11



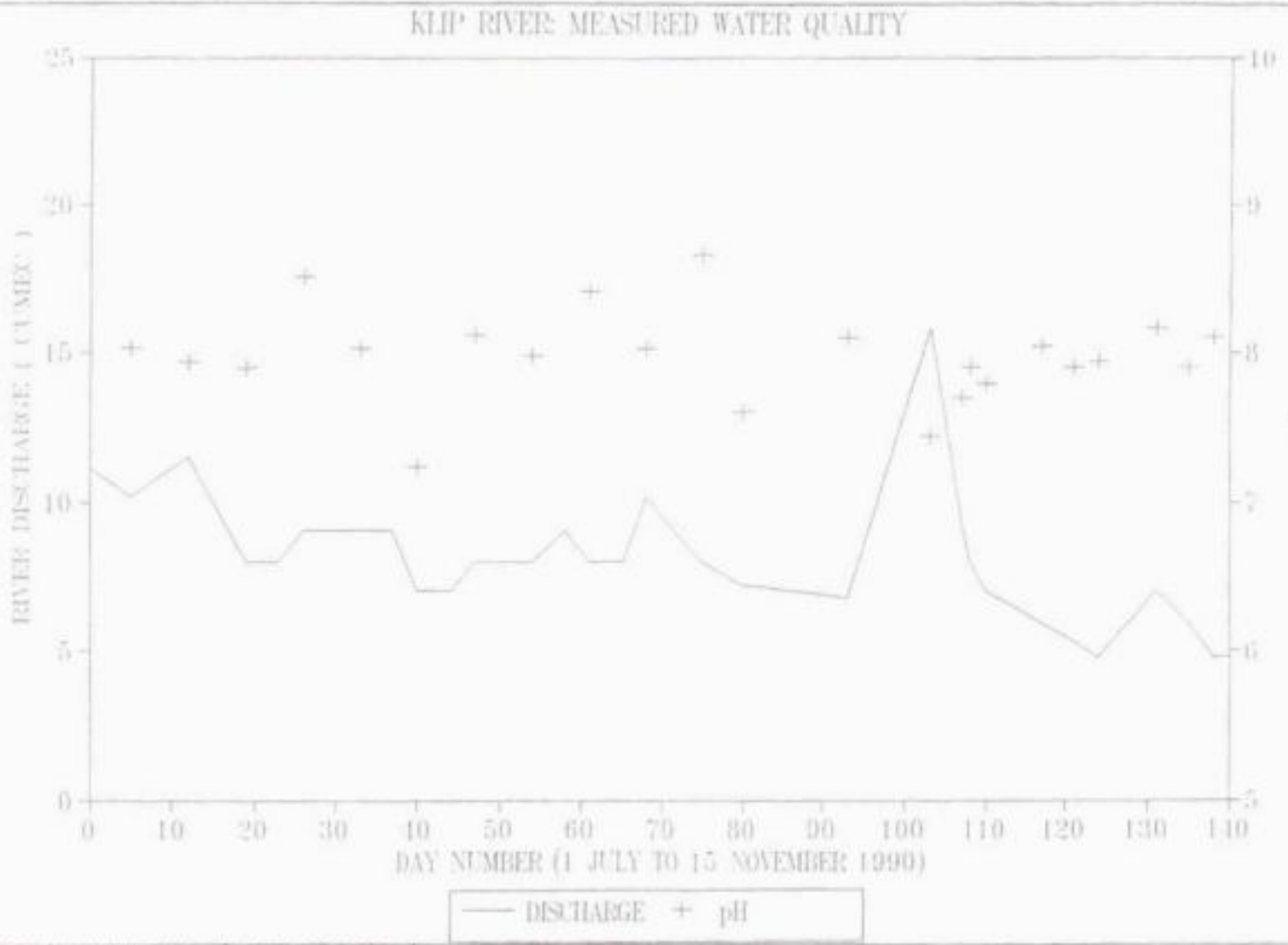
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured phosphate and discharge hydrograph for the Klip River.	FIGURE A4.6.12



NINHAM SHAND | UNIVERSITY OF CAPE TOWN | WATER RESEARCH COMMISSION

Measured chlorophyll-a and discharge hydrograph for the Klip River.

FIGURE A4.6.13

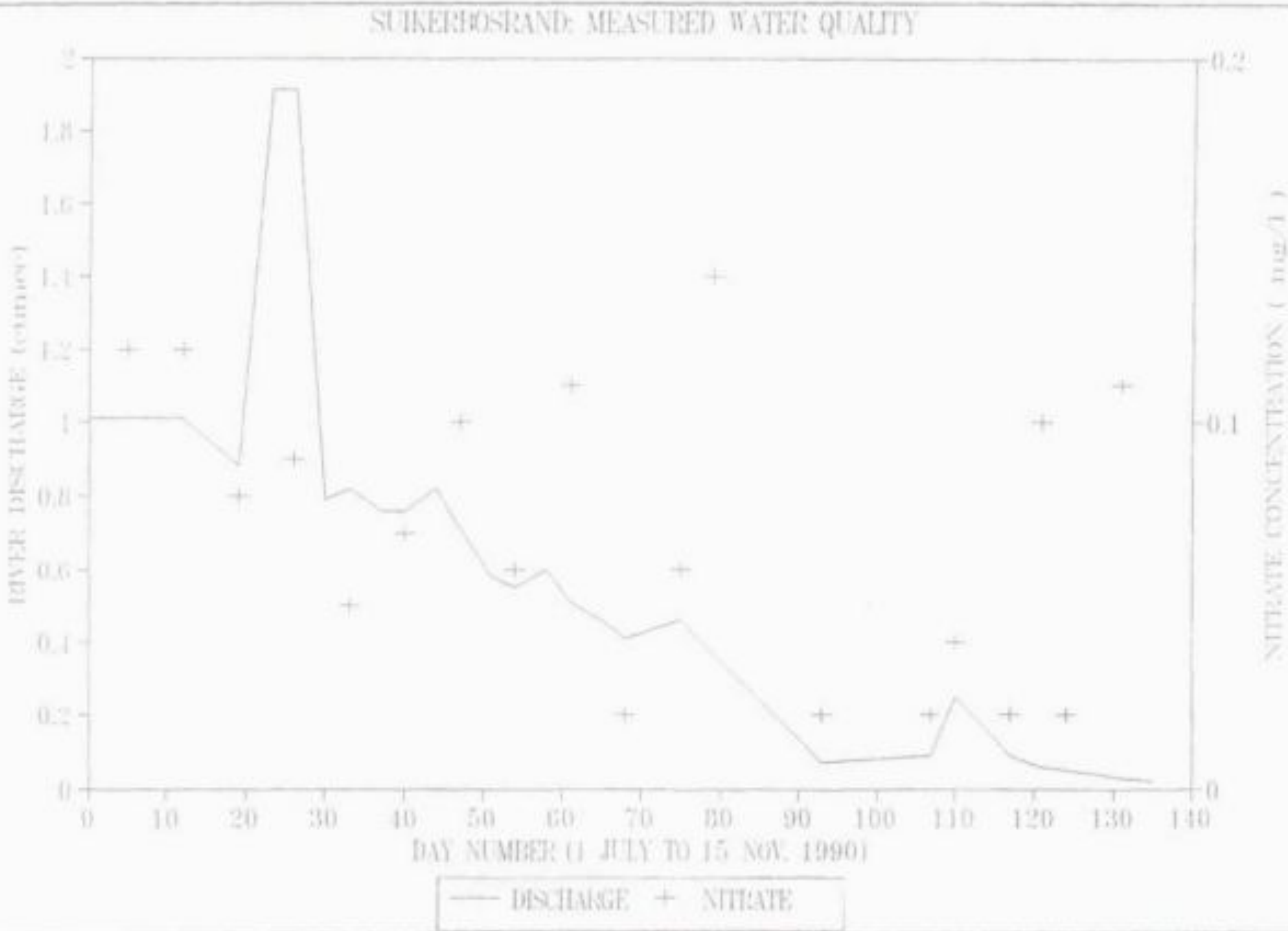


UNIVERSITY OF CAPE TOWN

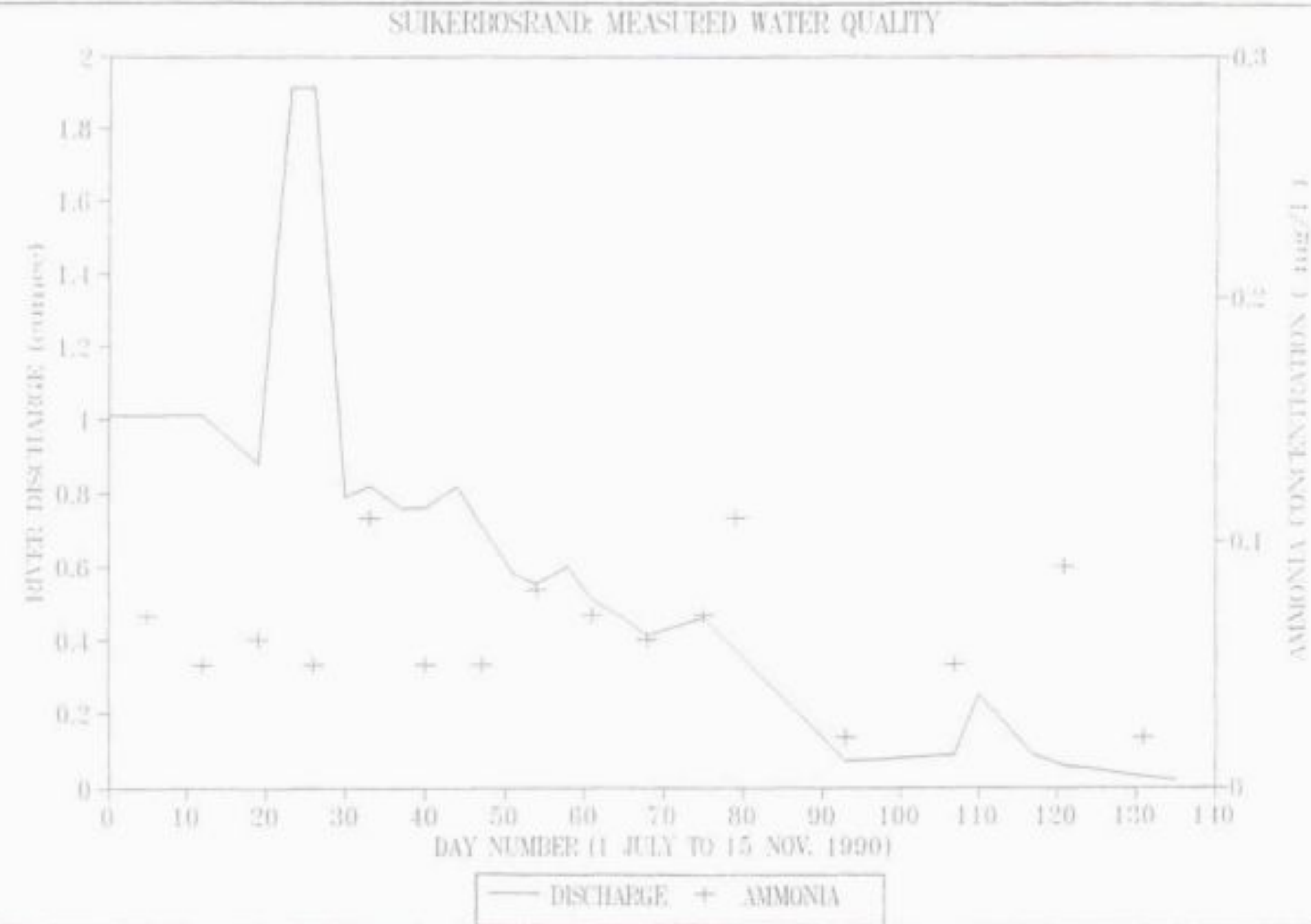
WATER RESEARCH COMMISSION

Measured pH and discharge hydrograph for the Klip River.

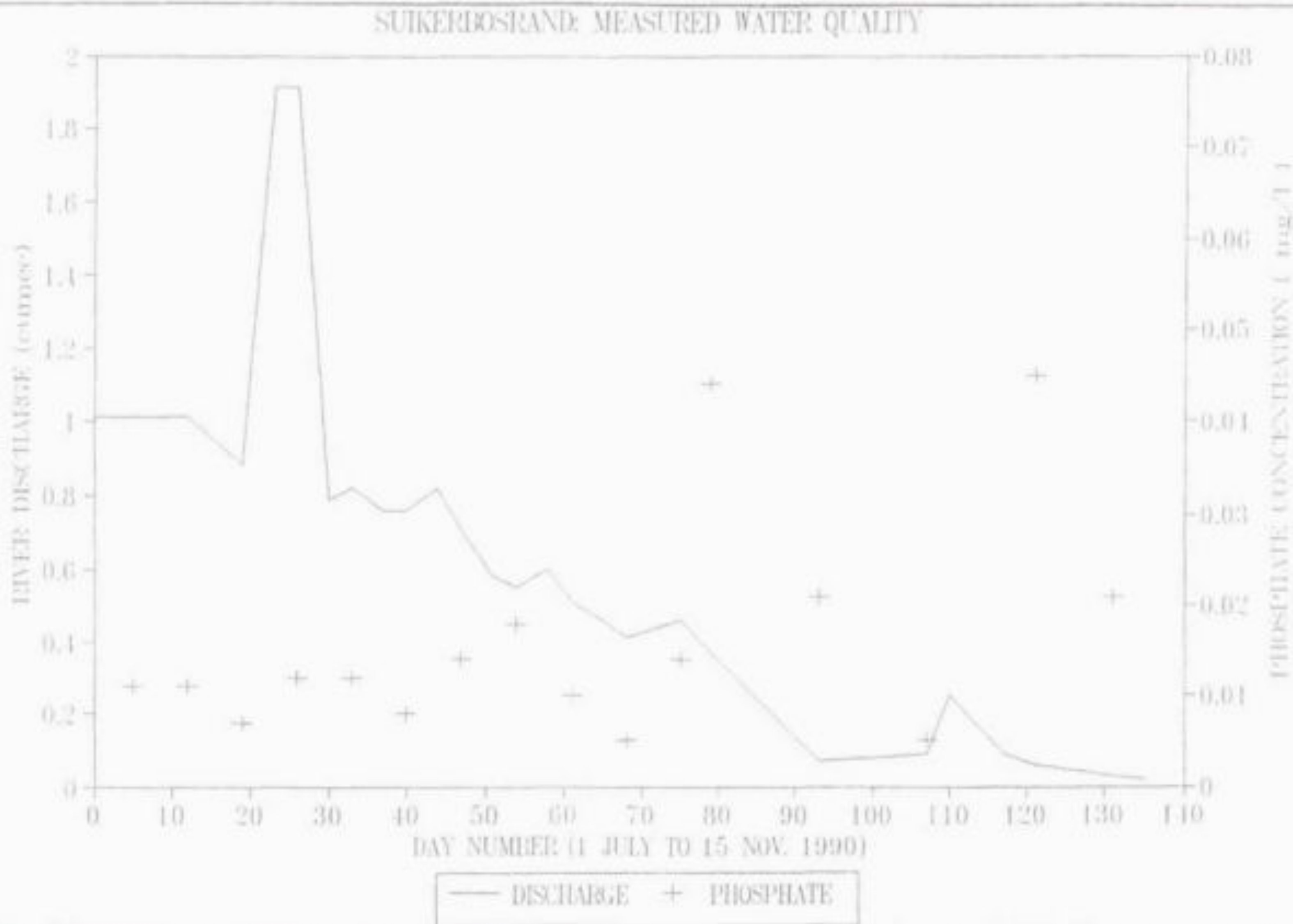
FIGURE A4.6.14



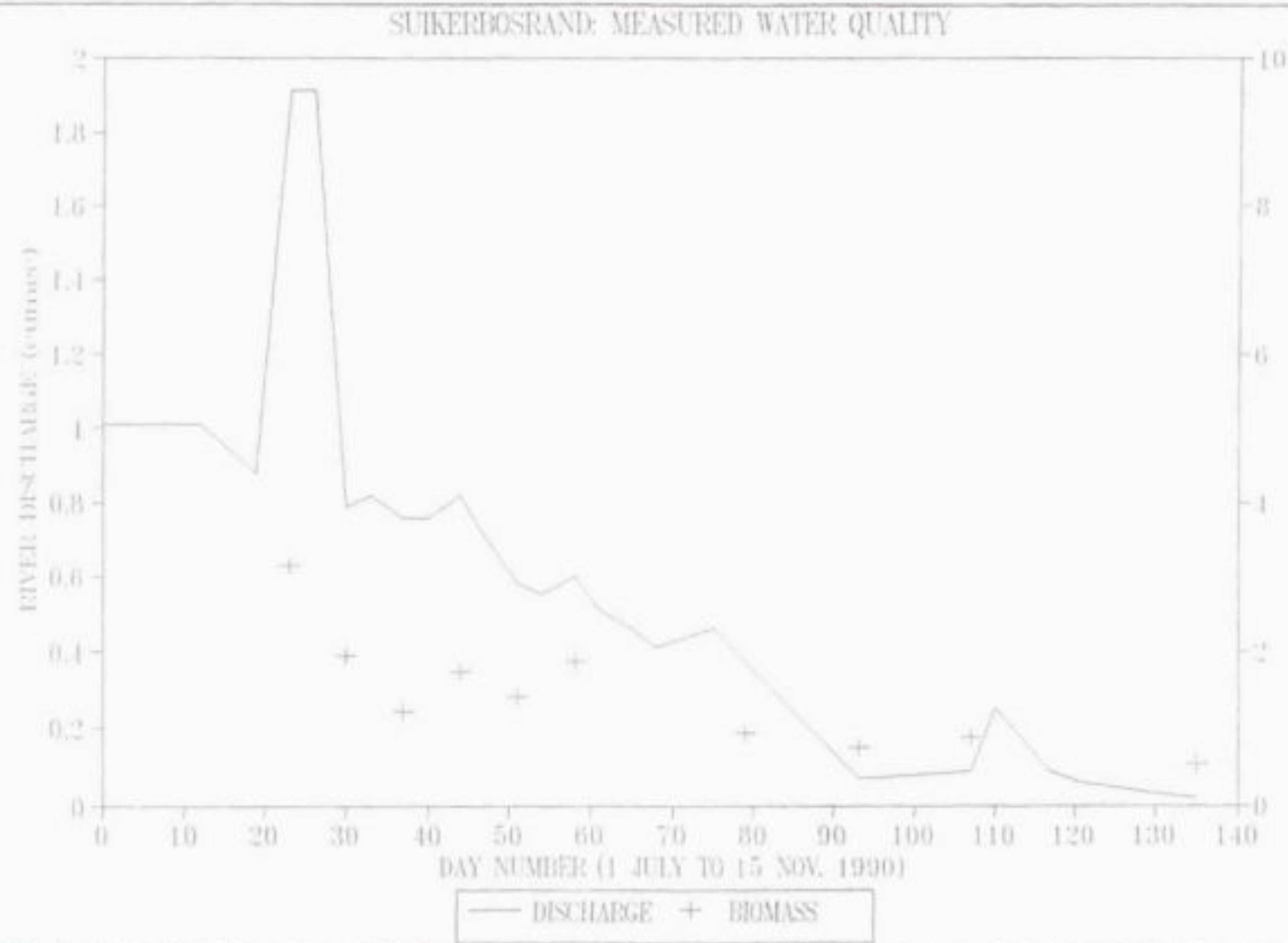
NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured nitrate and discharge hydrograph for the Suikerbosrand Spruit.	FIGURE A4.6.18



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION		FIGURE
			Measured ammonia and discharge hydrograph for the Suikerbosrand Spruit.	A4.6.16



	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured phosphate and discharge hydrograph for the Suikerbosrand Spruit.	FIGURE A4.6.17



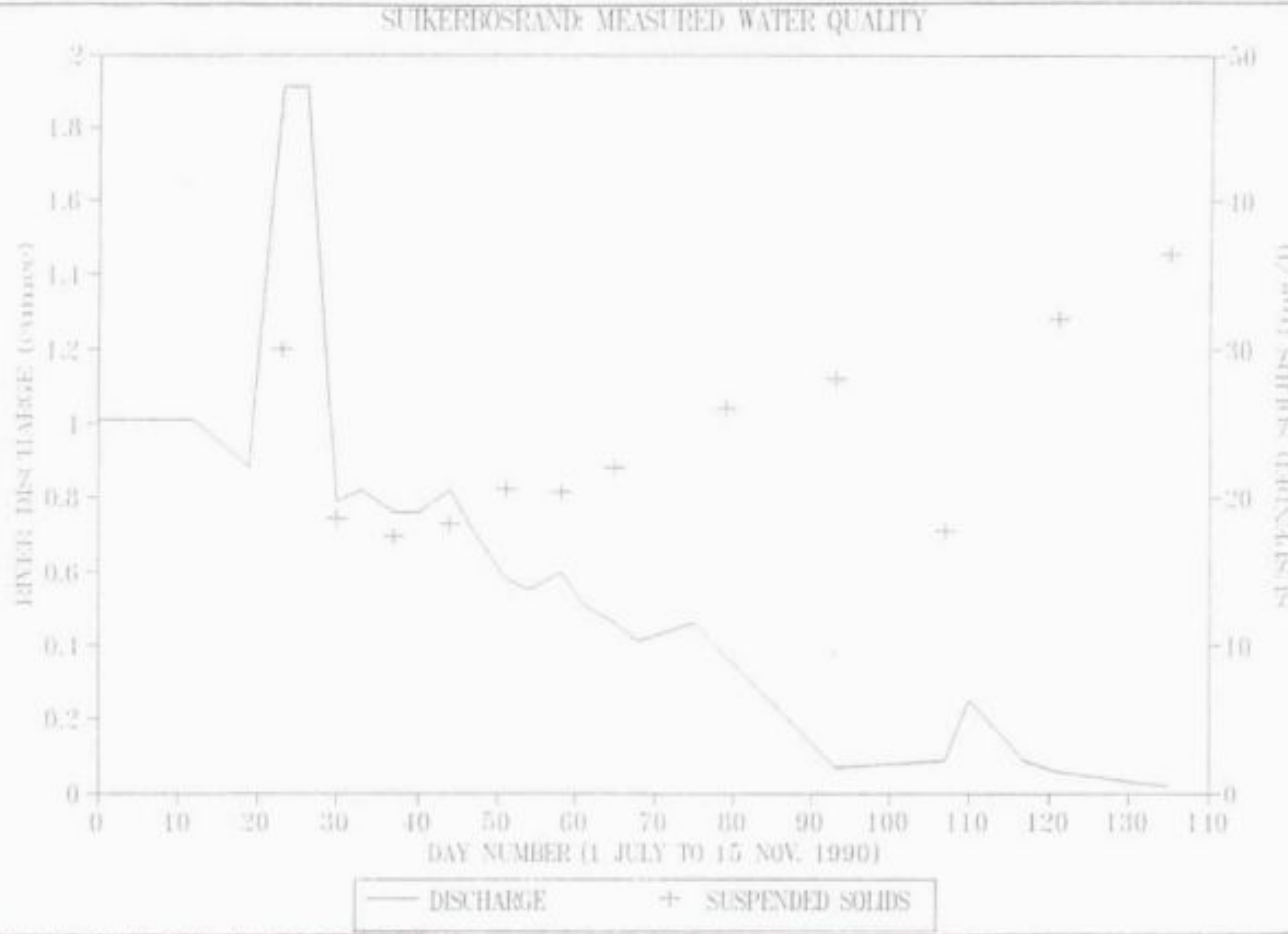
NINHAM SHAND

UNIVERSITY OF CAPE TOWN

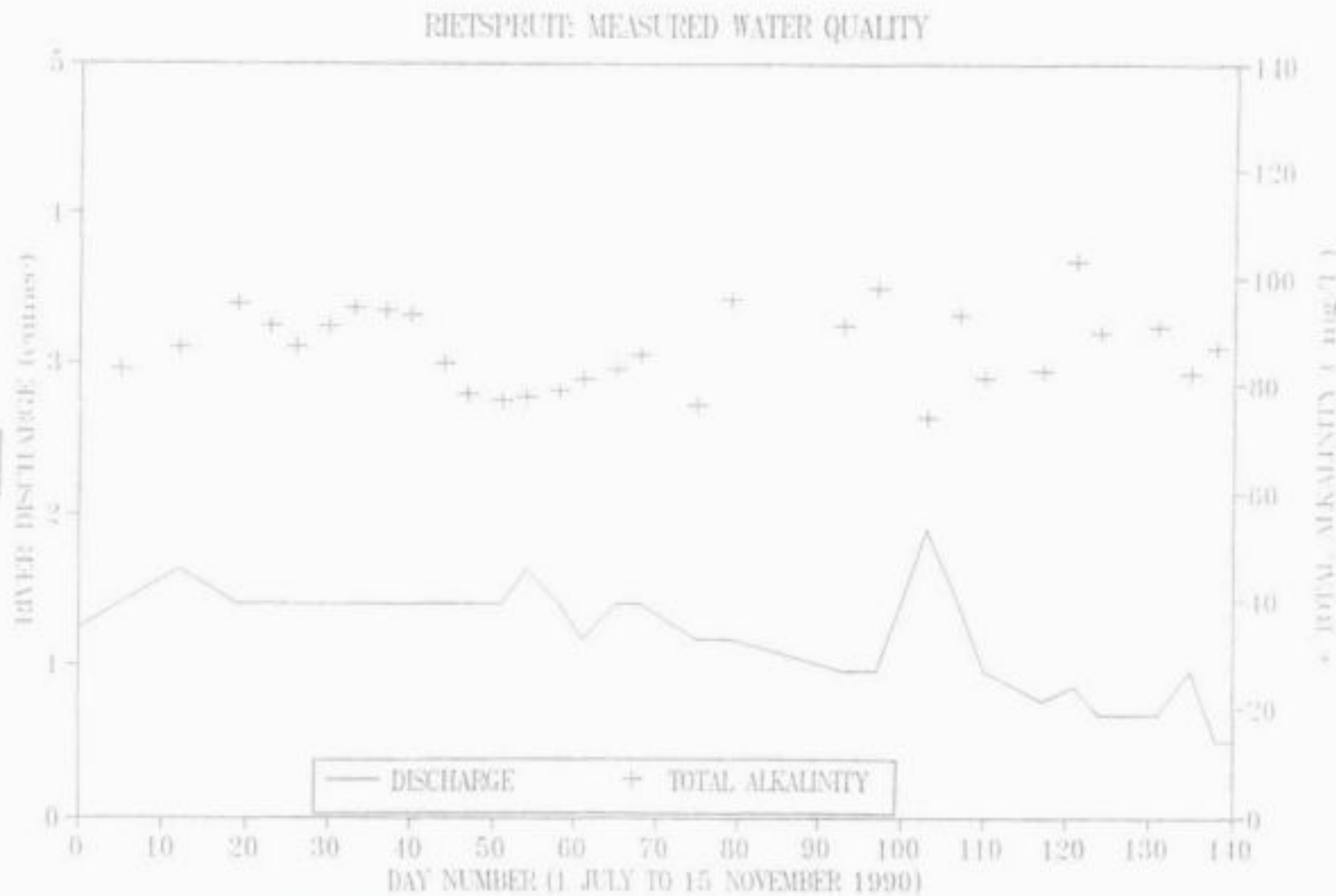
WATER RESEARCH COMMISSION

Measured algal biomass and discharge hydrograph for the Suikerbosrand Spruit.

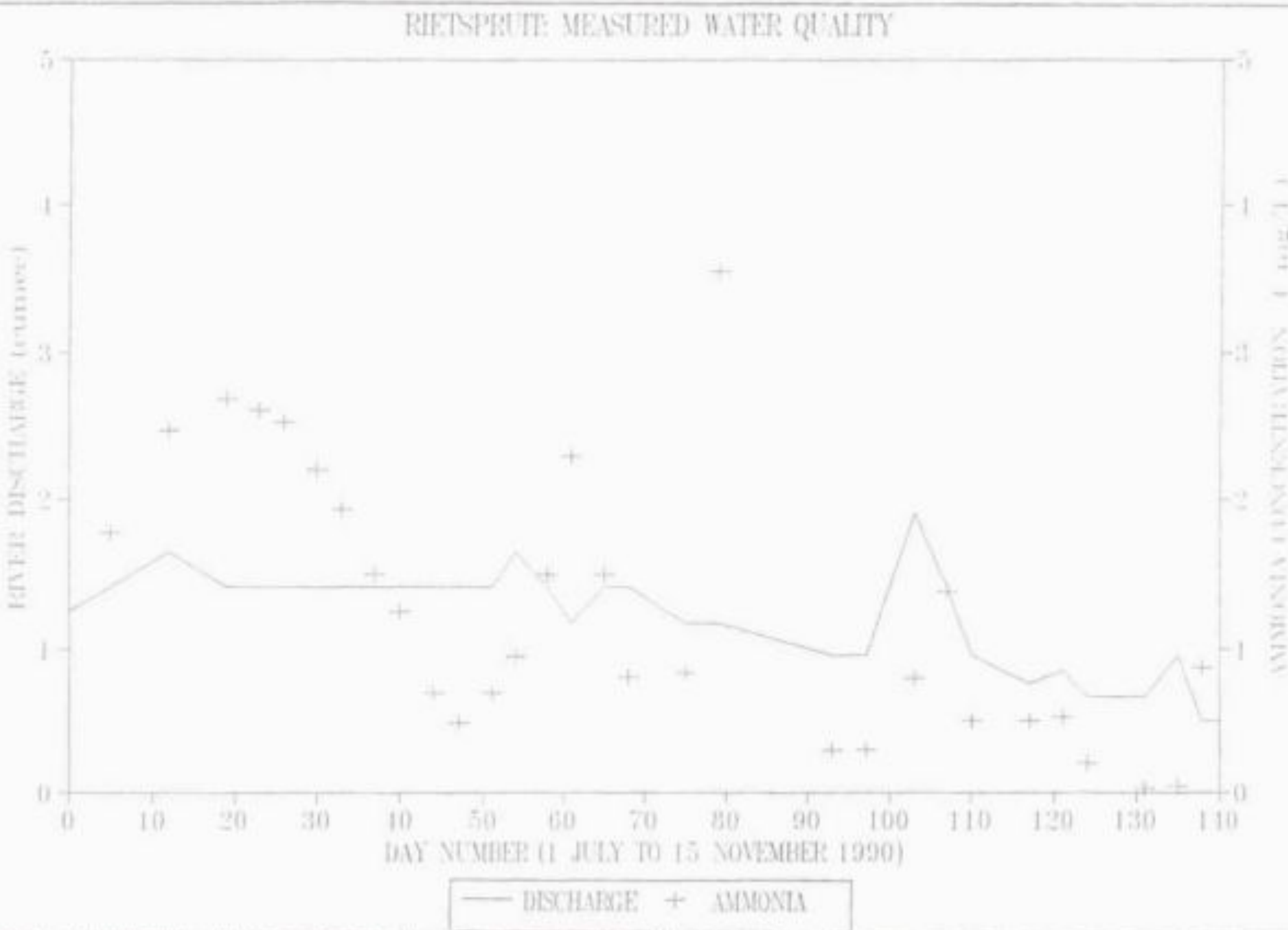
FIGURE A4.6.18



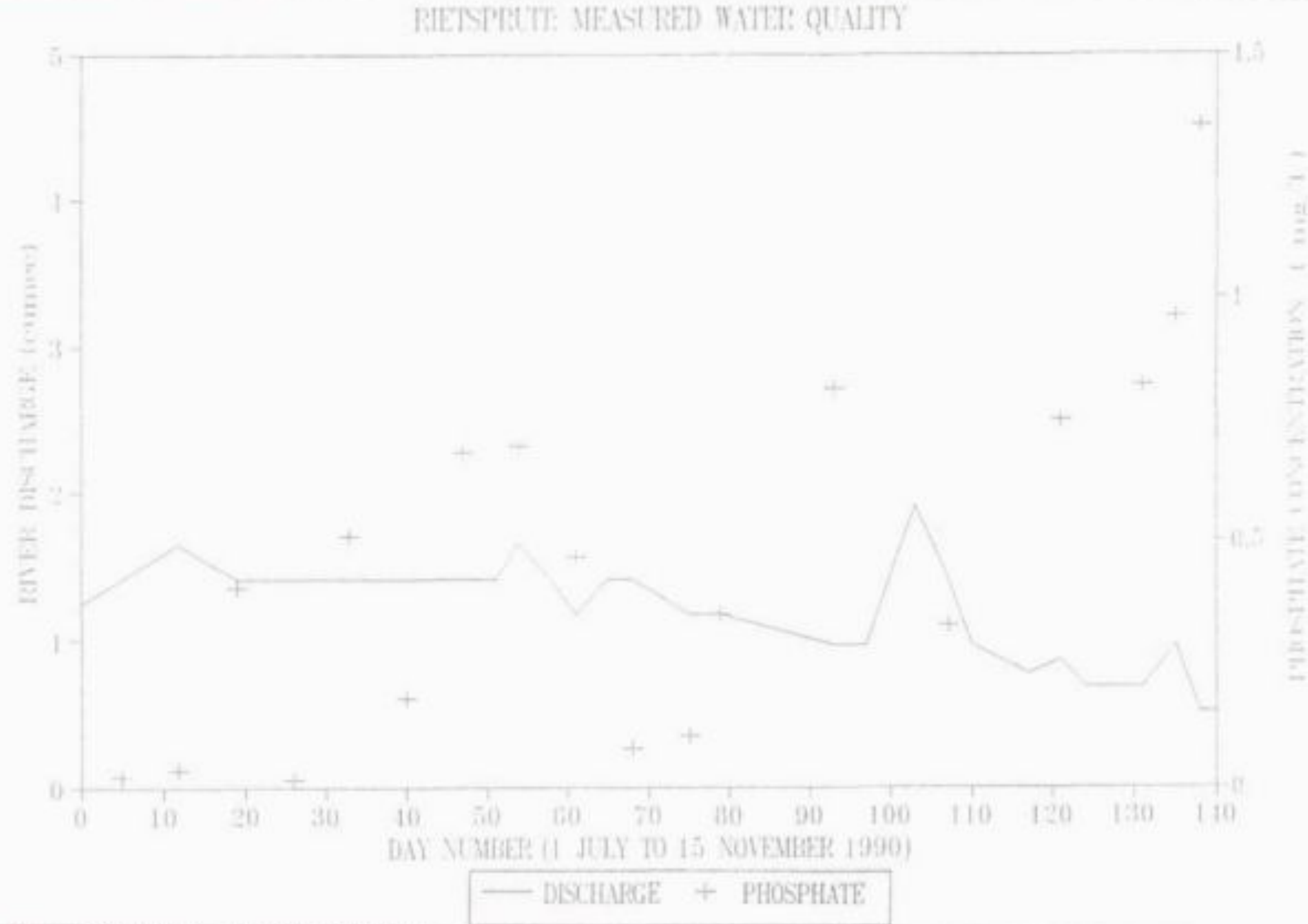
NEWMAN BRAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured suspended solids and discharge hydrograph for the Suikerbosrand Spruit.	FIGURE A4.6.19



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured total alkalinity and discharge hydrograph for the Rietspruit.	FIGURE A4.6.20



UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured ammonia and discharge hydrograph for the Rietspruit.	FIGURE A4.6.21



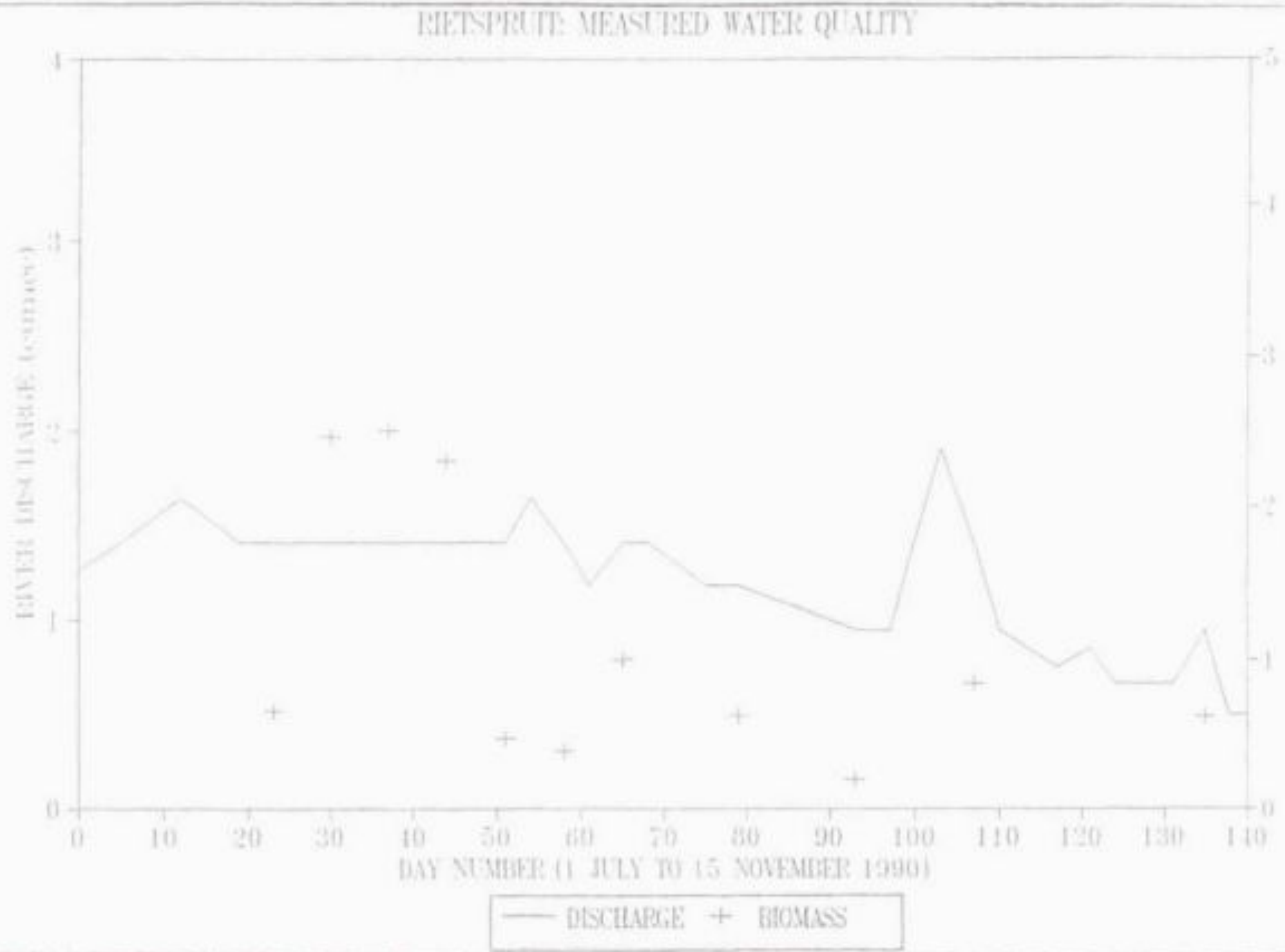
NINHAM SHAND

UNIVERSITY OF CAPE TOWN

WATER RESEARCH COMMISSION

Measured phosphate and discharge hydrograph for the Rietspruit.

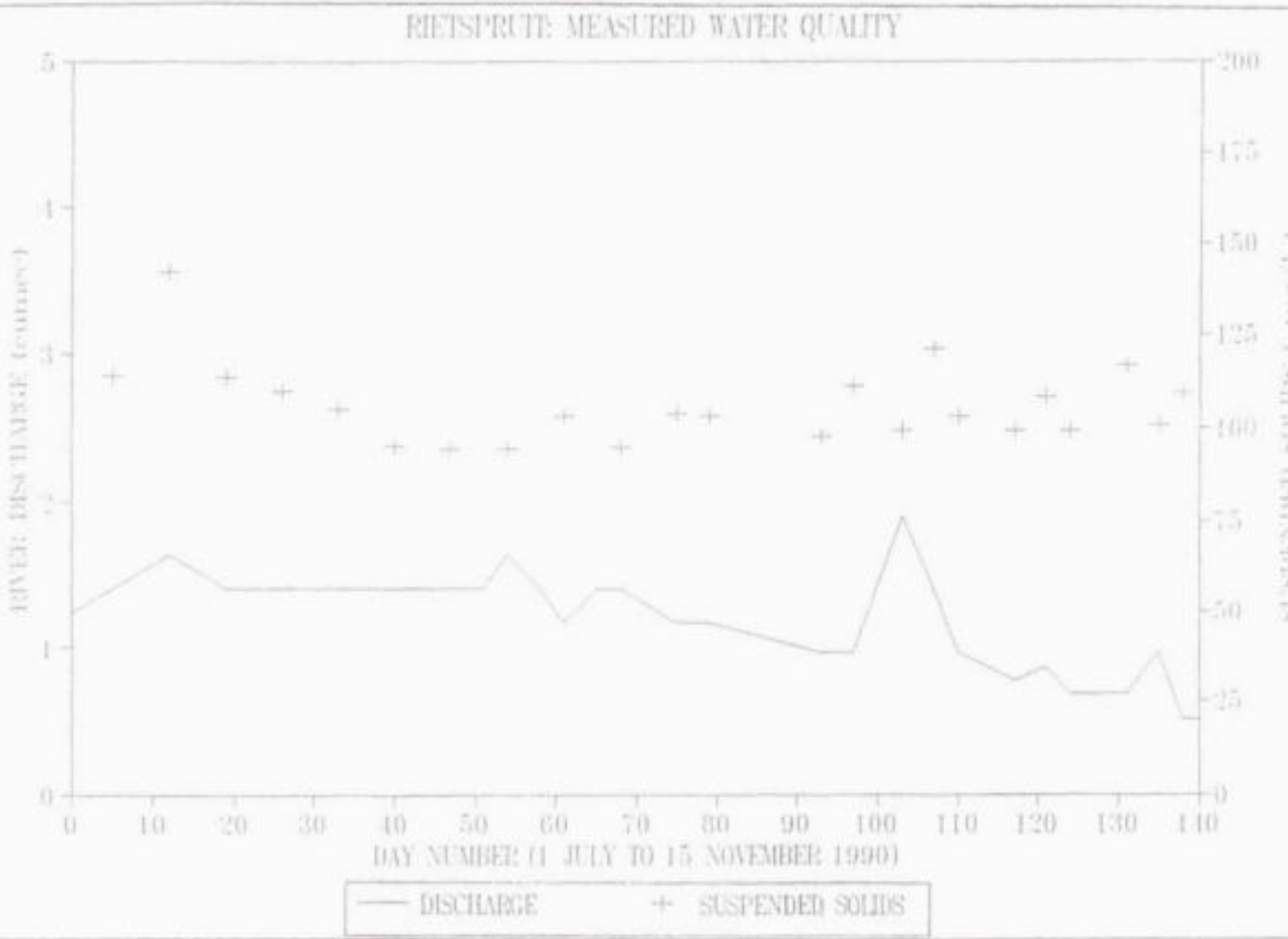
FIGURE A4.6.22



UNIVERSITY OF CAPE TOWN | WATER RESEARCH COMMISSION

FIGURE A4.6.23

Measured algal biomass and discharge hydrograph for the Rietspruit.



NINHAM SHAND | UNIVERSITY OF CAPE TOWN | WATER RESEARCH COMMISSION

Measured suspended solids and discharge hydrograph for the Rietspruit.

FIGURE A4.6.24

Figure A4.6.25

Two-dimensional plot of the simulated and measured water temperature in the Vaal Barrage.

Simulation Day: 18

Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▼
Withdrawal ▲

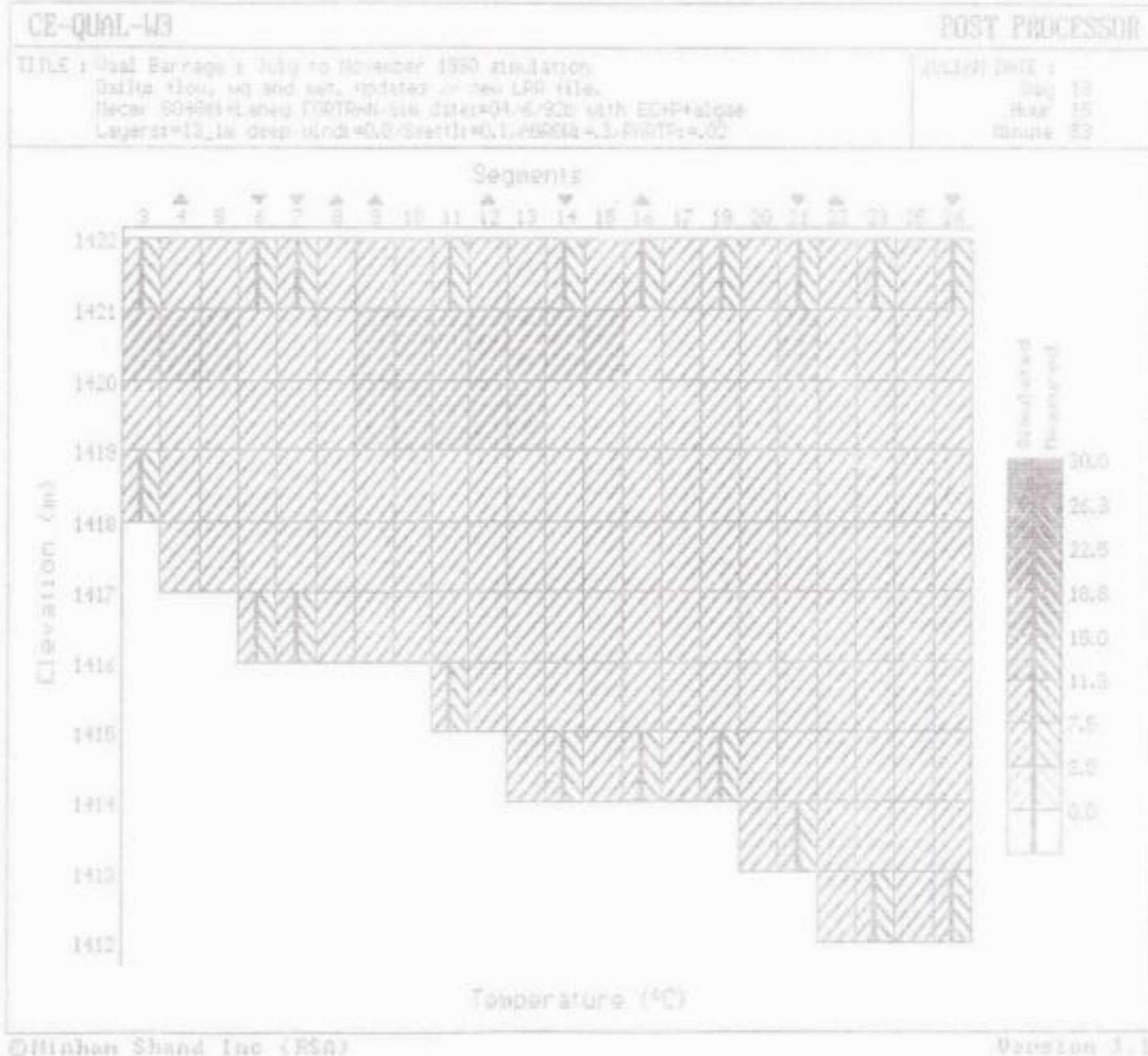


Figure A4.6.26

Two-dimensional plot of the simulated and measured water temperature in the Vaal Barrage.

Simulation Day: 45

Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▾
Withdrawal ▴

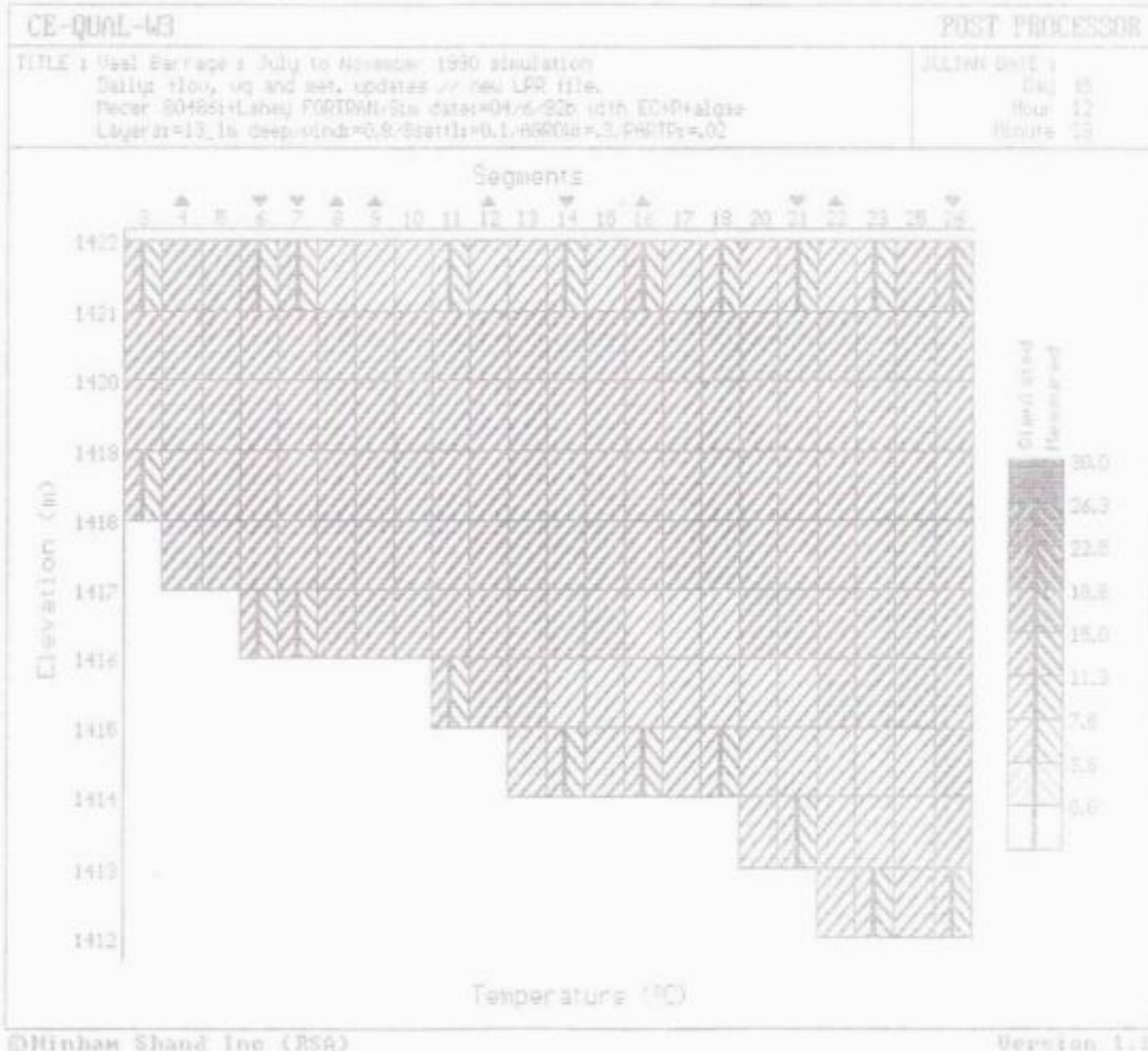


Figure A4.6.27

Two-dimensional plot of the simulated and measured water temperature in the Vaal Barrage.

Simulation Day: 92

Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▾
Withdrawal ▴

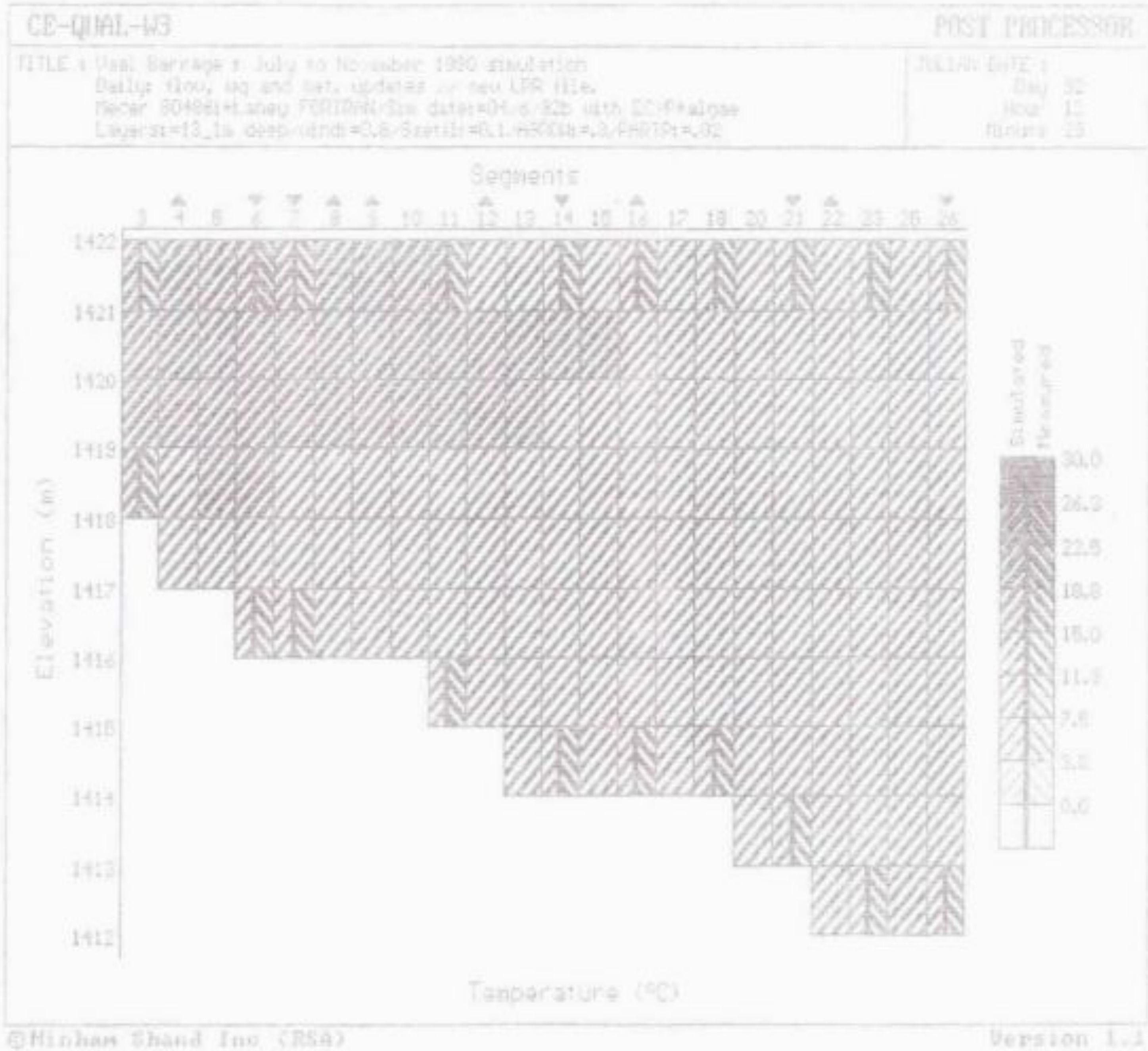


Figure A4.6.28

Two-dimensional plot of the simulated and measured water temperature in the Vaal Barrage.

Simulation Day: 109

Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▾
Withdrawal ▴

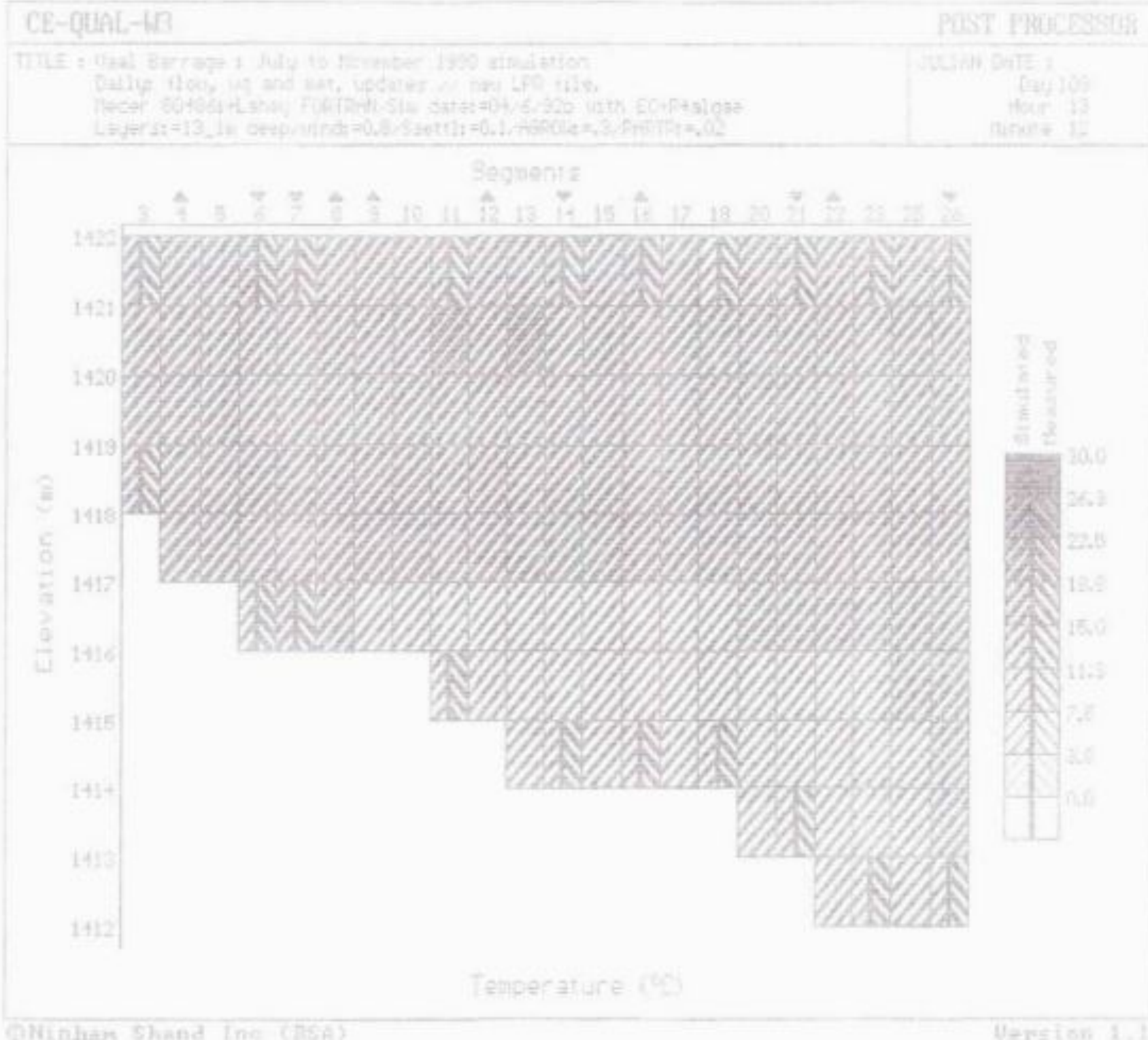


Figure A4.6.29

Plot showing the simulated and measured surface water temperature at Segments 3 to 26 in the Vaal Barrage.

Day number 4

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

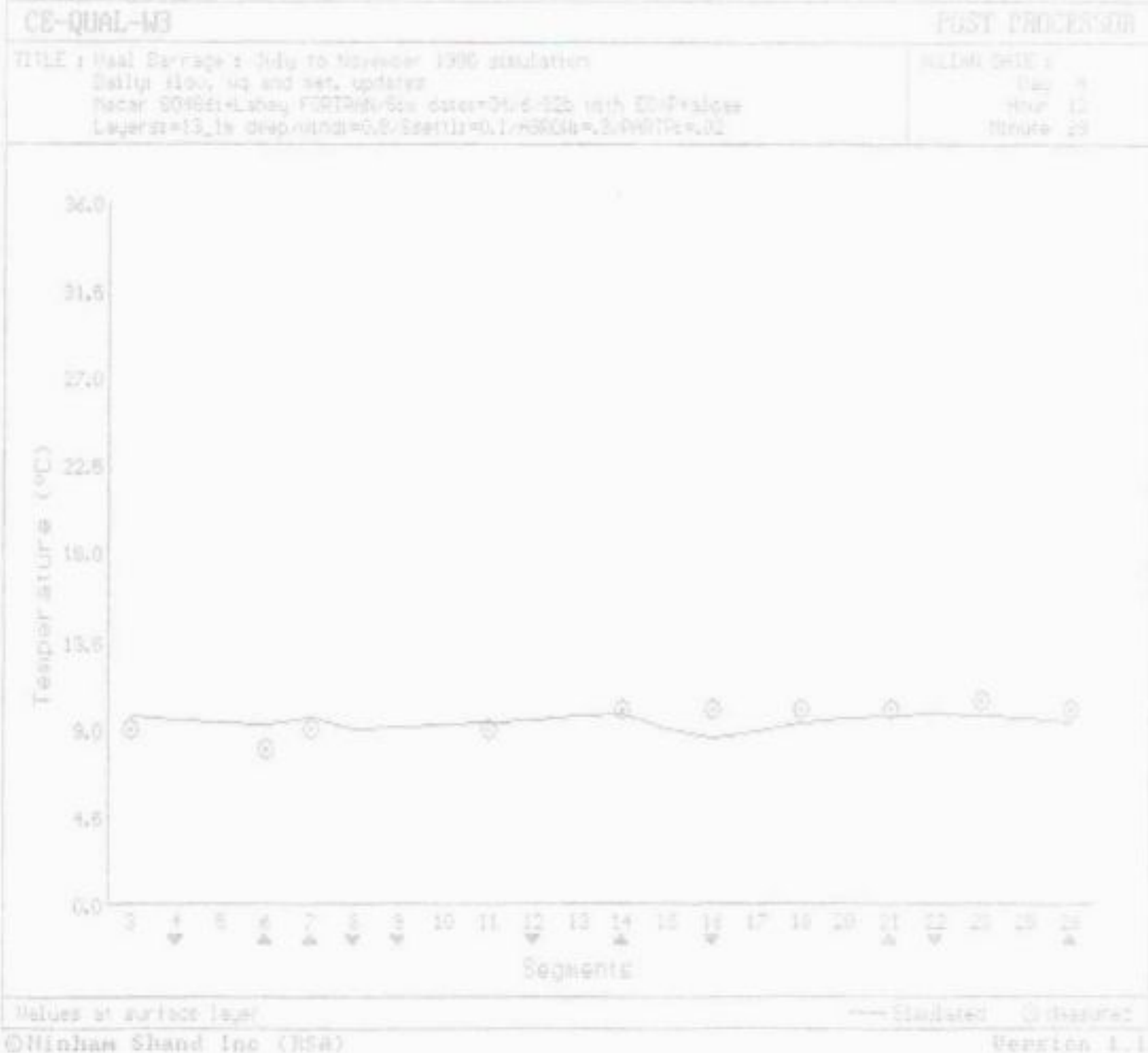


Figure A4.6.30

Plot showing the simulated and measured surface water temperature at Segments 3 to 26 in the Vaal Barrage.

Day number 32

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

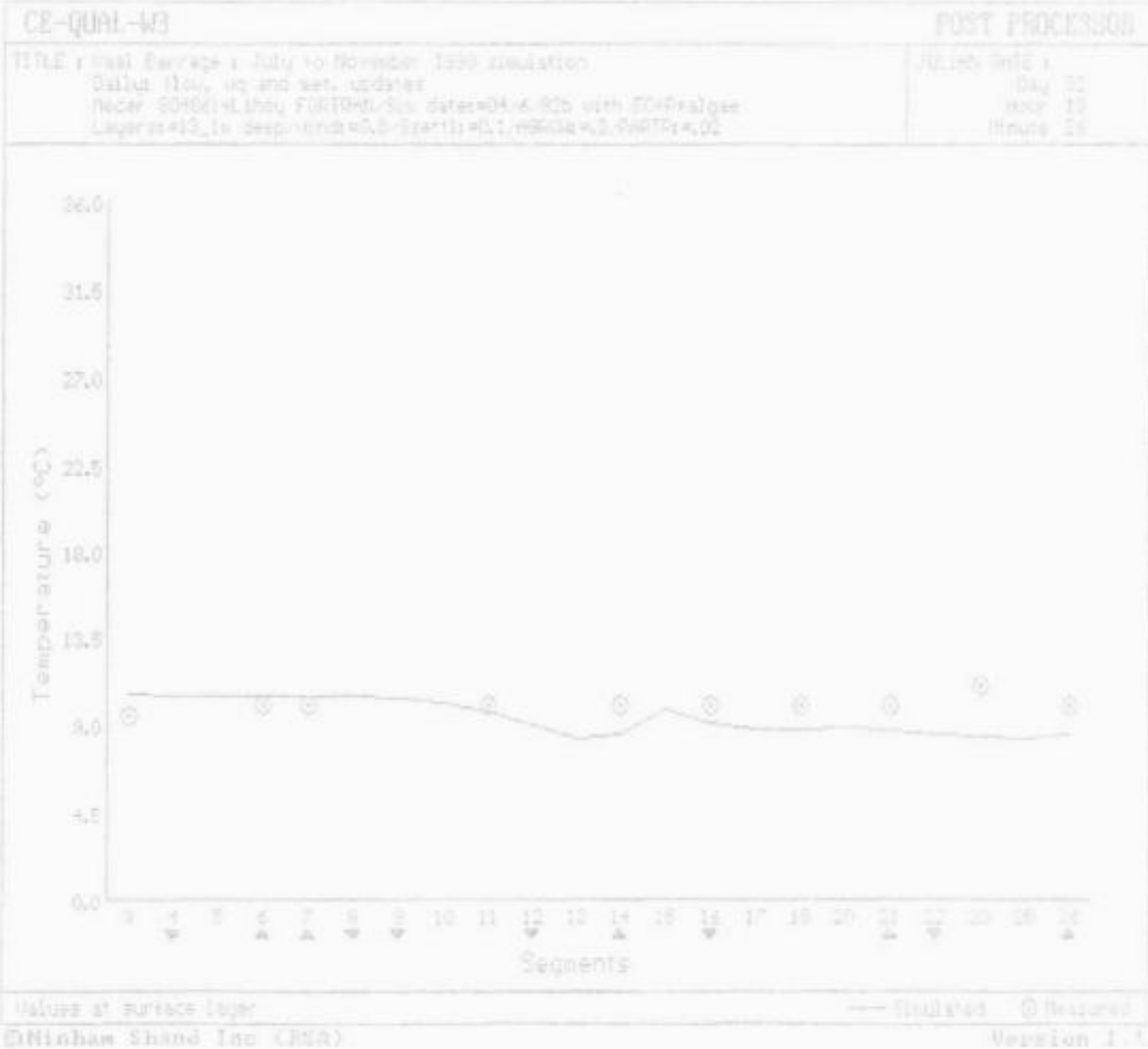


Figure A4.6.31

Plot showing the simulated and measured surface water temperature at Segments 3 to 26 in the Vaal Barrage.

Day number 109

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

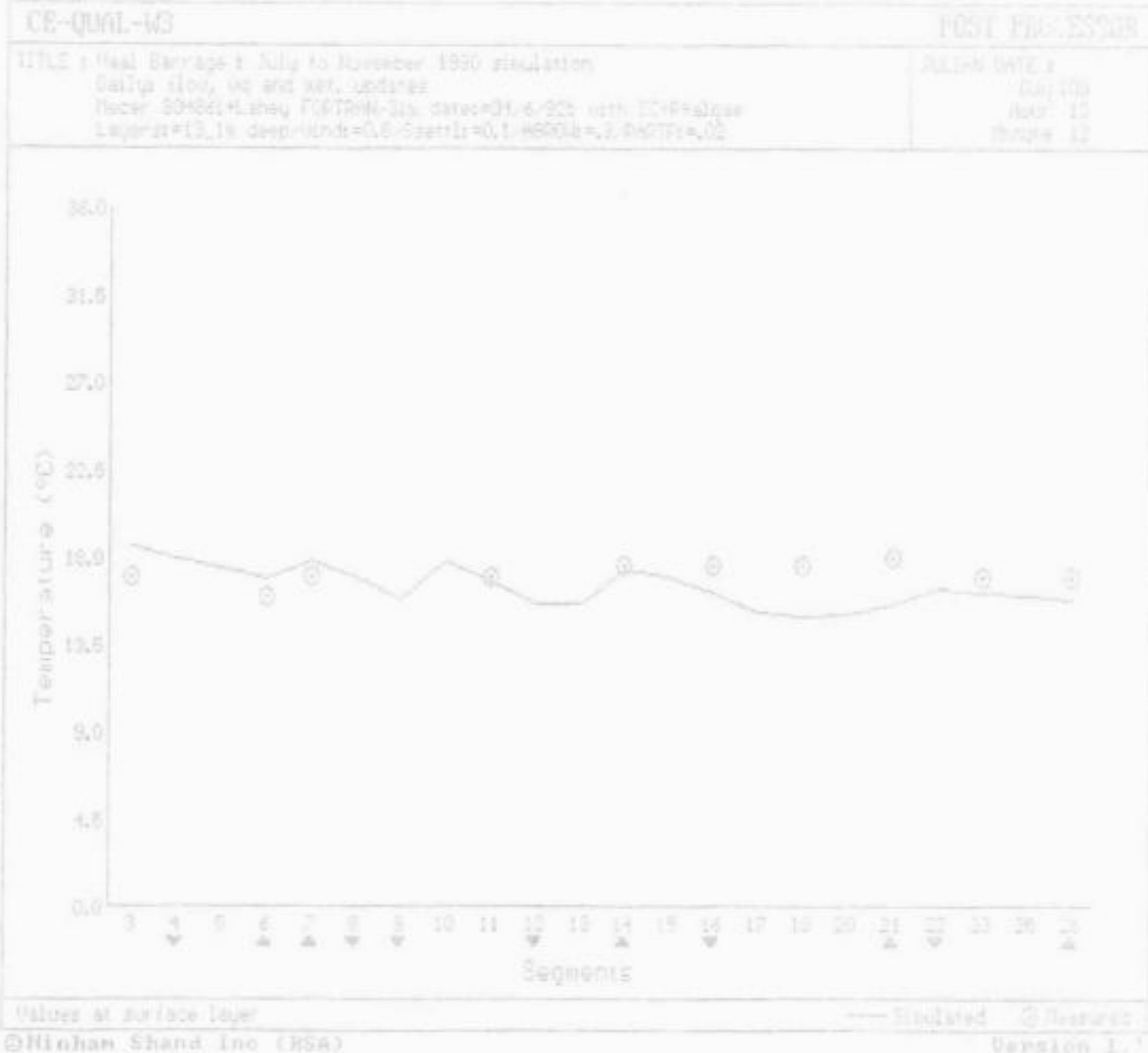


Figure A4.6.32

Time series plot of the simulated and measured electrical conductivity in the Vaal Barrage at:

Segment number 6

SURFACE LAYER

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

Tracer: Conductivity
Units: mS/m

Figure A4.6.33

Time series plot of the simulated and measured electrical conductivity in the Vaal Barrage at:

Segment number 14

SURFACE LAYER

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

Tracer: Conductivity
Units: mS/m

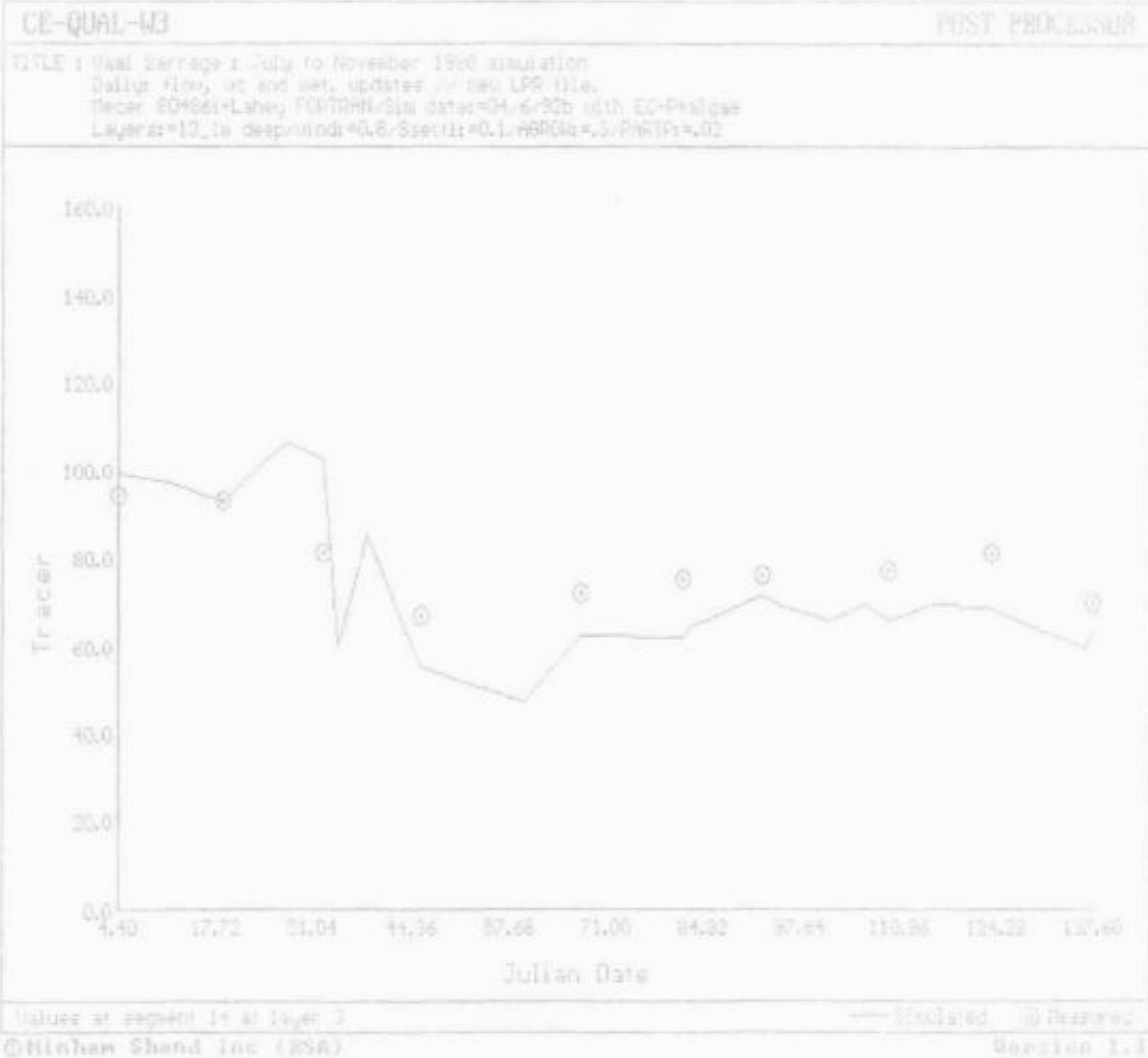


Figure A4.6.34

Time series plot of the simulated and measured electrical conductivity in the Vaal Barrage at:

Segment number 18

SURFACE LAYER

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▾
Withdrawal ▴

Tracer: Conductivity
Units: mS/m

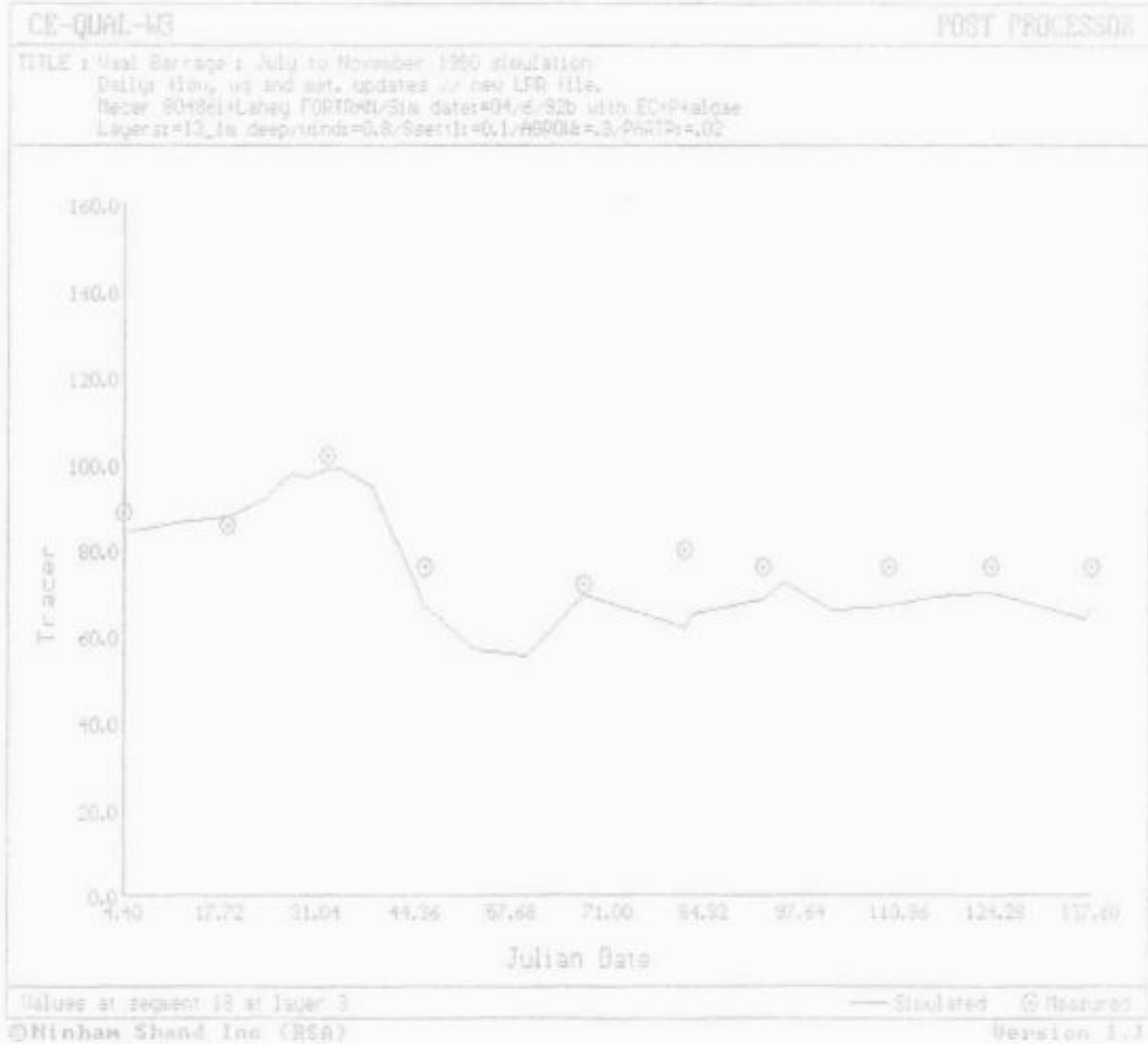


Figure A4.6.35

Time series plot of the simulated and measured electrical conductivity in the Vaal Barrage at:

Segment number 26

SURFACE LAYER

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▾
Withdrawal ▴

Tracer: Conductivity
Units: mS/m

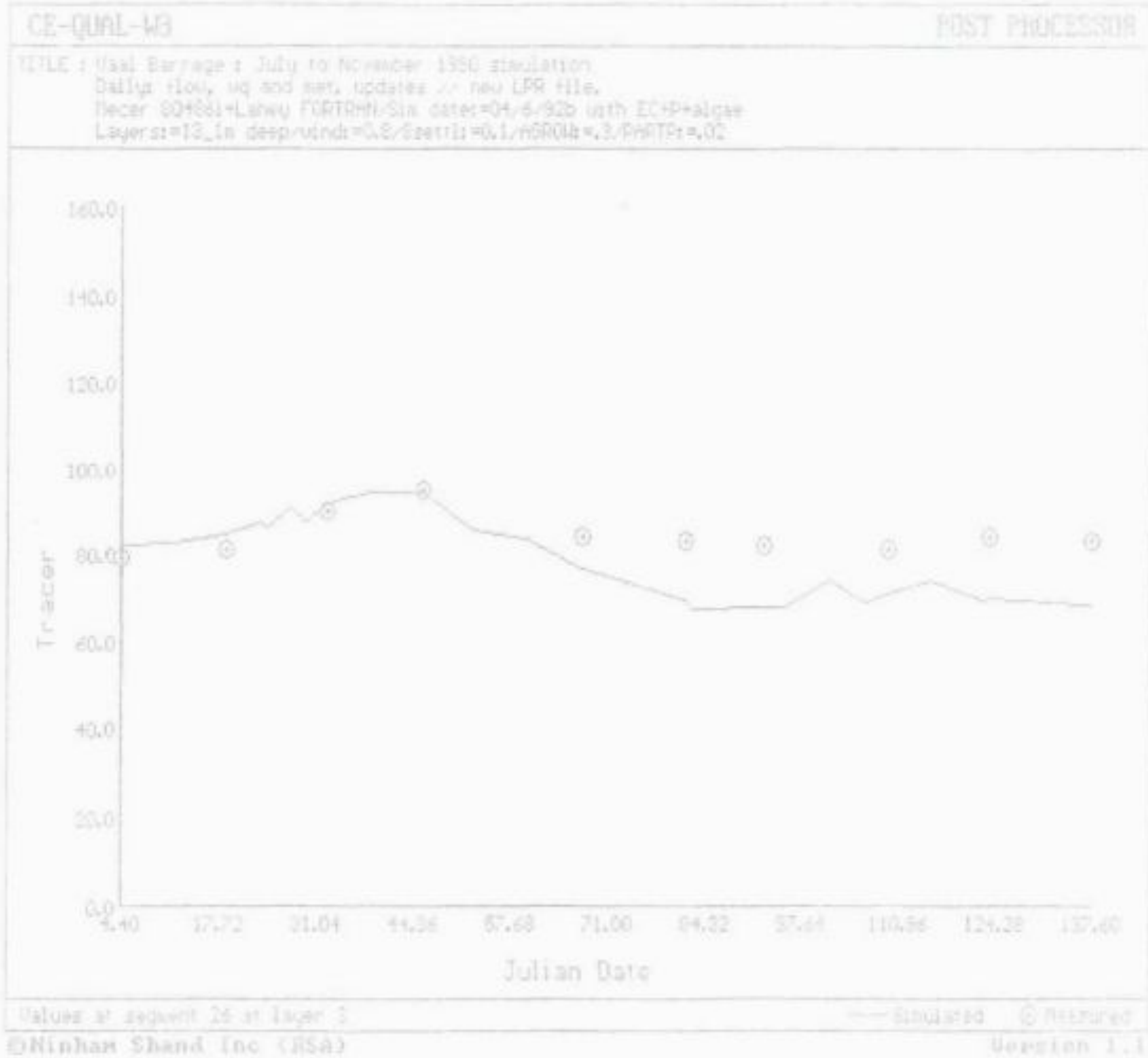


Figure A4.6.36

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 29

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

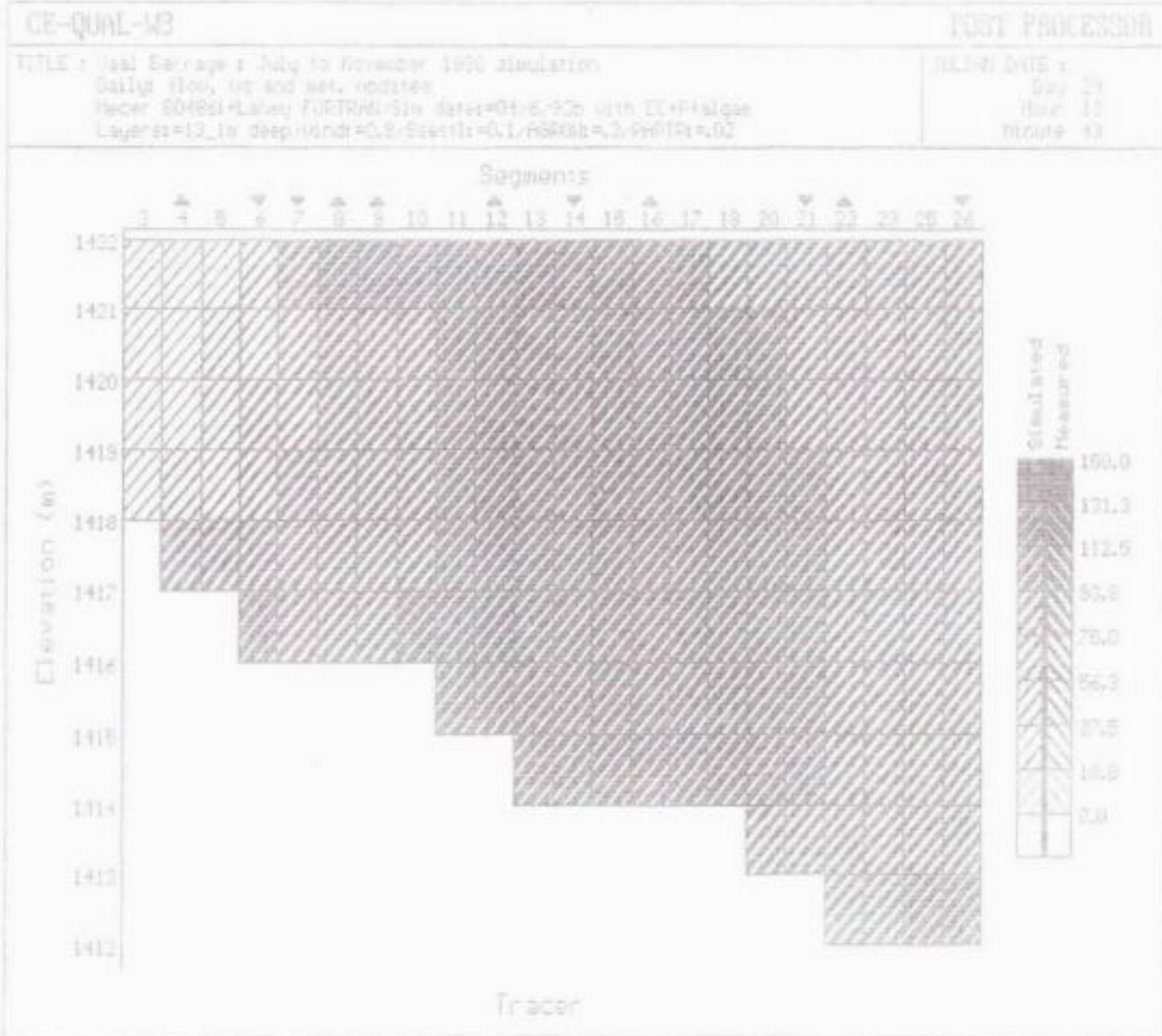


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Figure A4.6.37

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 32

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

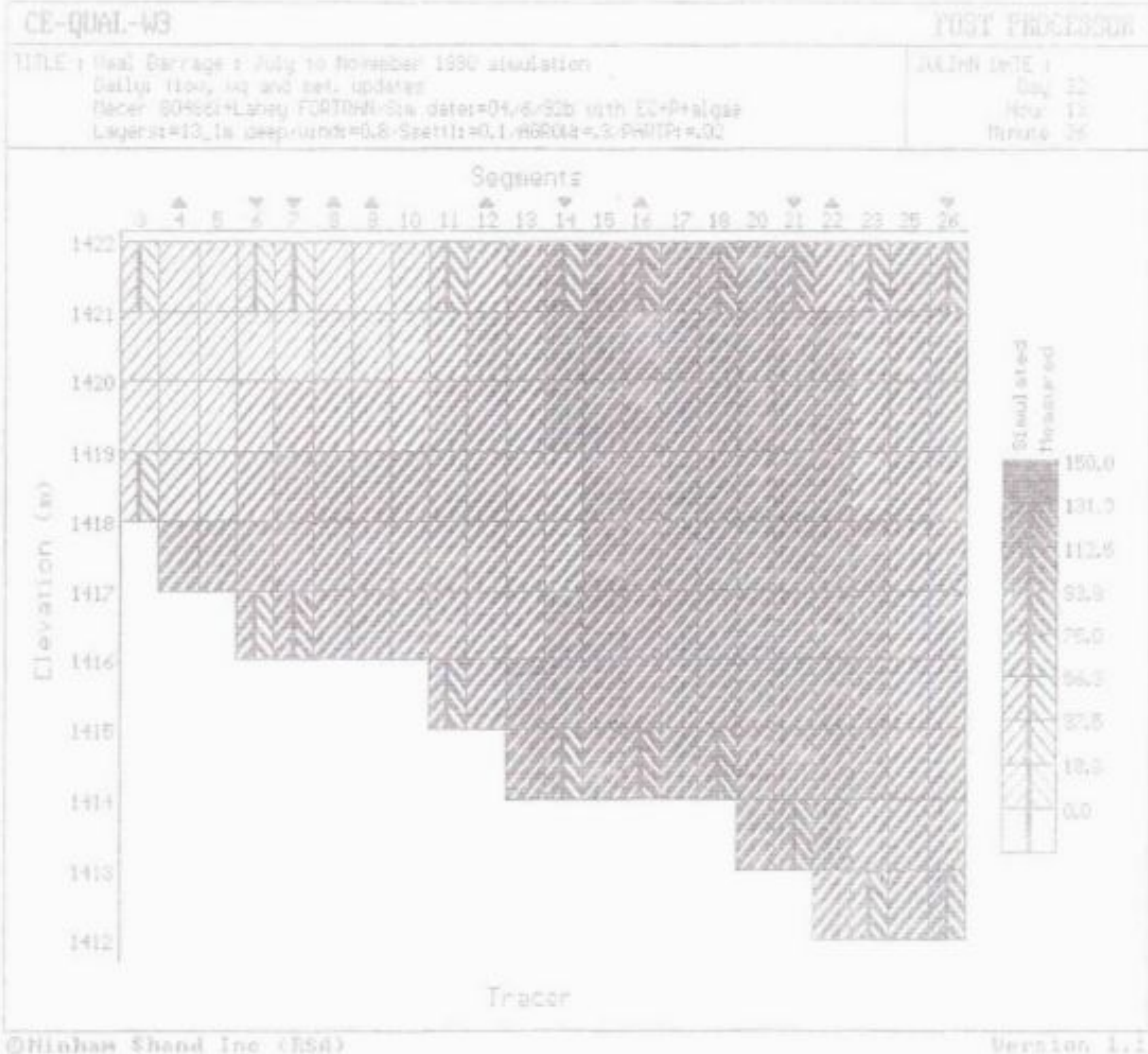

Figure A4.6.38

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 34

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

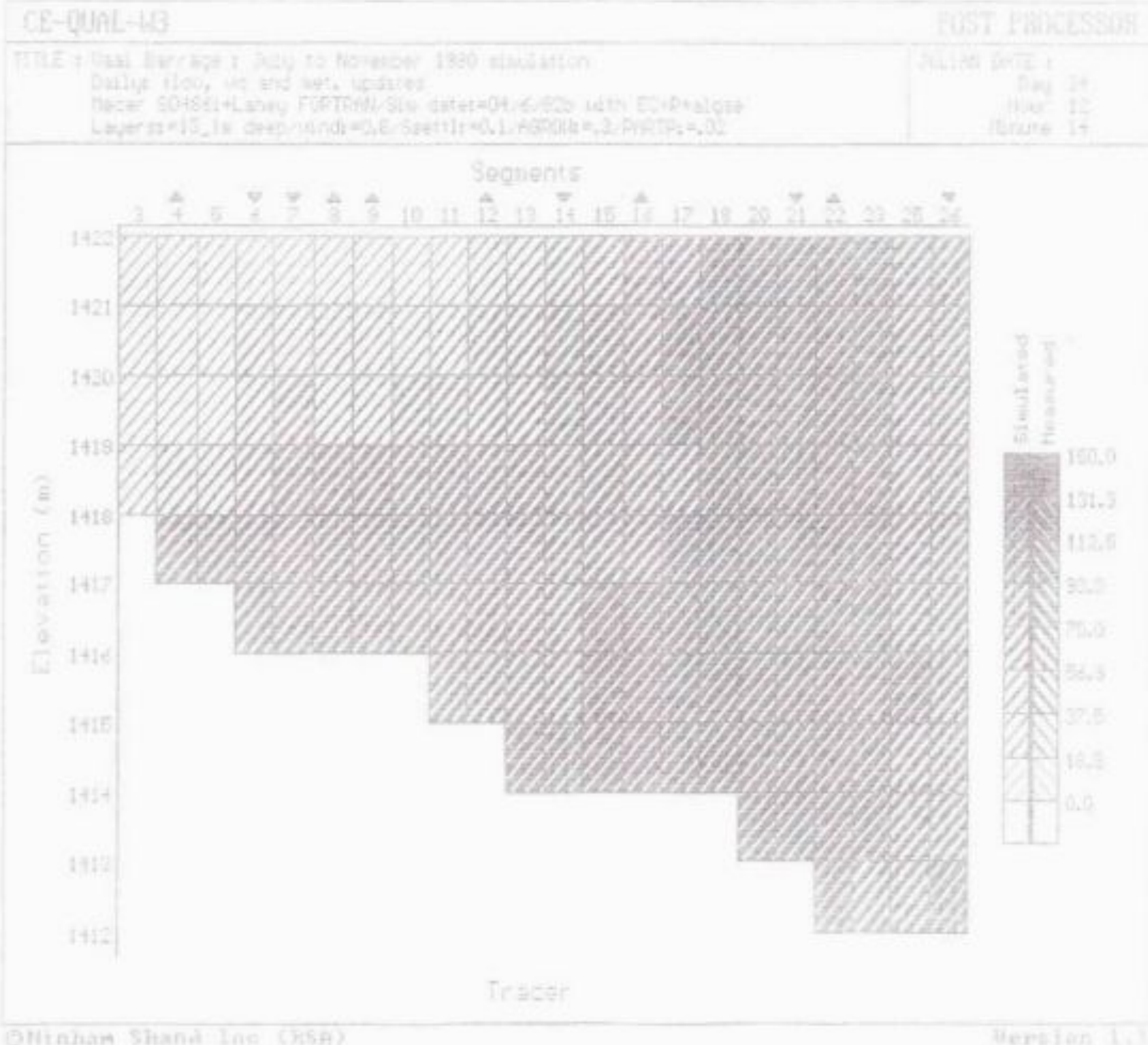

Figure A4.6.39

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 45

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

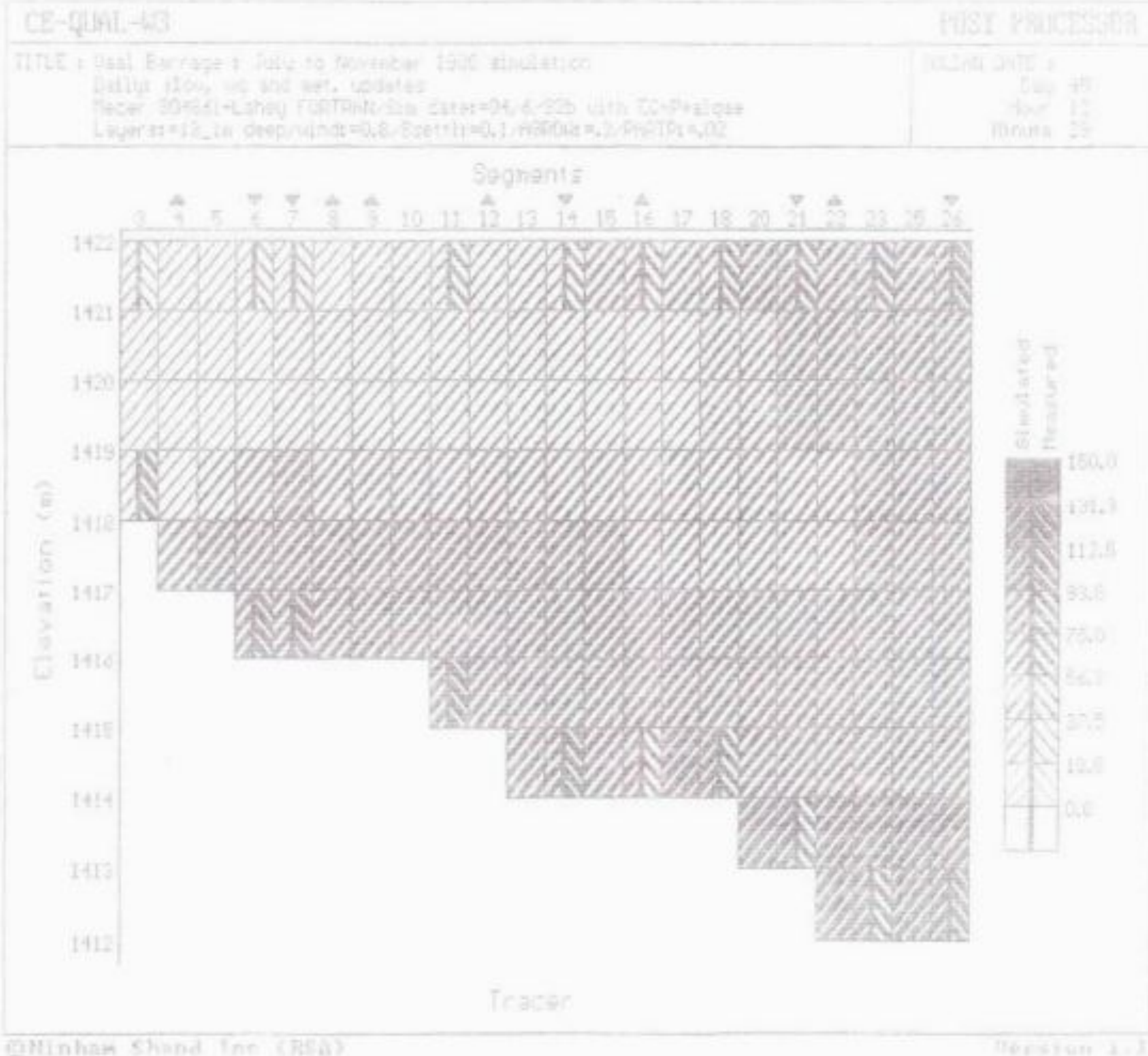

Figure A4.6.40

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 59

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

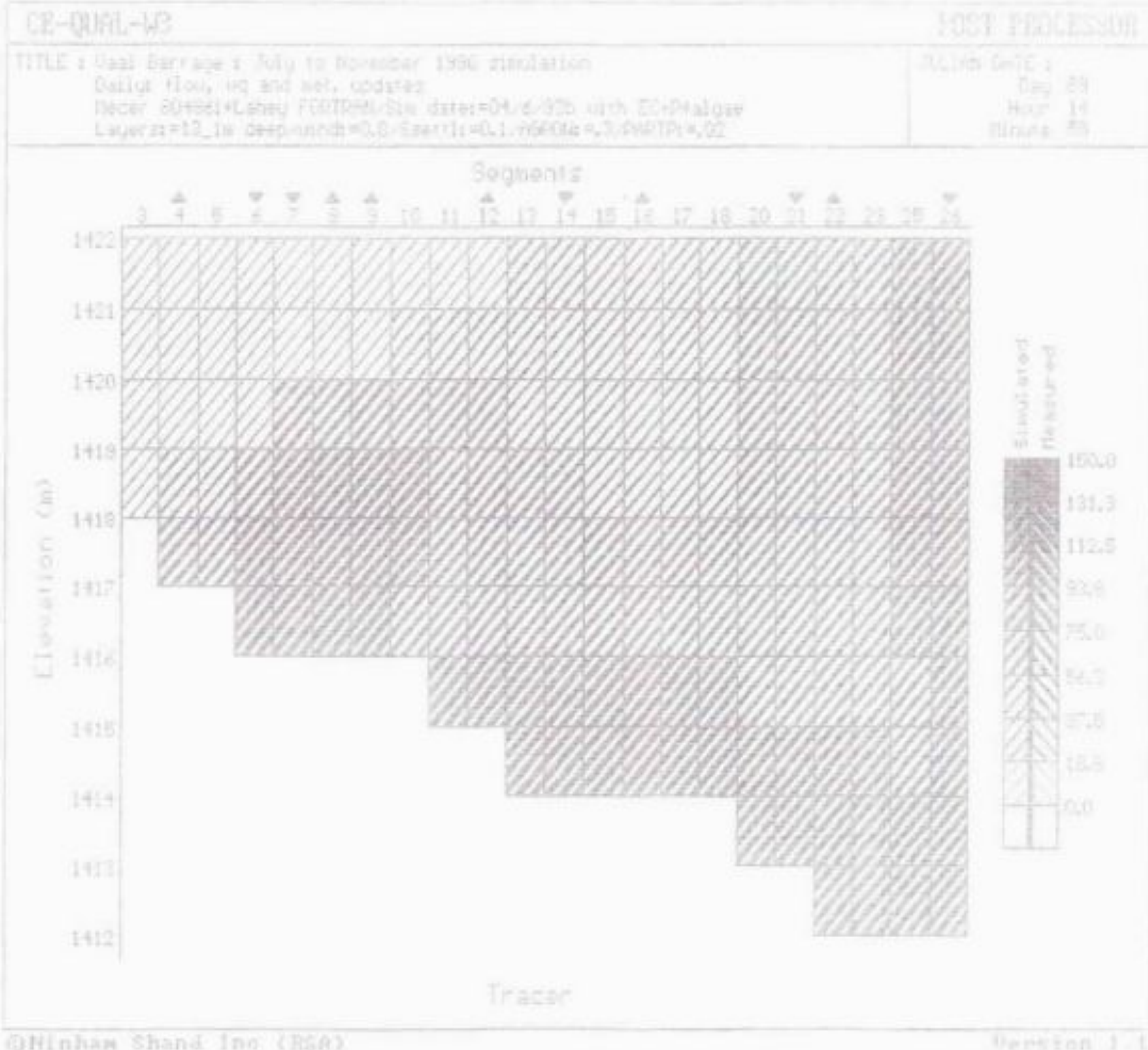

Figure A4.6.41

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 67

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

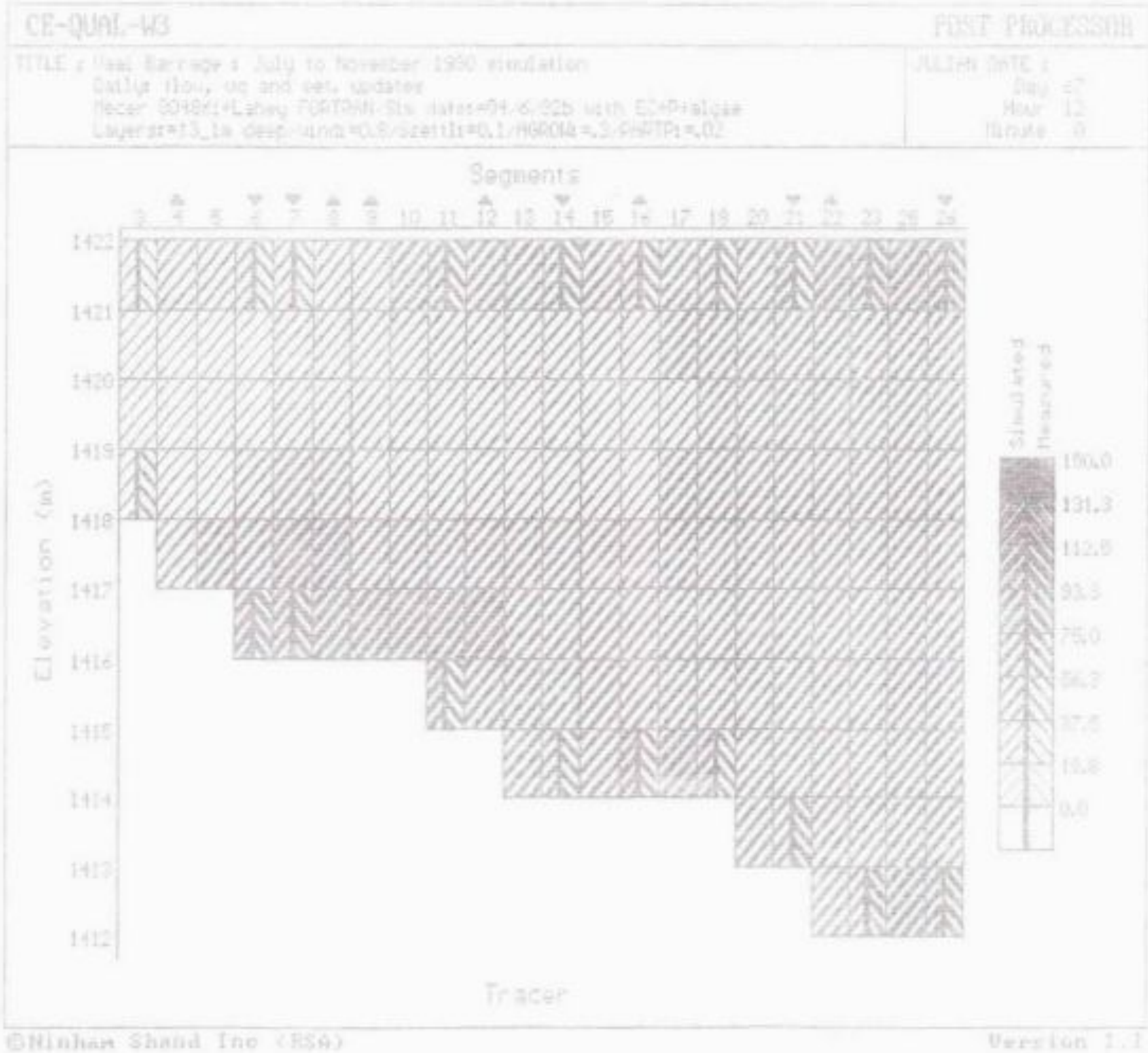

Figure A4.6.42

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 92

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

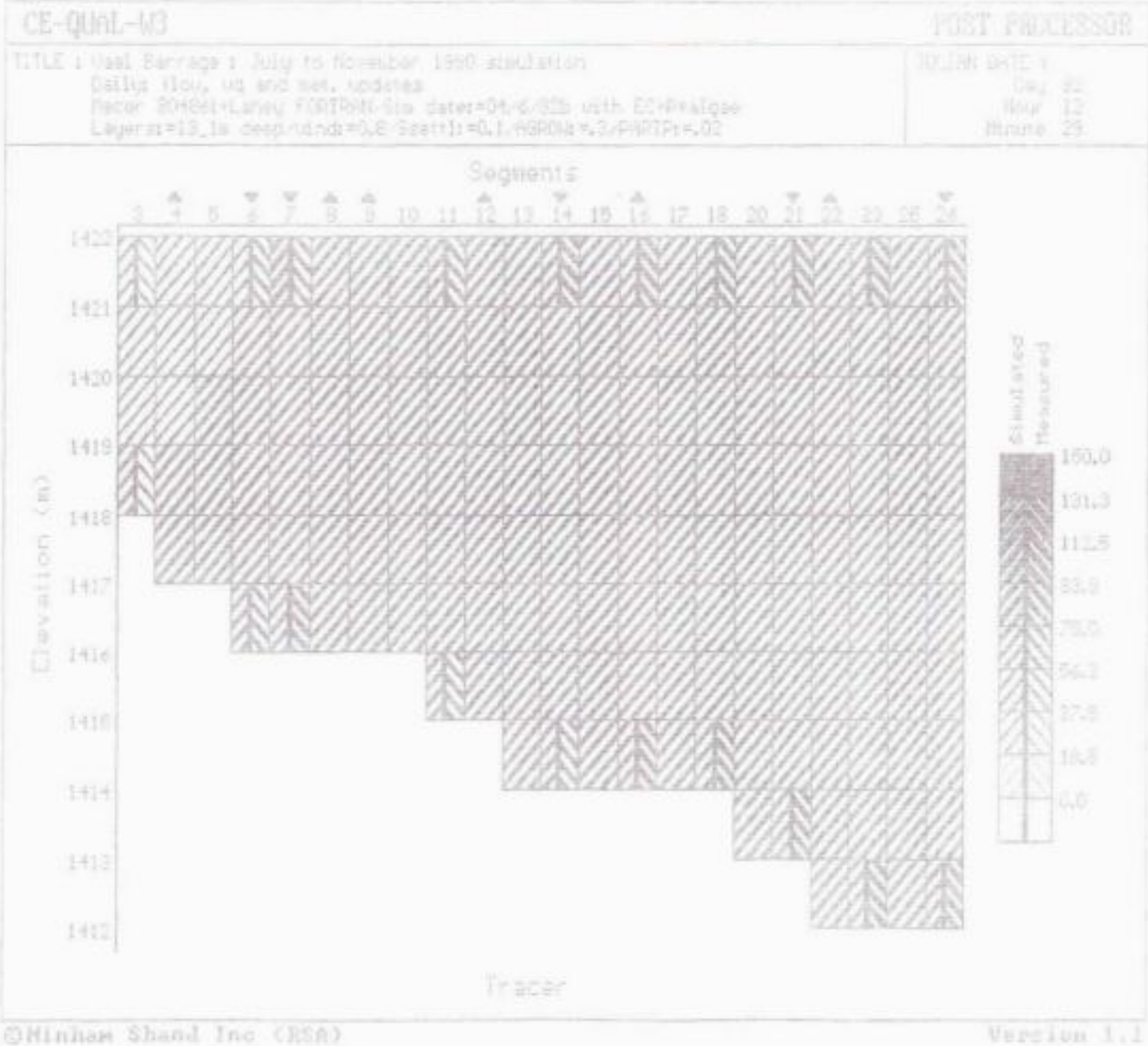

Figure A4.6.43

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 109

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

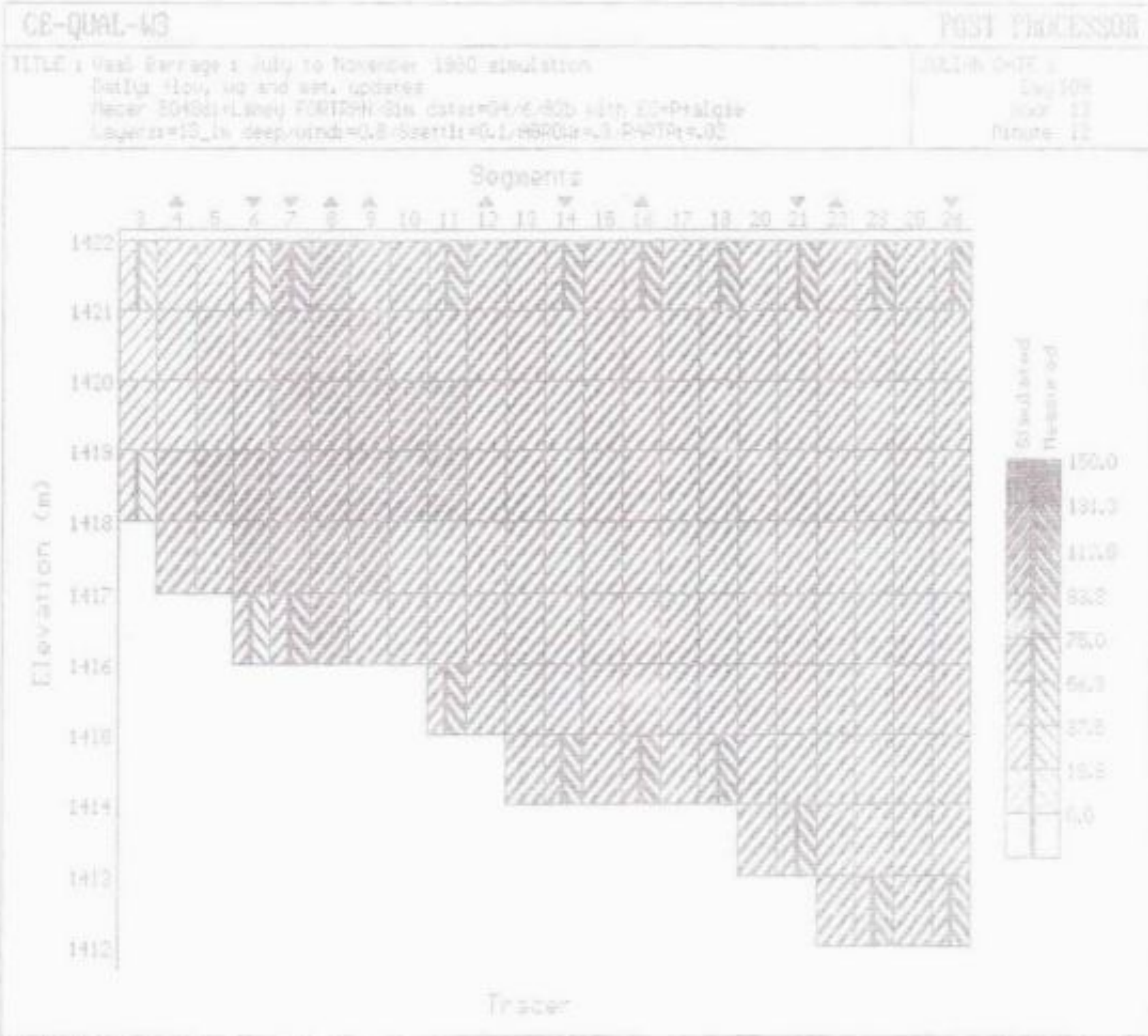

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Figure A4.6.44

Two-dimensional plot showing the simulated and measured conductivity at Segments 3 through to 26 in the Vaal Barrage.

Segment 3 is located near Lethabo Weir and Segment 26 located at the Vaal Barrage.

Day number: 137

Day of beginning of release from Vaal Dam: 21

Units: mS/m
Tracer: conductivity

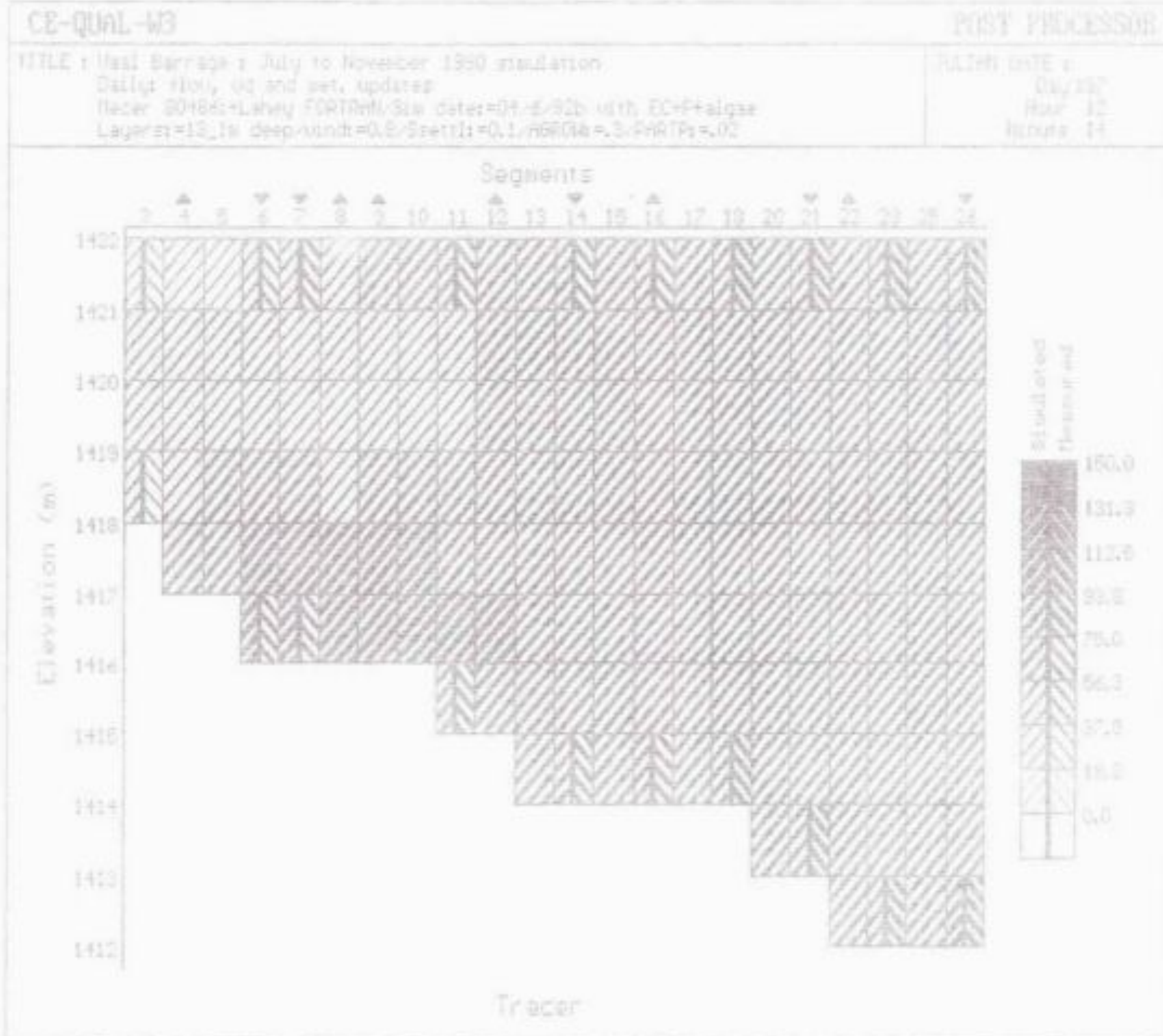

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Figure A4.6.45

Plot showing the simulated and measured electrical conductivity in the Vaal Barrage at segments 3 to 26.

SURFACE LAYER

DAY NUMBER: 4

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▲
Withdrawal ▼

Tracer: Conductivity
Units: mS/m

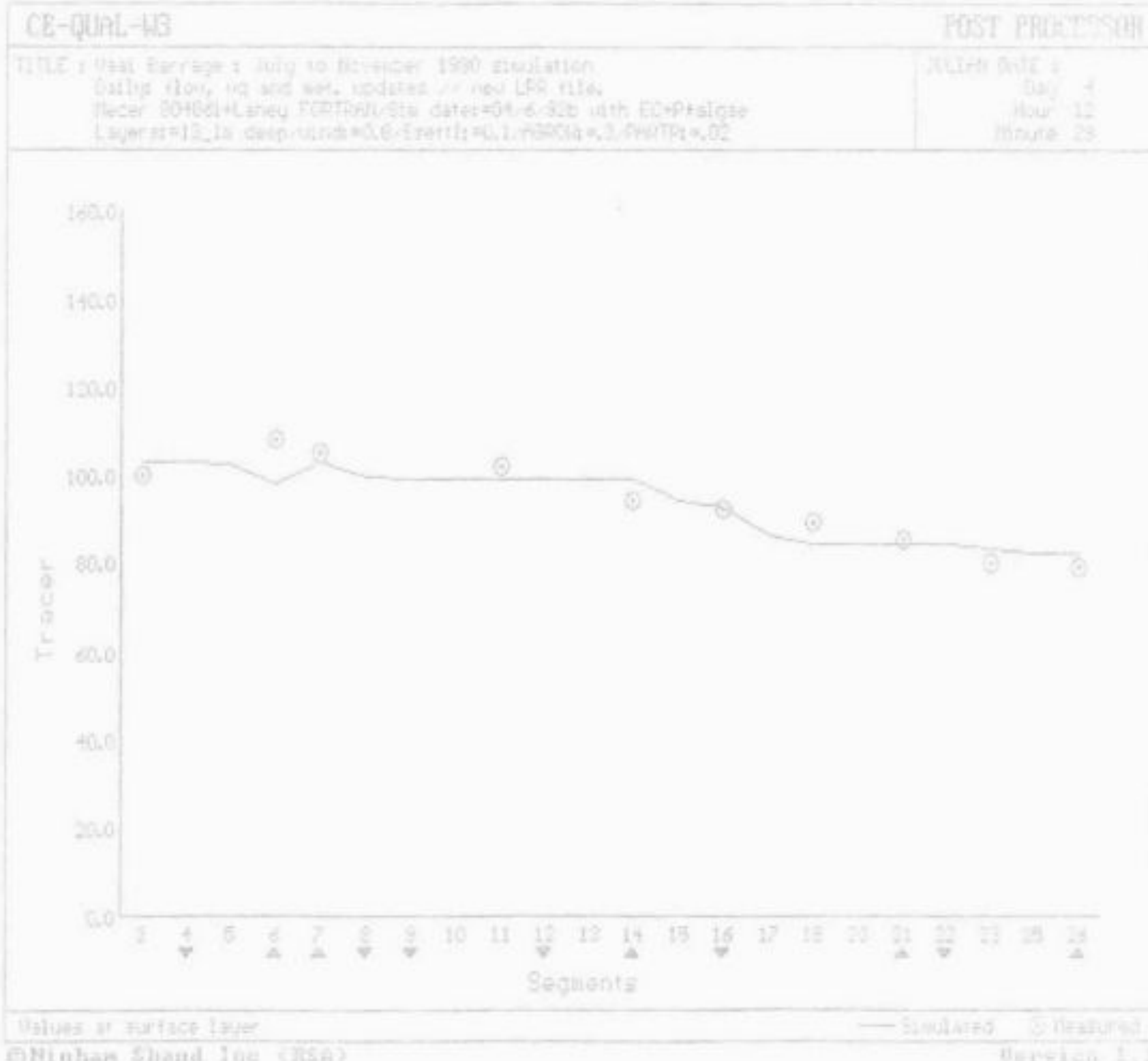

Figure A4.6.46

Plot showing the simulated and measured electrical conductivity in the Vaal Barrage at segments 3 to 26.

SURFACE LAYER

DAY NUMBER: 18

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▲
Withdrawal ▼

Tracer: Conductivity
Units: mS/m

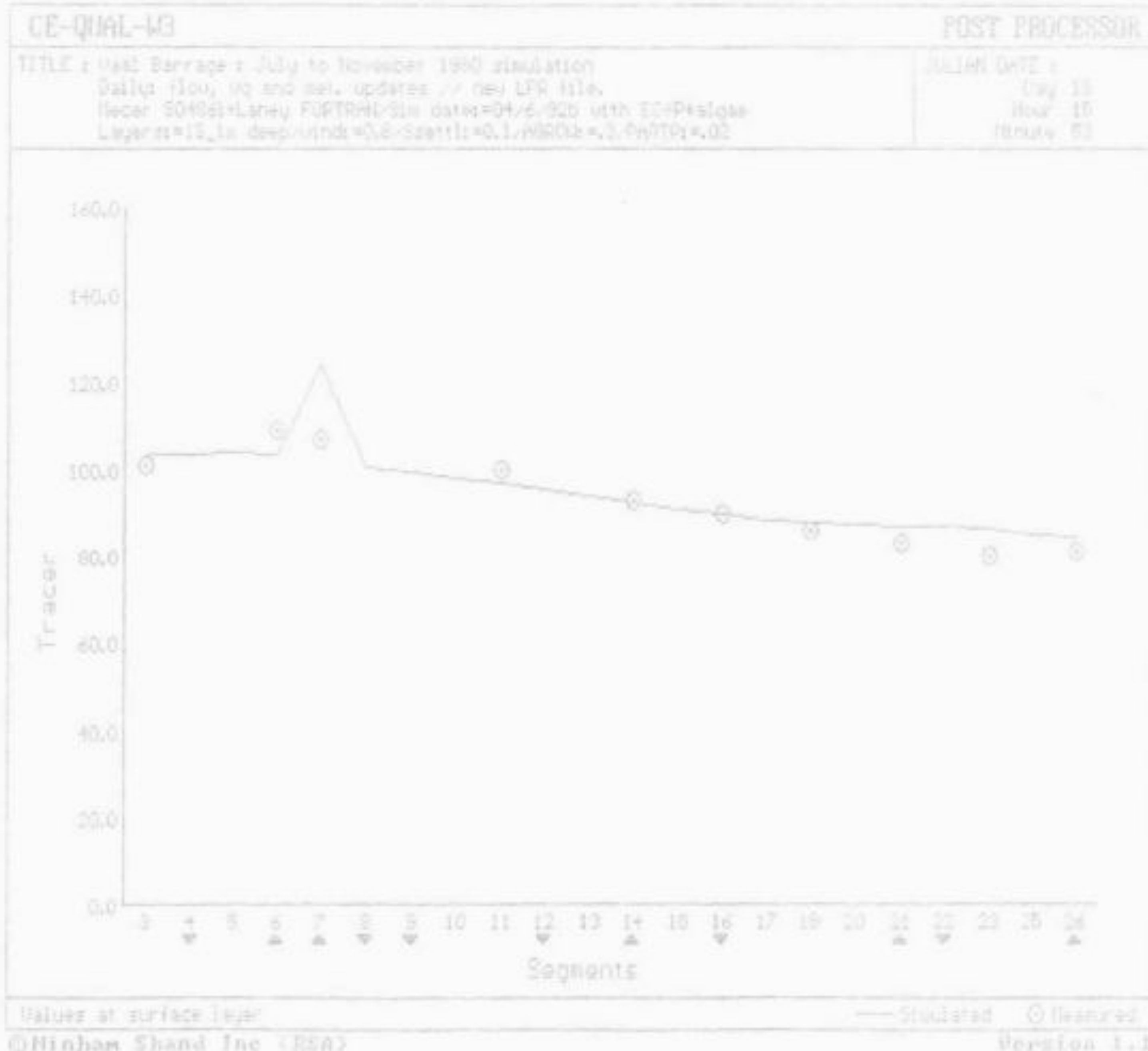

Figure A4.6.47

Plot showing the simulated and measured electrical conductivity in the Vaal Barrage at segments 3 to 26.

SURFACE LAYER

DAY NUMBER: 32

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▲
Withdrawal ▼

Tracer: Conductivity
Units: mS/m

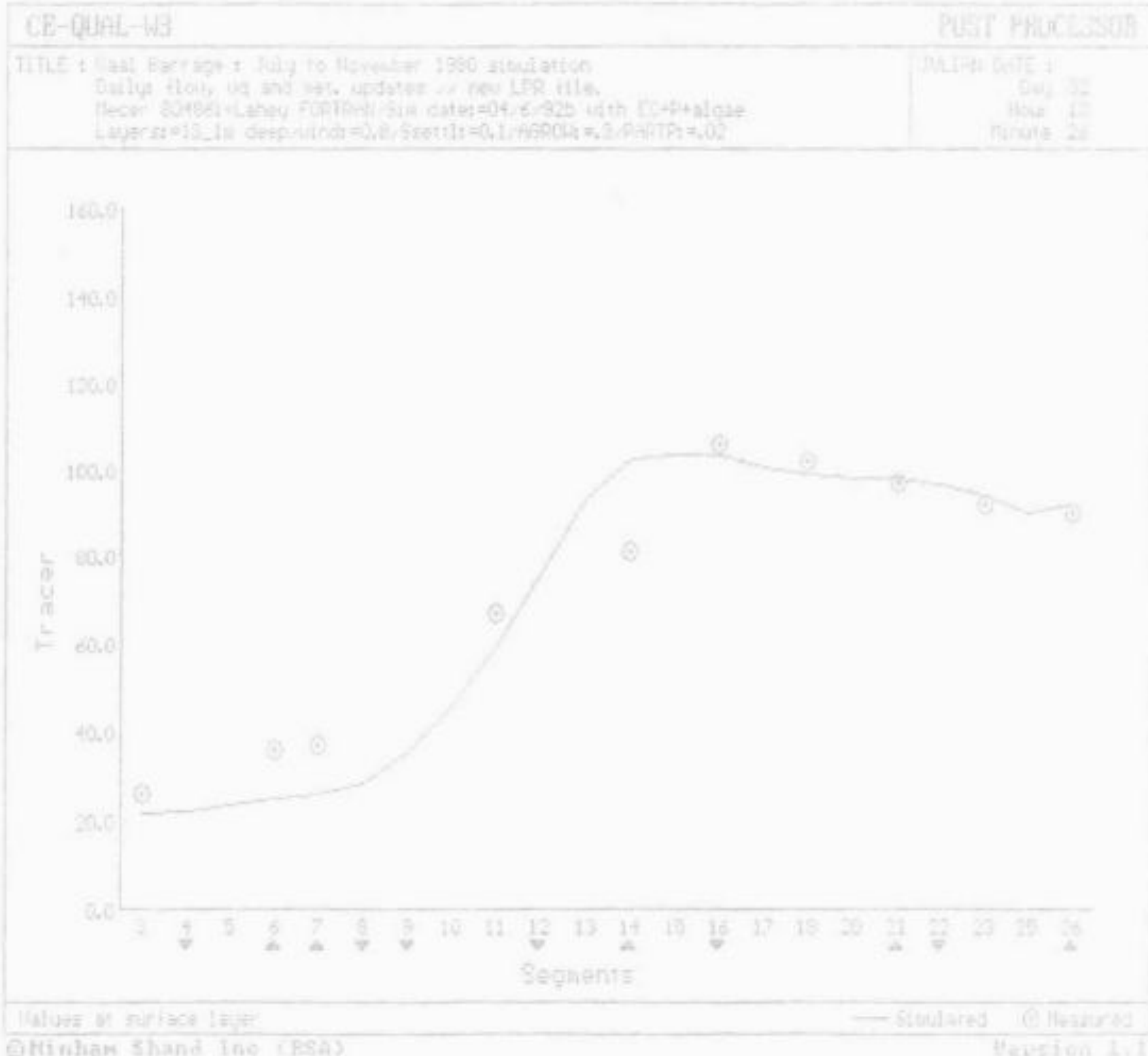

Figure A4.6.48

Plot showing the simulated and measured electrical conductivity in the Vaal Barrage at segments 3 to 26.

SURFACE LAYER

DAY NUMBER: 45

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▲
Withdrawal ▼

Tracer: Conductivity
Units: mS/m

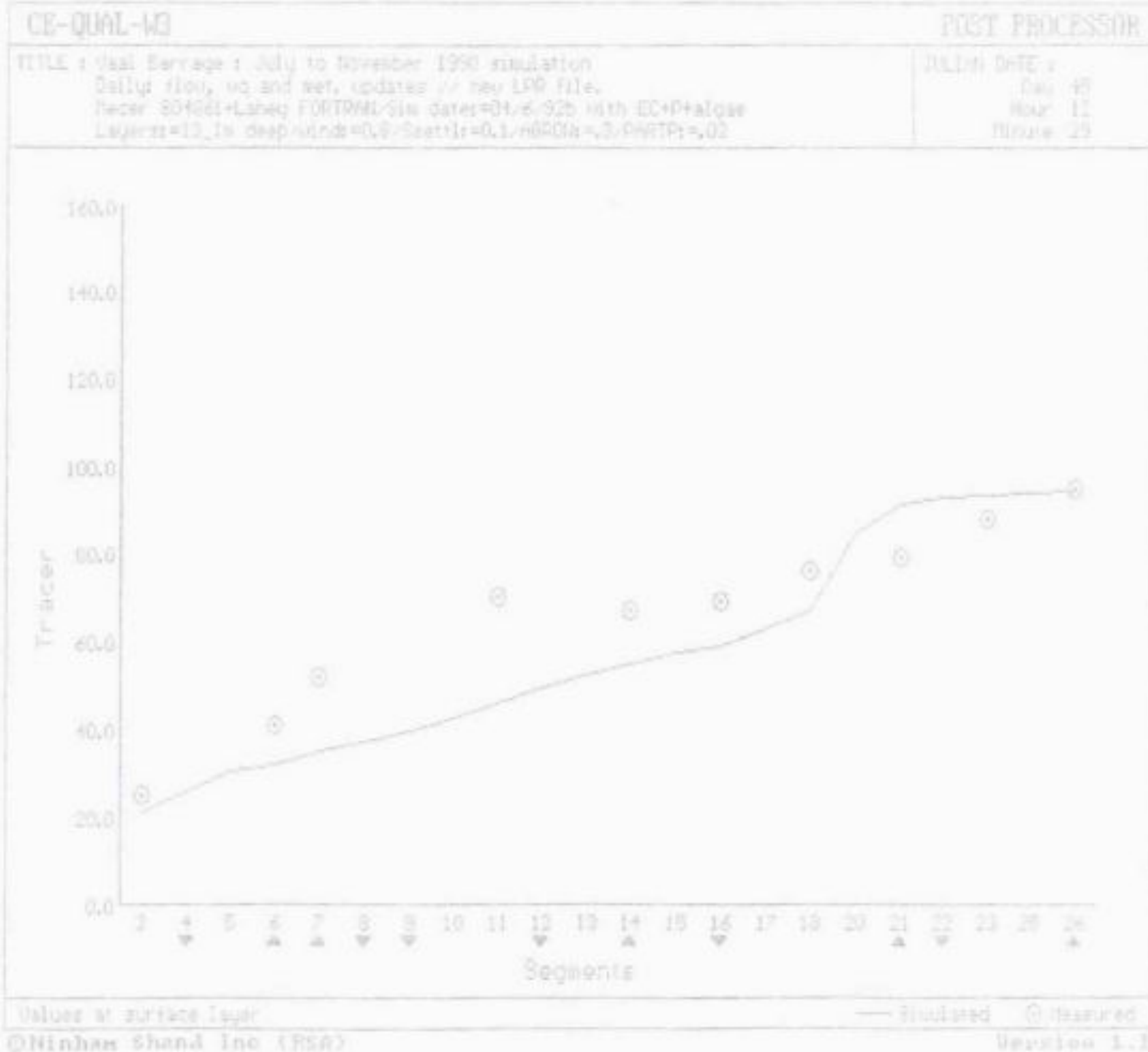

Figure A4.6.49

Plot showing the simulated and measured electrical conductivity in the Vaal Barrage at segments 3 to 26.

SURFACE LAYER

DAY NUMBER: 67

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▲
Withdrawal ▼

Tracer: Conductivity
Units: mS/m

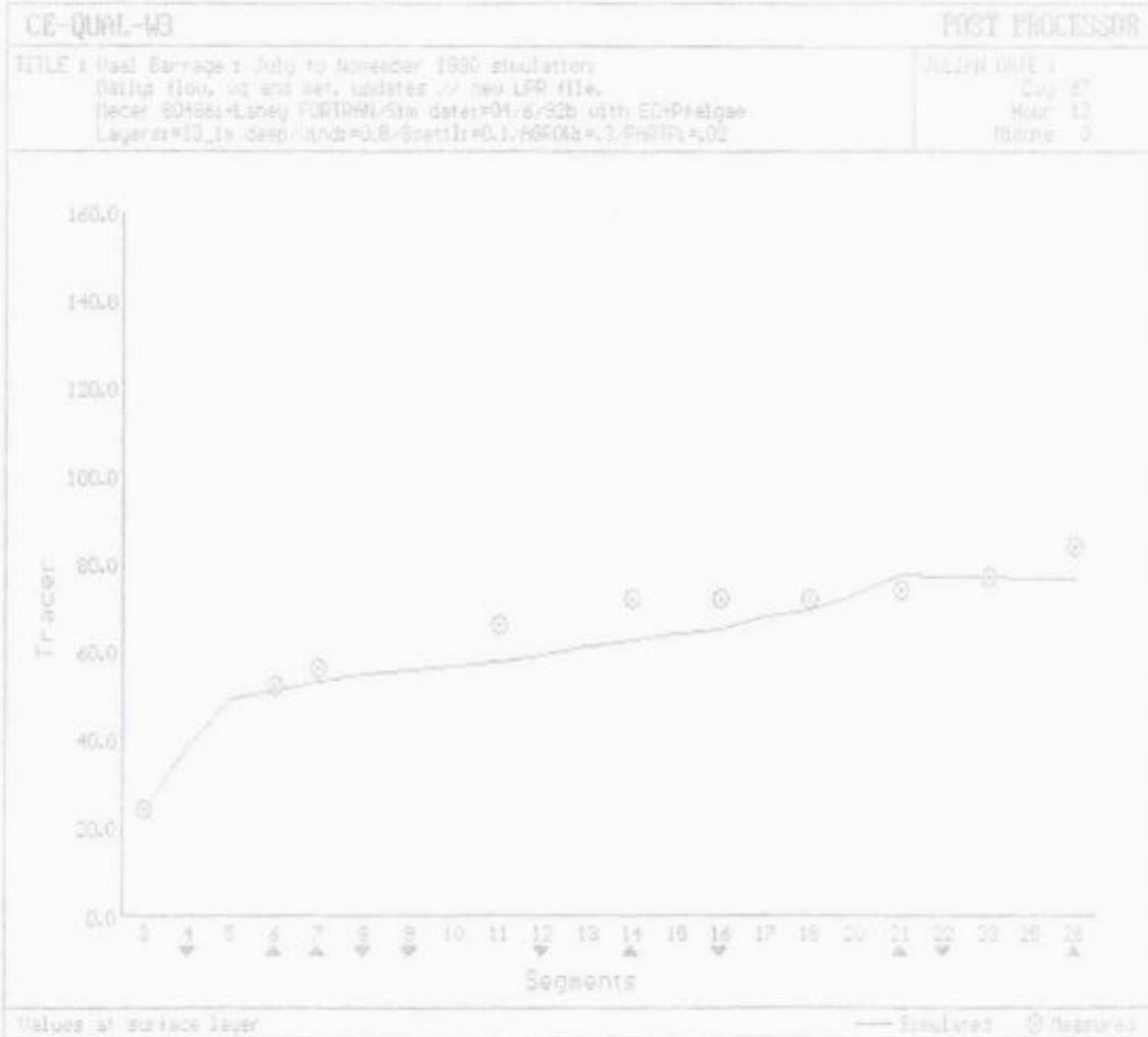

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Figure A4.6.50

Plot showing the simulated and measured electrical conductivity in the Vaal Barrage at segments 3 to 26.

SURFACE LAYER

DAY NUMBER: 81

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▲
Withdrawal ▼

Tracer: Conductivity
Units: mS/m

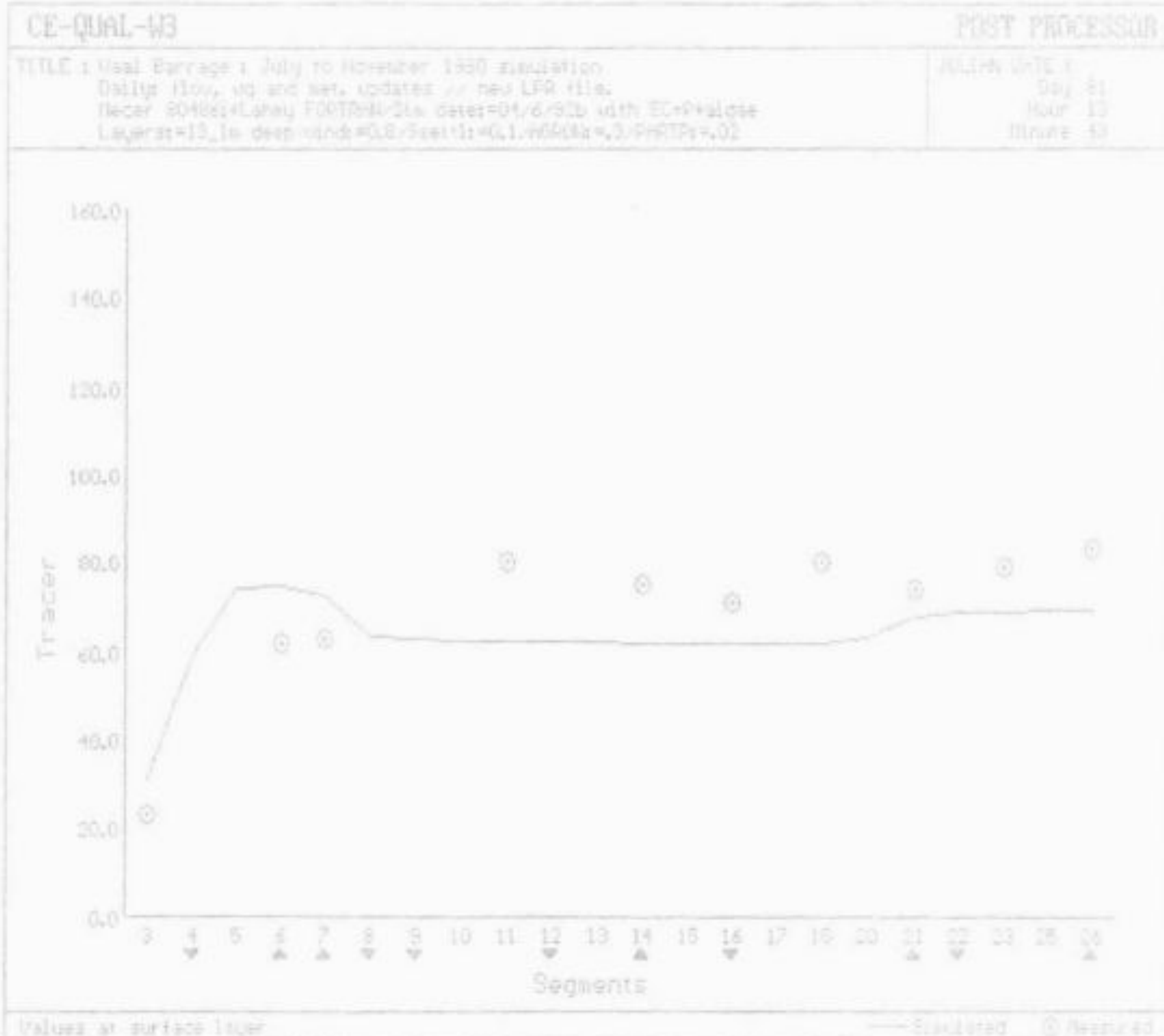

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Figure A4.6.51

Plot showing the simulated and measured electrical conductivity in the Vaal Barrage at segments 3 to 26.

SURFACE LAYER

DAY NUMBER: 109

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▲
Withdrawal ▼

Tracer: Conductivity
Units: mS/m

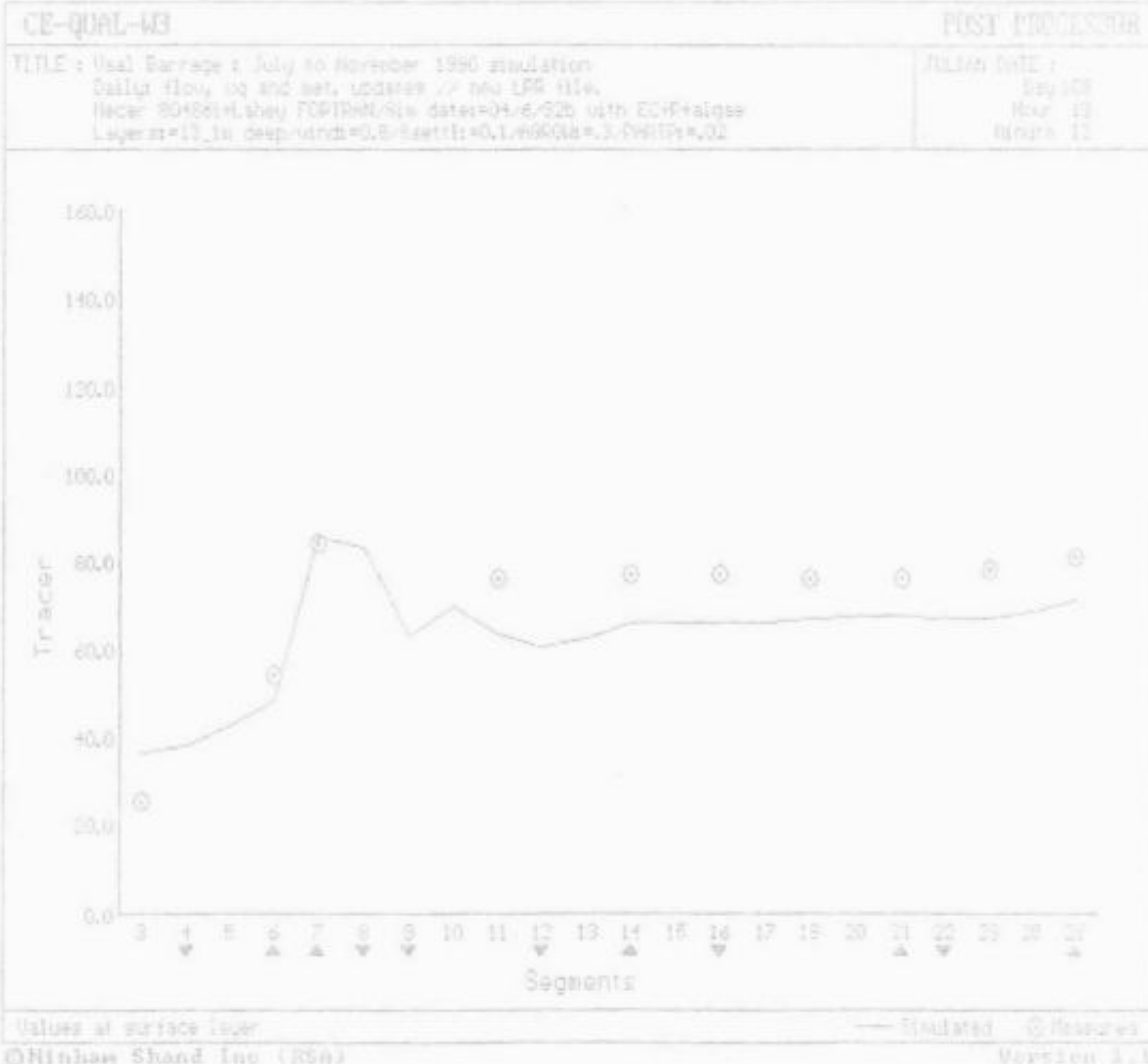

Figure A4.6.52

Plot showing the simulated and measured electrical conductivity in the Vaal Barrage at segments 3 to 26.

SURFACE LAYER

DAY NUMBER: 123

NOTE:
Segment 3 is the upstream boundary and 26 is located at the Vaal Barrage.

KEY:
Inflow: ▲
Withdrawal ▼

Tracer: Conductivity
Units: mS/m

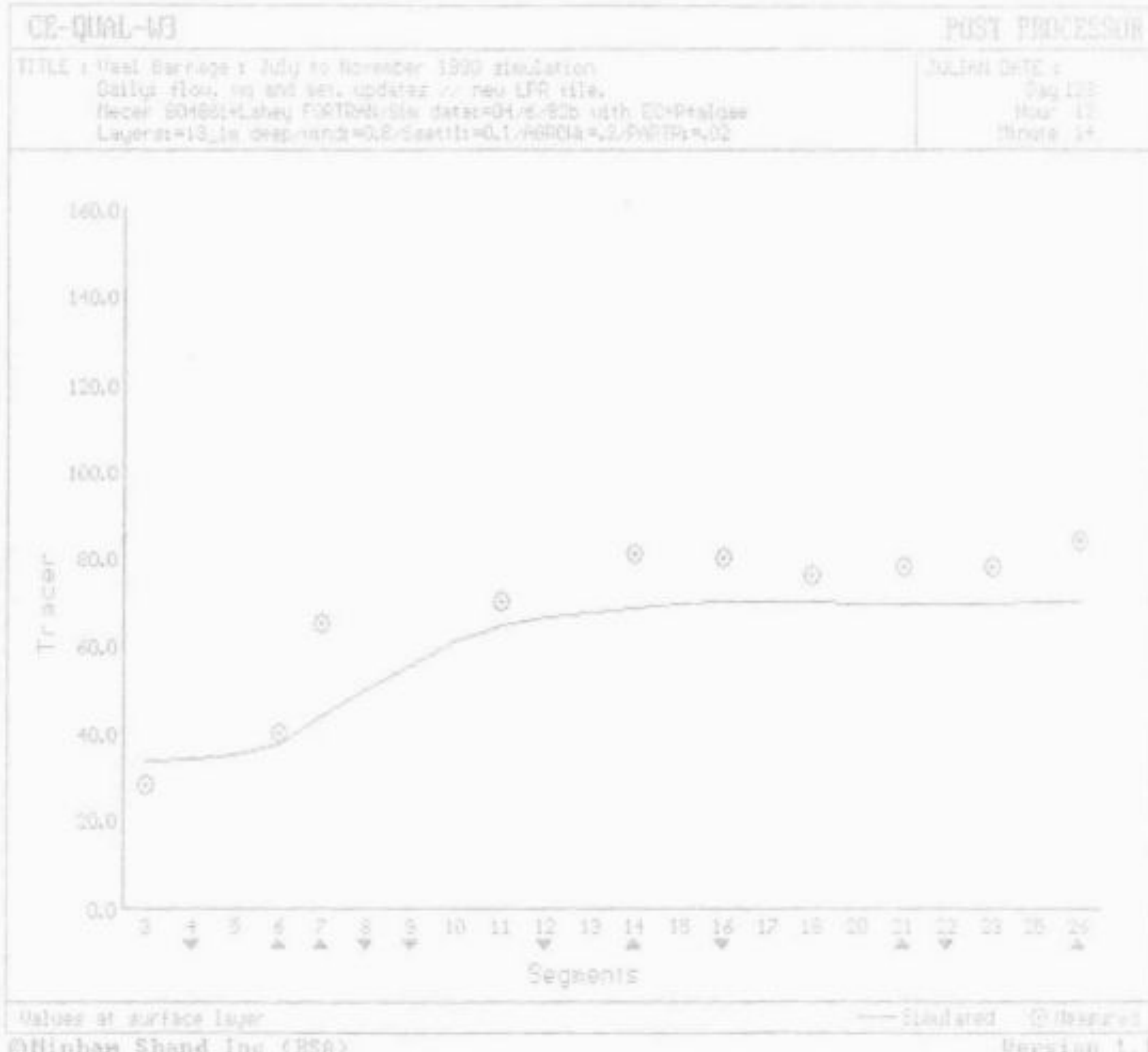

Figure A4.6.53

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 11

Units: mg/l
Variable: TDS

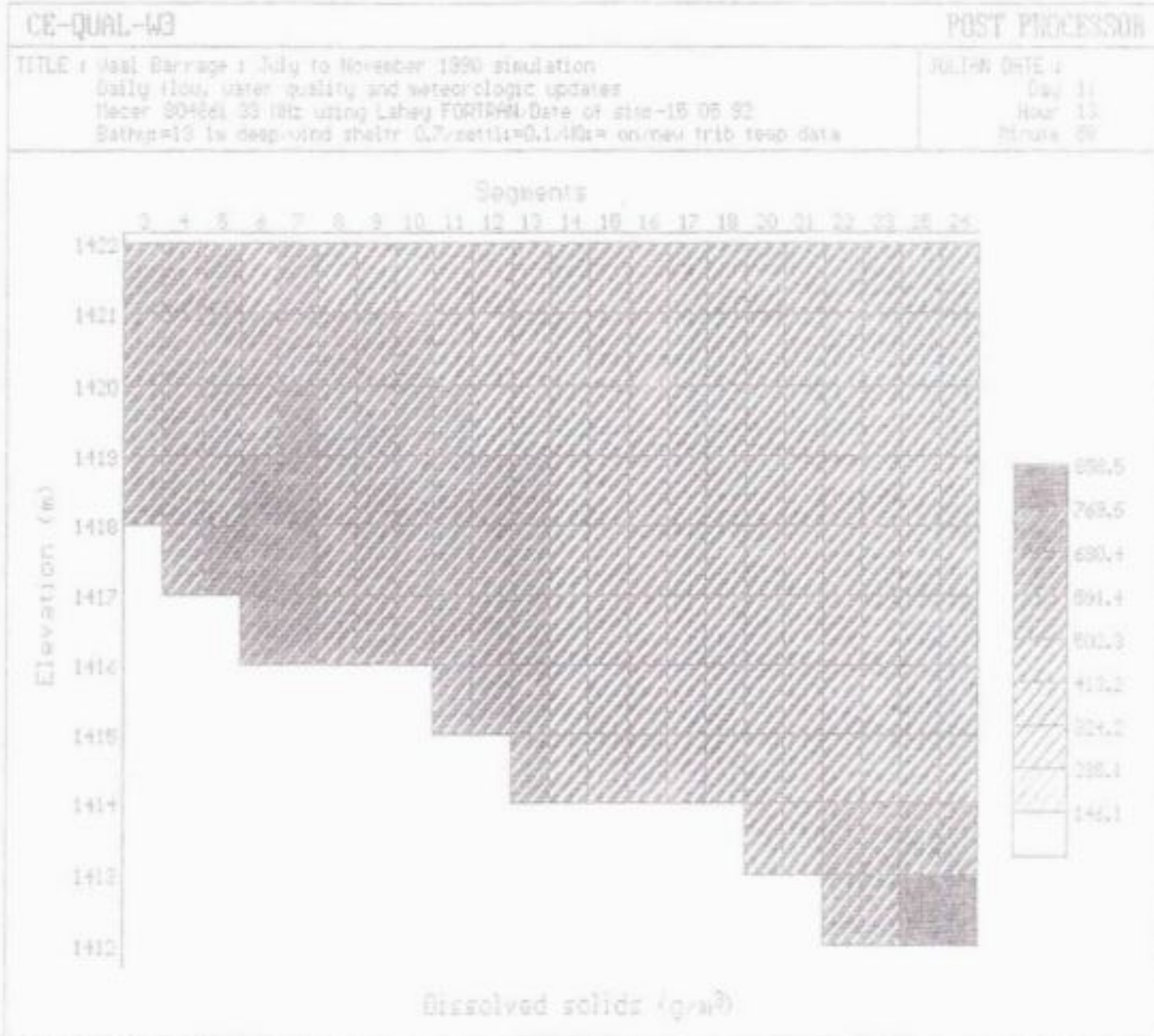

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Figure A4.6.54

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 23

Units: mg/l
Variable: TDS

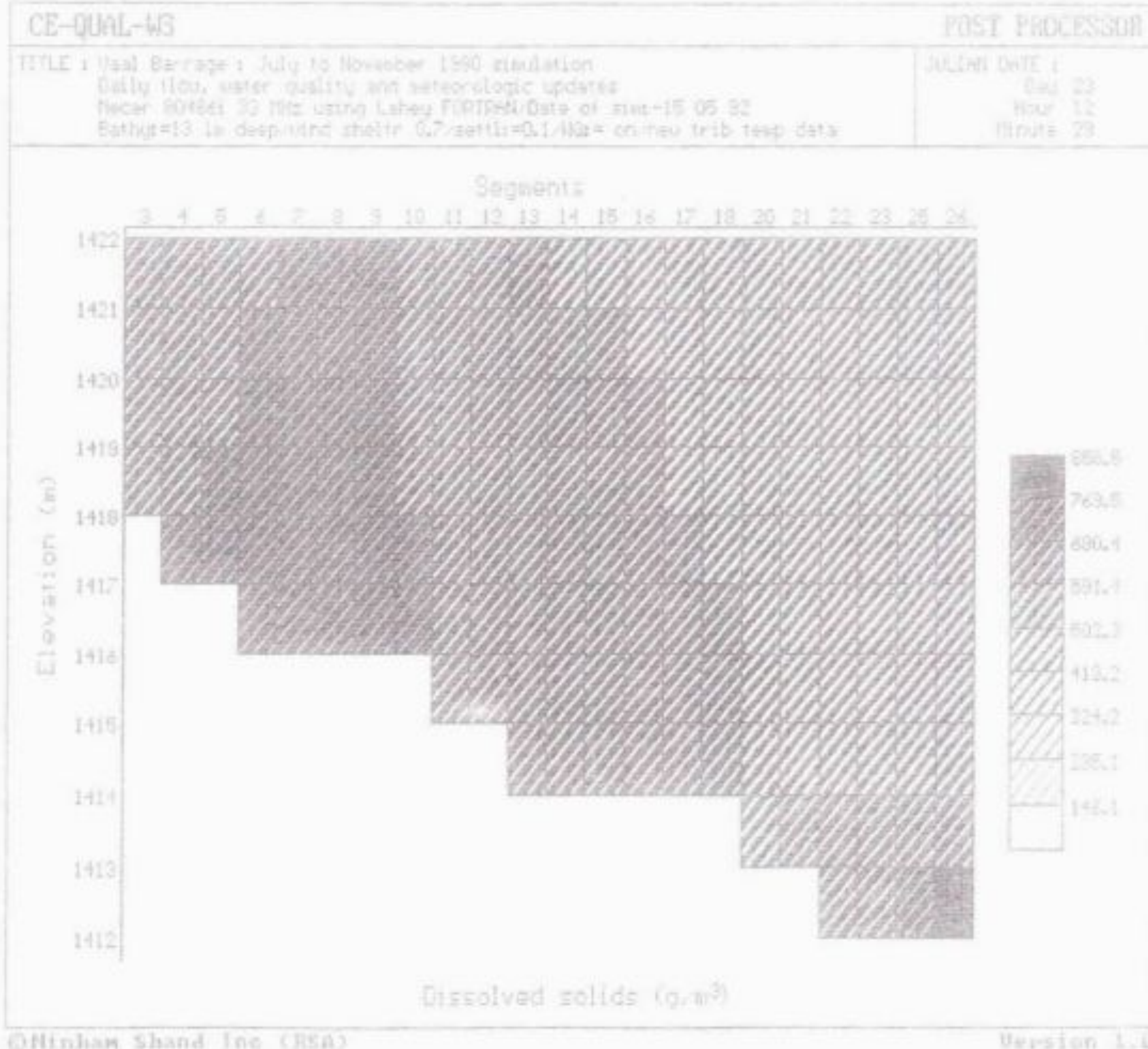

Figure A4.6.55

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 29

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: TDS

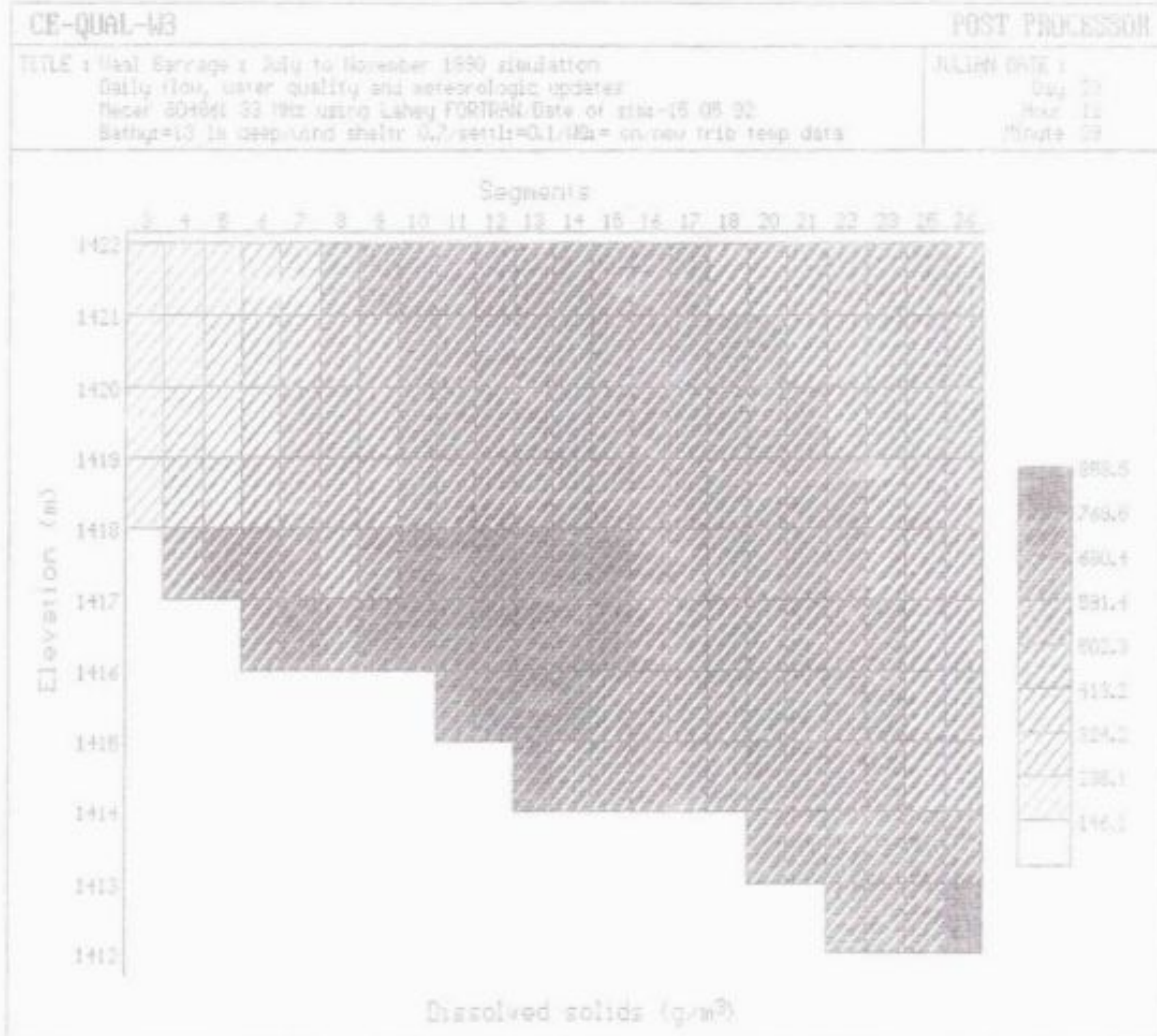

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Figure A4.6.56

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 34

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: TDS

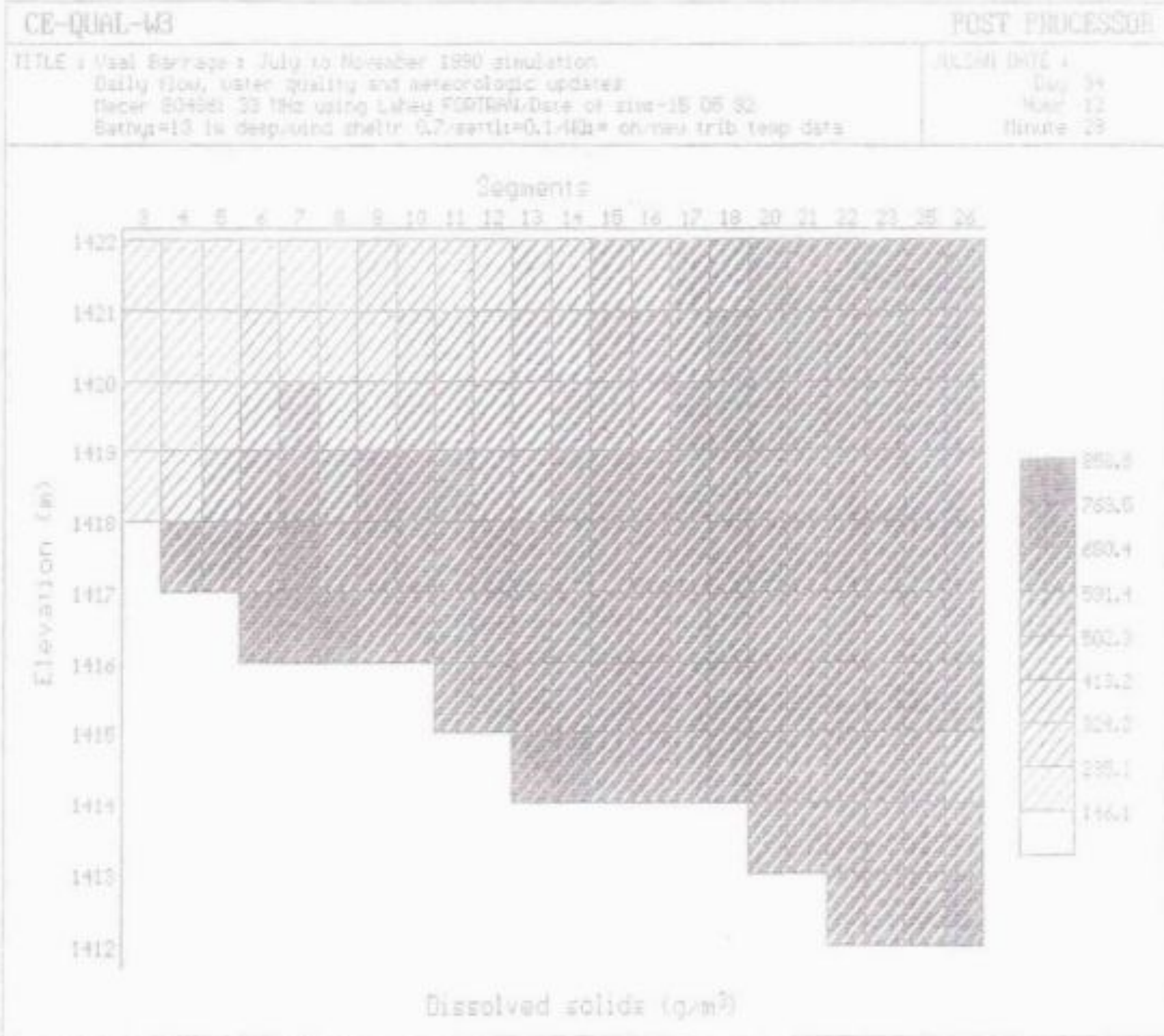

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Figure A4.6.57

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 38

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: TDS

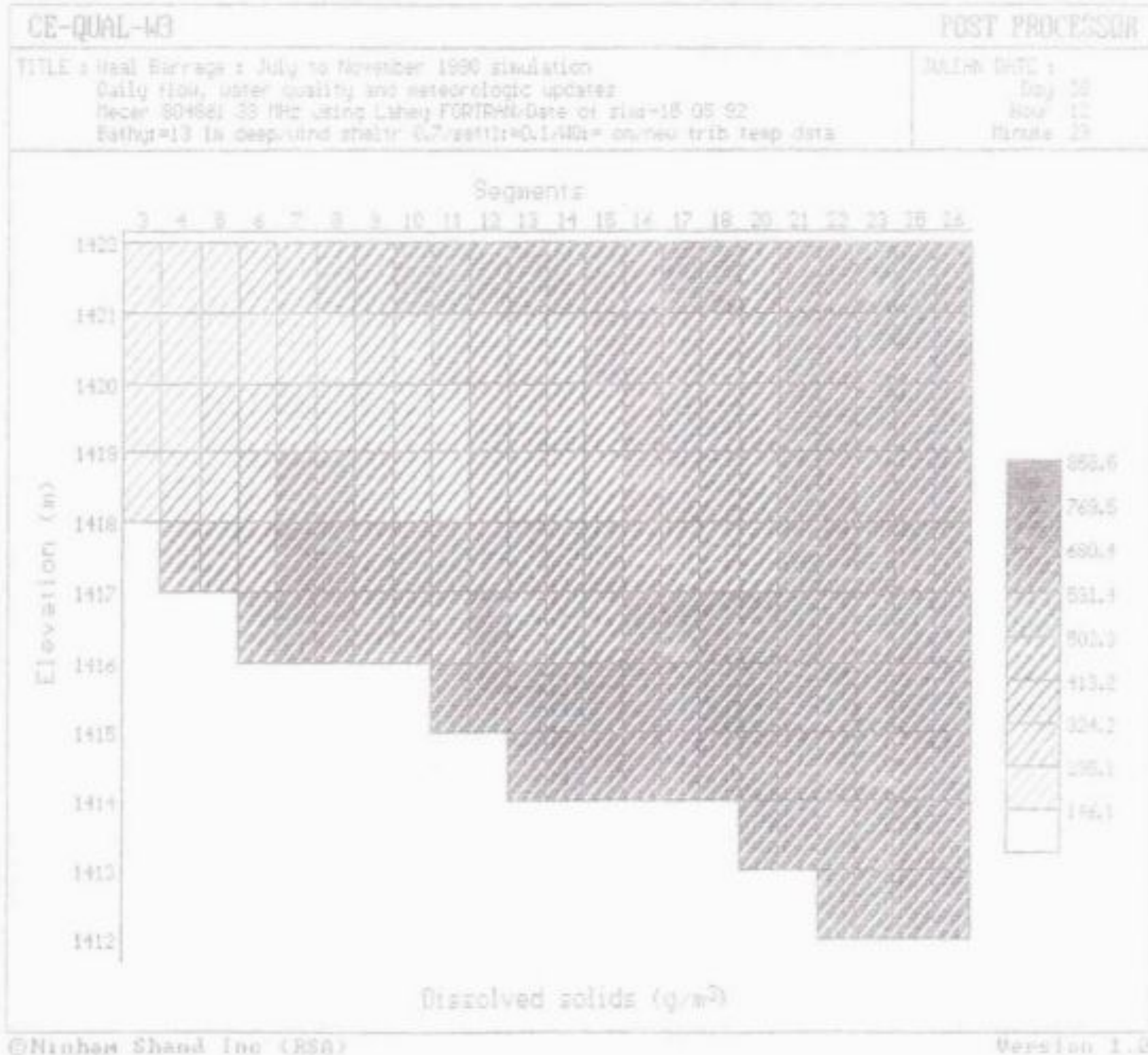

Figure A4.6.58

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 52

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: TDS

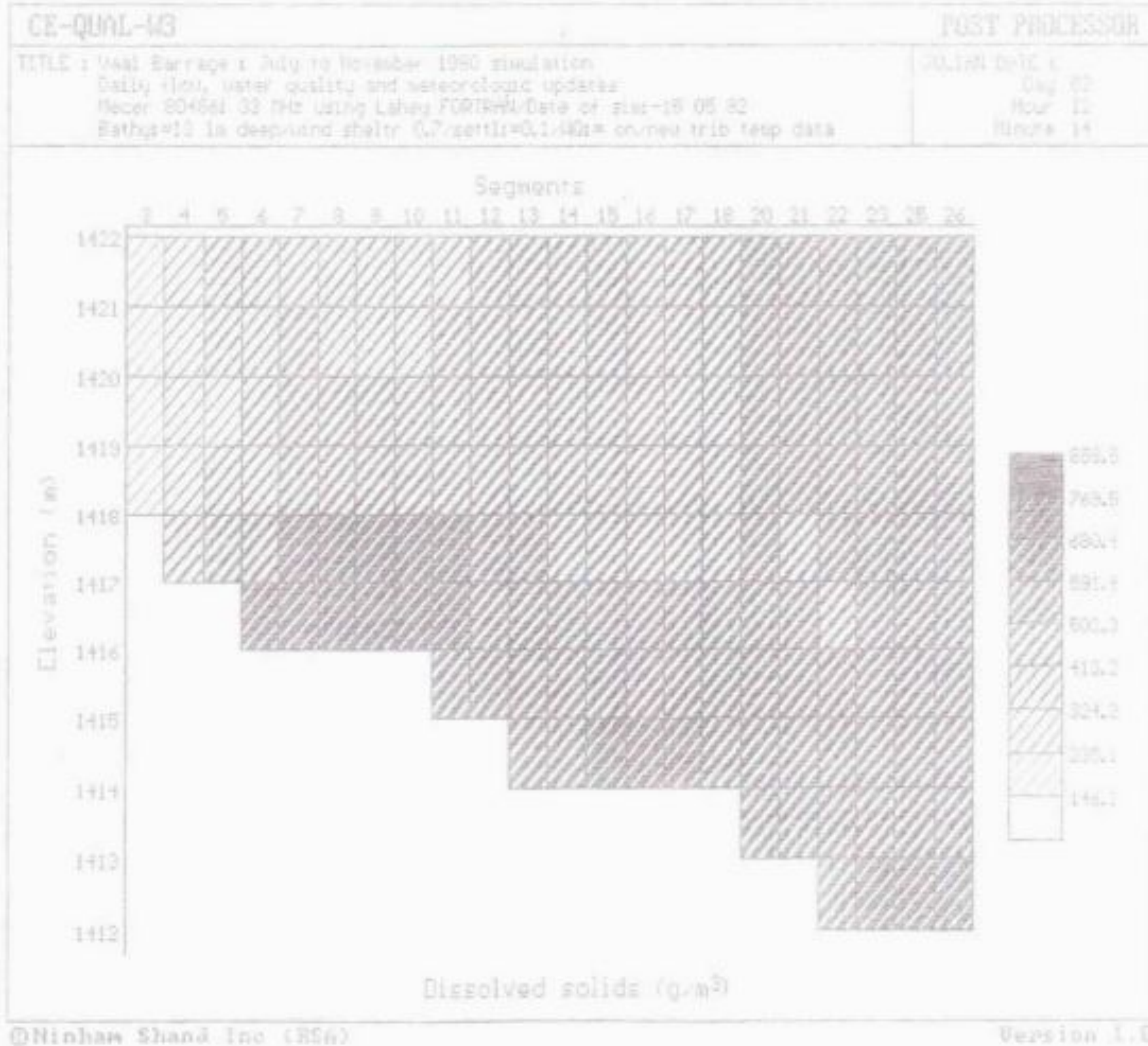

Figure A4.6.59

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 59

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: TDS

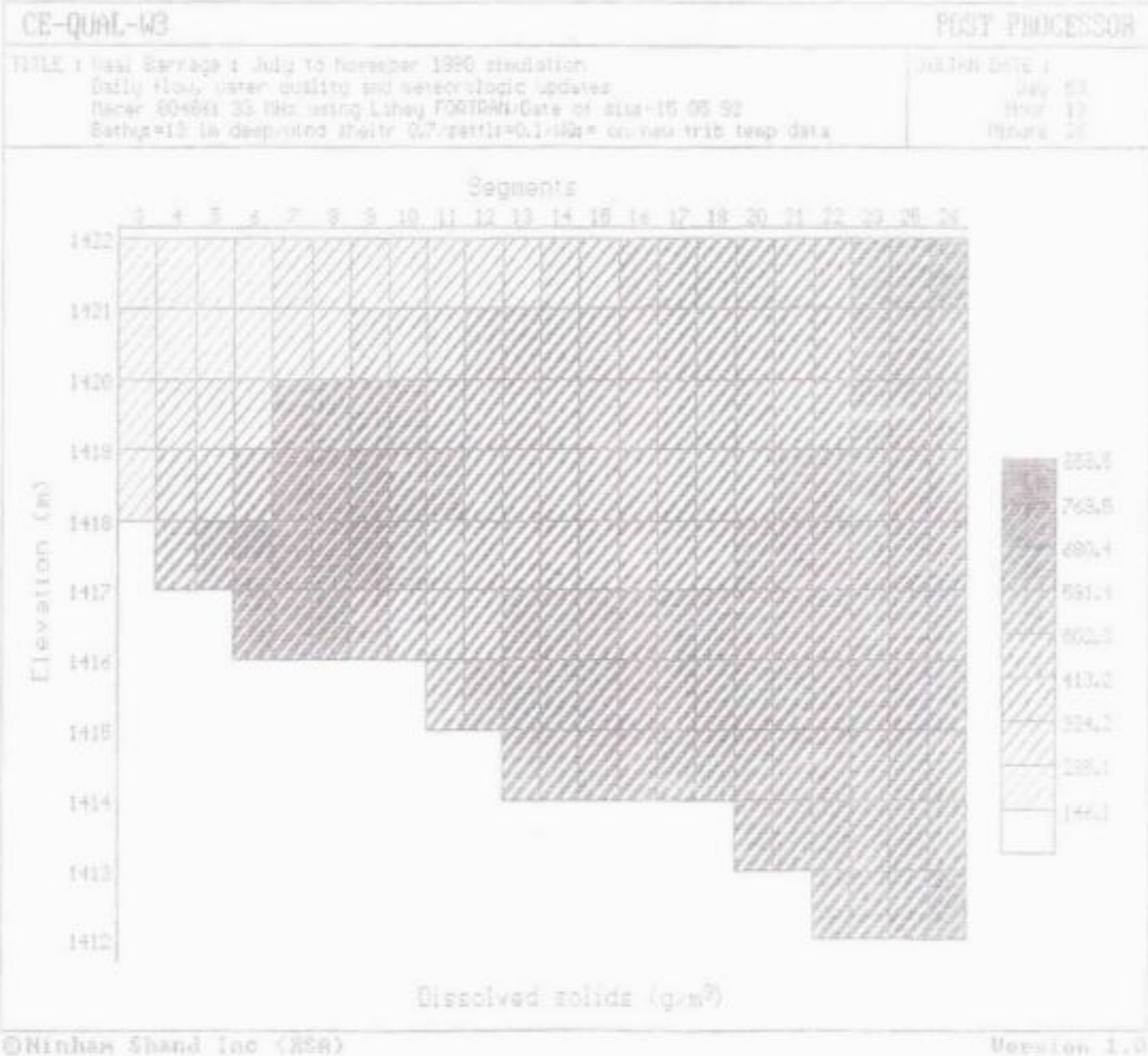

Figure A4.6.60

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 81

Beginning of release from Vaal Dam:
Day 21

Units: mg/l
Variable: TDS

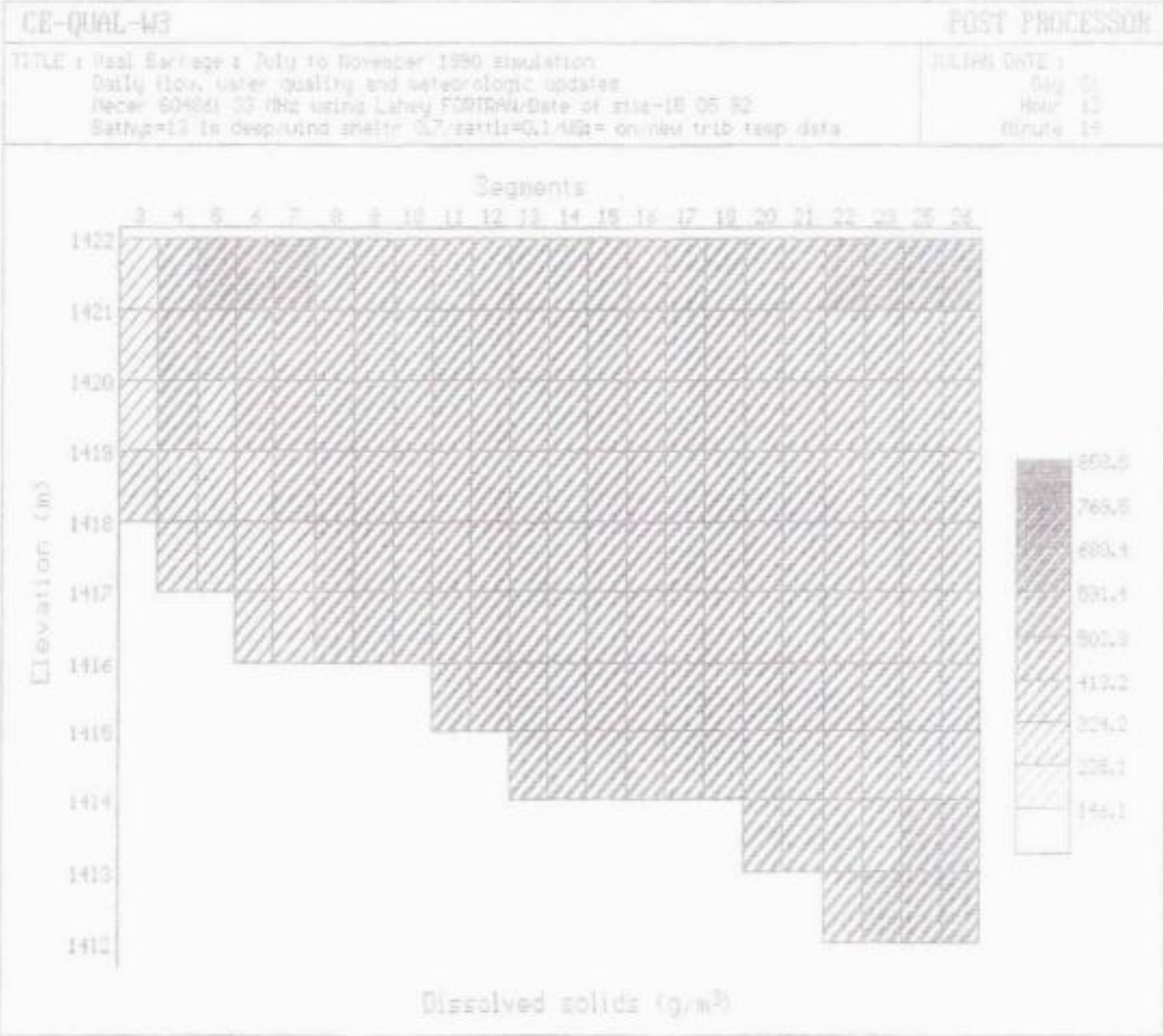

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Figure A4.6.61

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 109

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: TDS

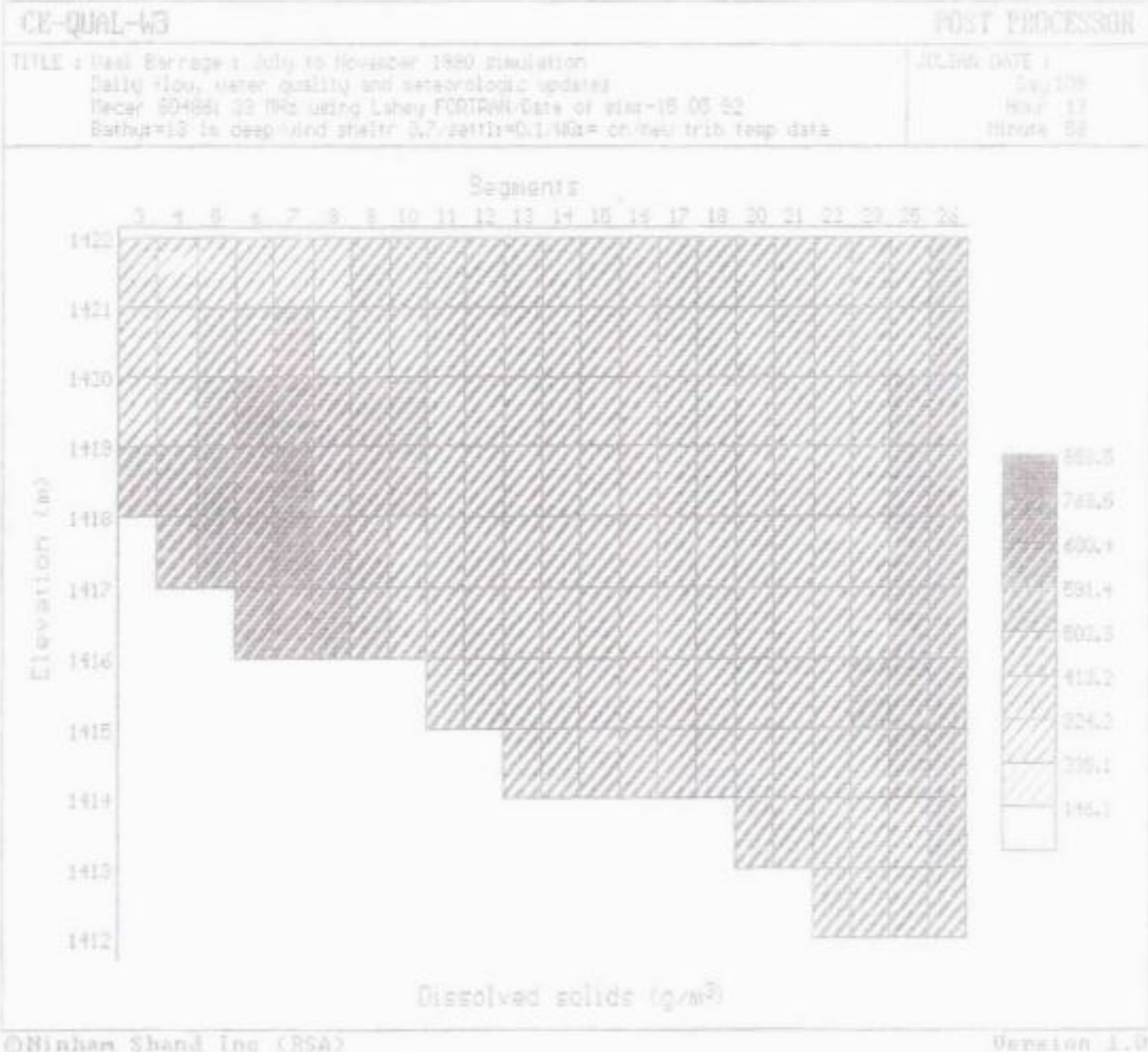

Figure A4.6.62

Two-dimensional plot showing the simulated TDS in Segments 3 through to 26 in the Vaal Barrage.

Day number: 123

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: TDS

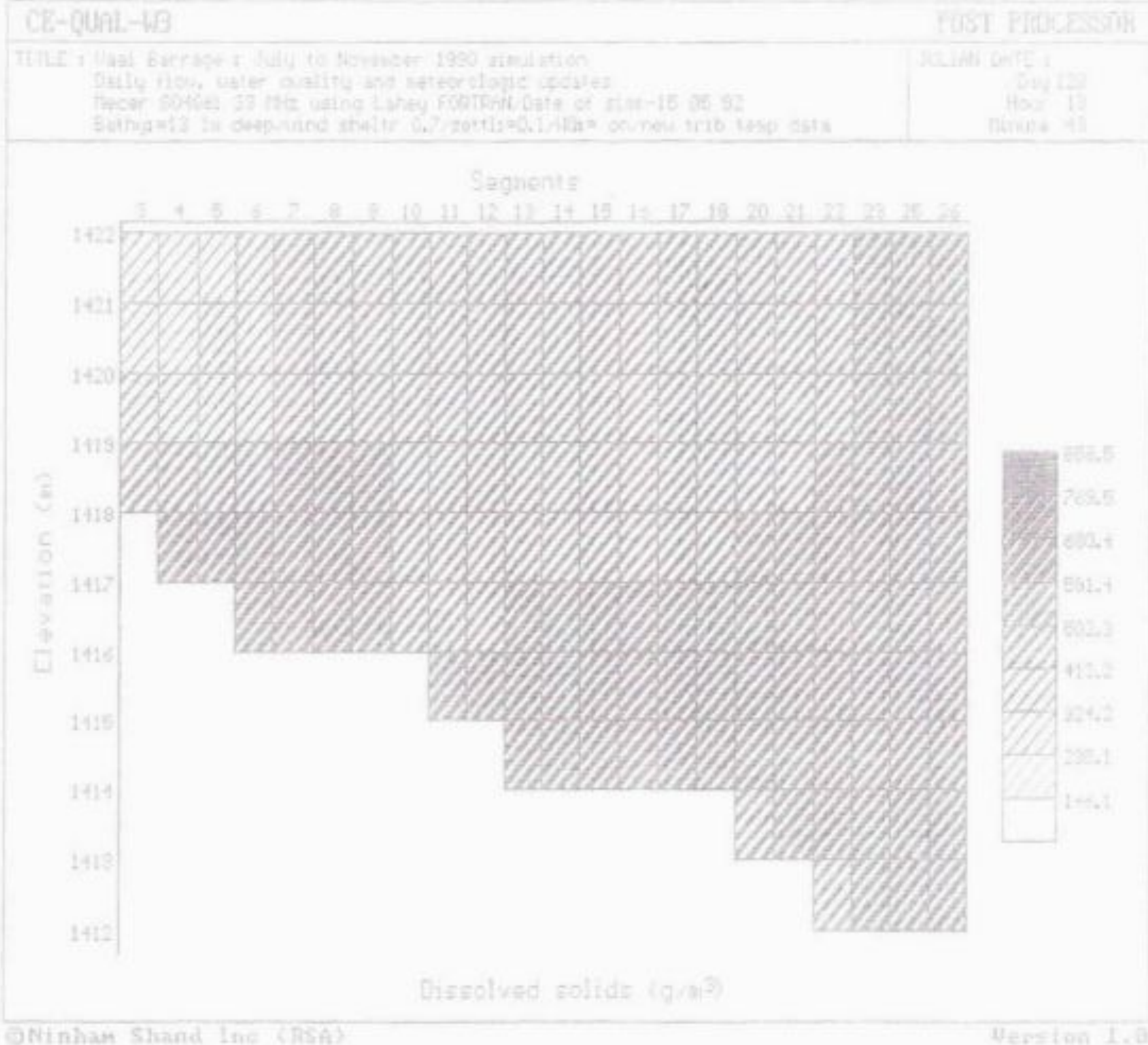

Figure A4.6.63

Two-dimensional plot showing the simulated suspended solids concentration in Segments 3 through to 26 in the Vaal Barrage.

Day number: 23

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: Suspended solids

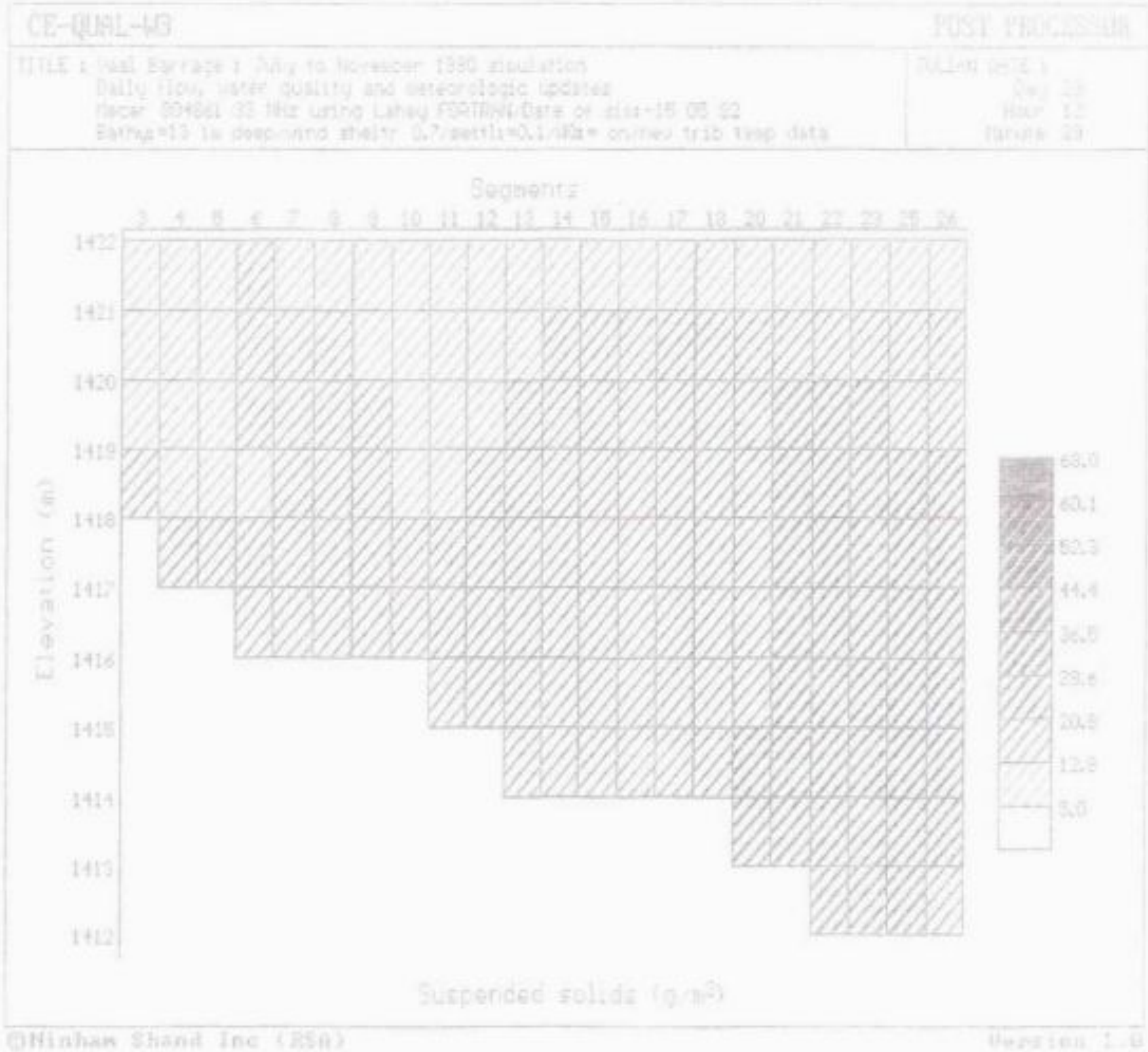

Figure A4.6.64

Two-dimensional plot showing the simulated suspended solids concentration in Segments 3 through to 26 in the Vaal Barrage.

Day number: 29

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: Suspended solids

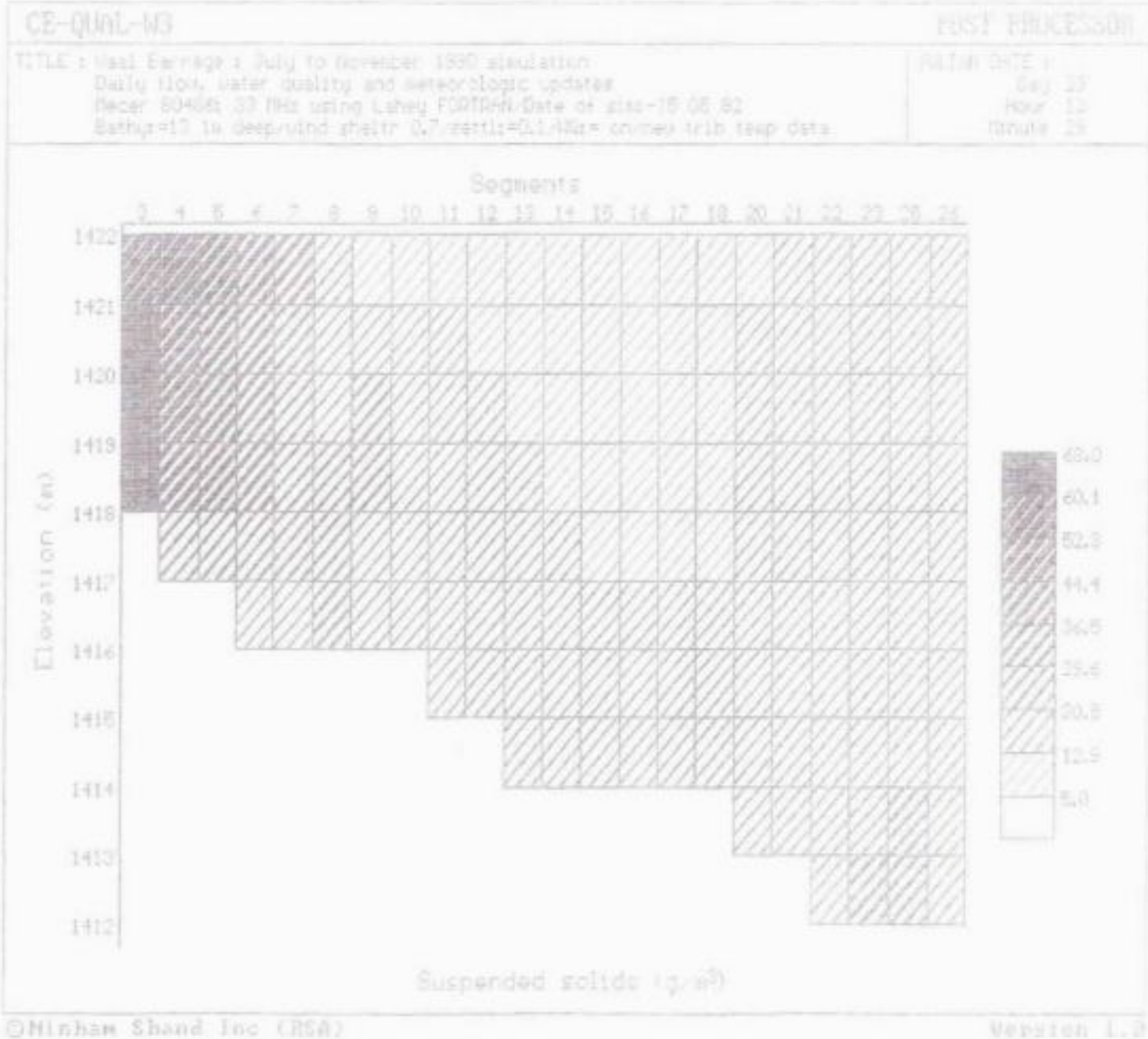

Figure A4.6.65

Two-dimensional plot showing the simulated suspended solids concentration in Segments 3 through to 26 in the Vaal Barrage.

Day number: 34

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: Suspended solids

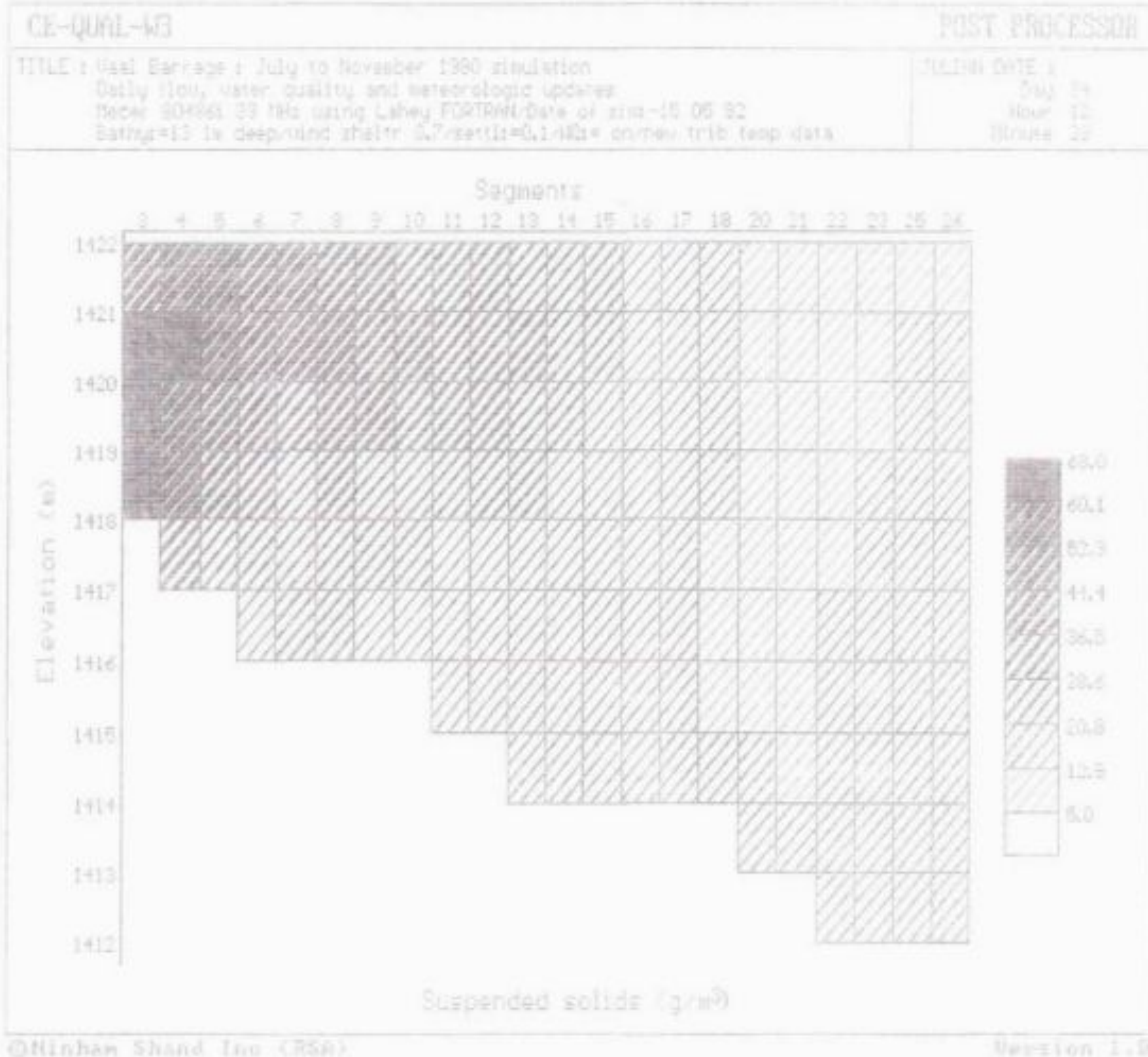

Figure A4.6.66

Two-dimensional plot showing the simulated suspended solids concentration in Segments 3 through to 26 in the Vaal Barrage.

Day number: 45

Beginning of release from Vaal Dam: Day 21

Units: mg/l
Variable: Suspended solids

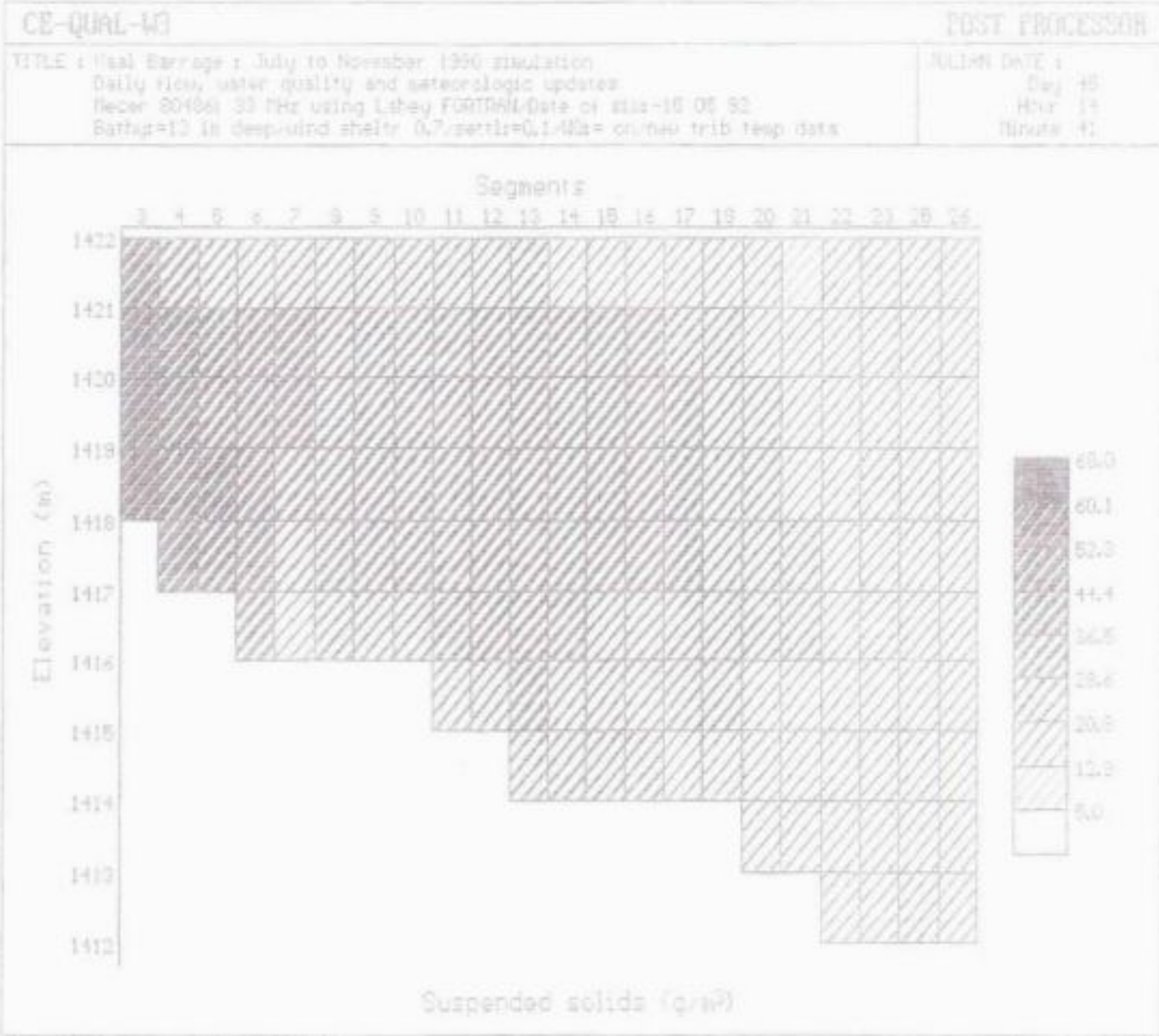

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Figure A4.6.67

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 18

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▼
Withdrawal: ▲

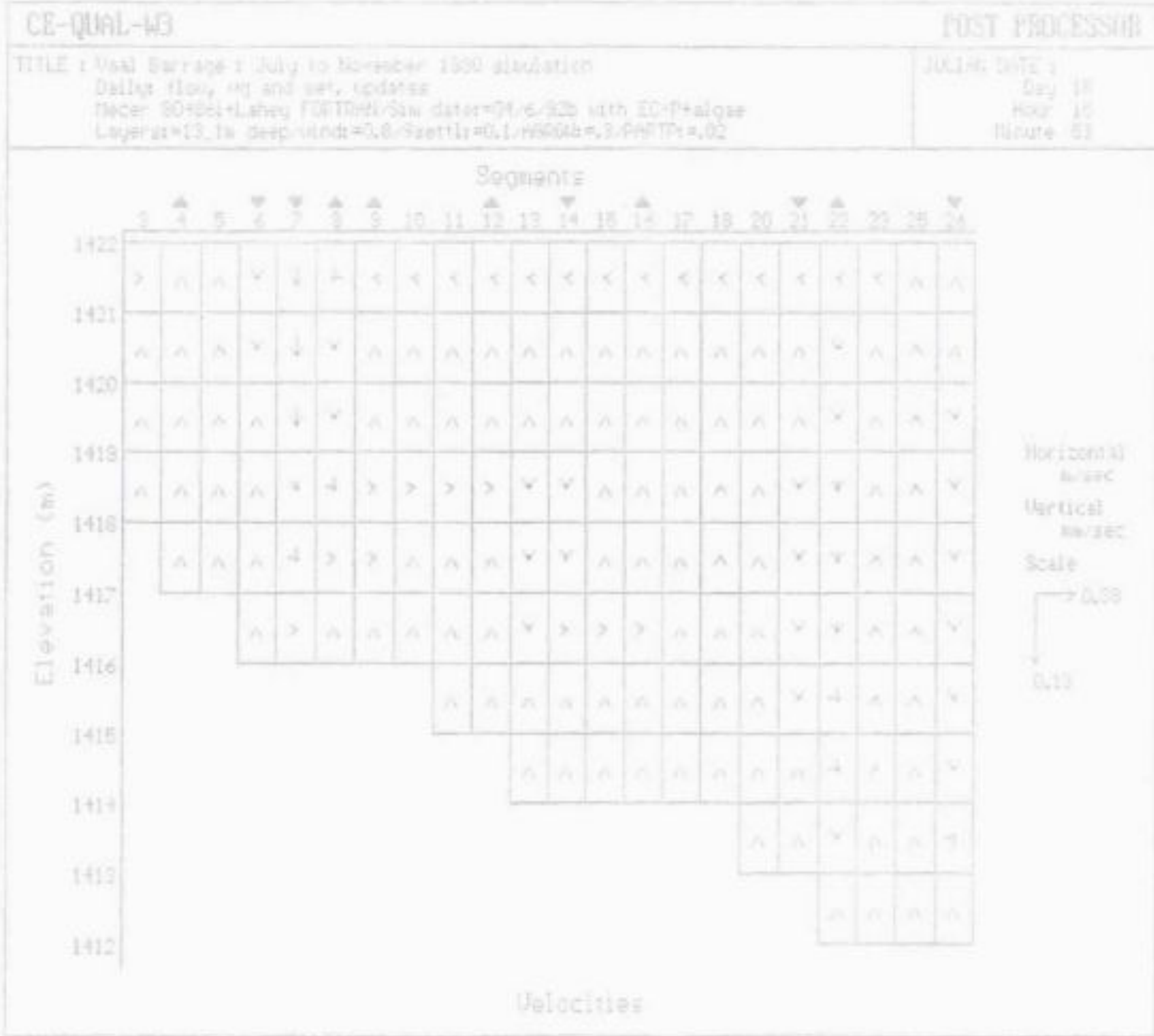

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Figure A4.6.68

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 29

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

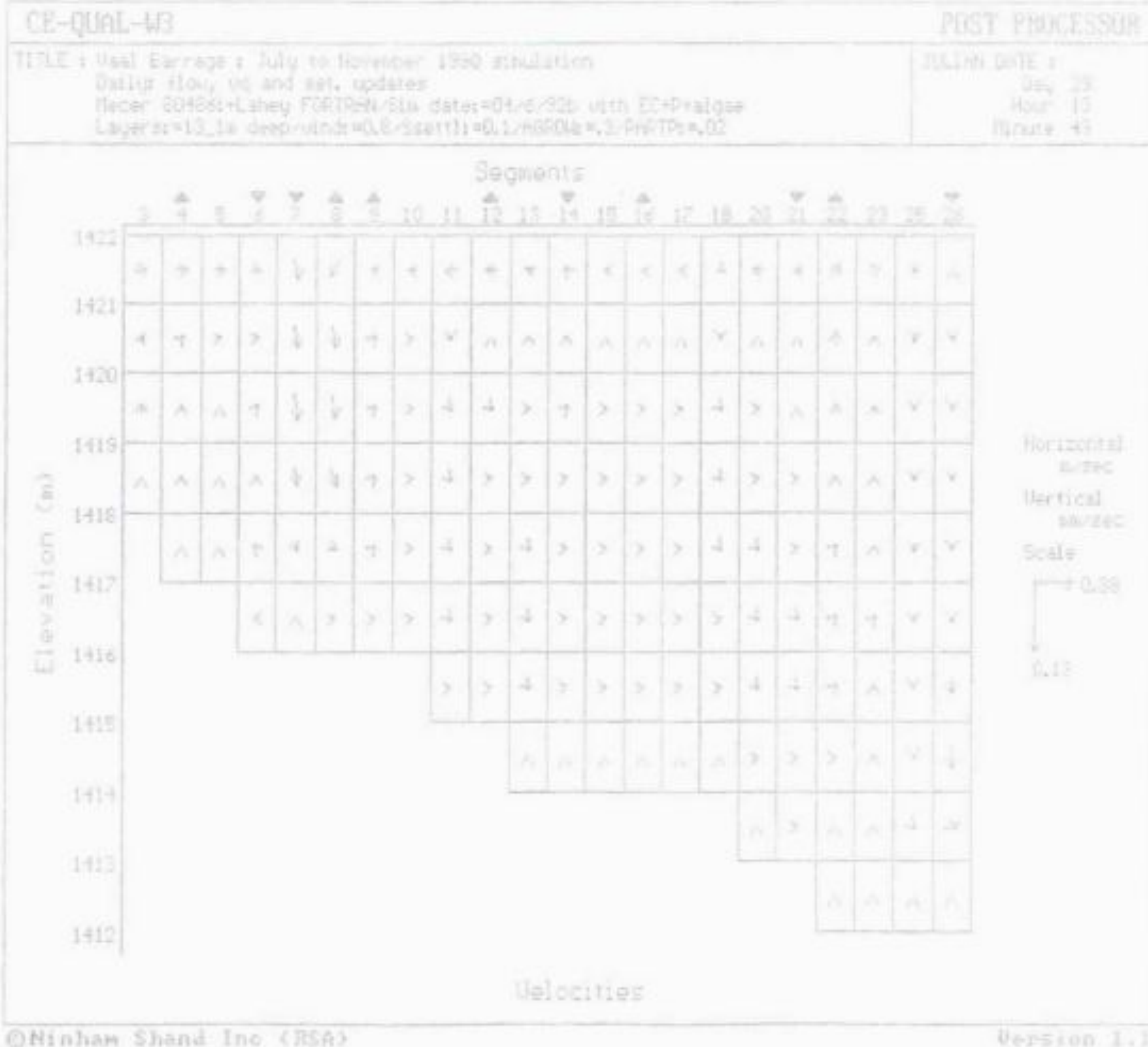

Figure A4.6.69

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 34

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

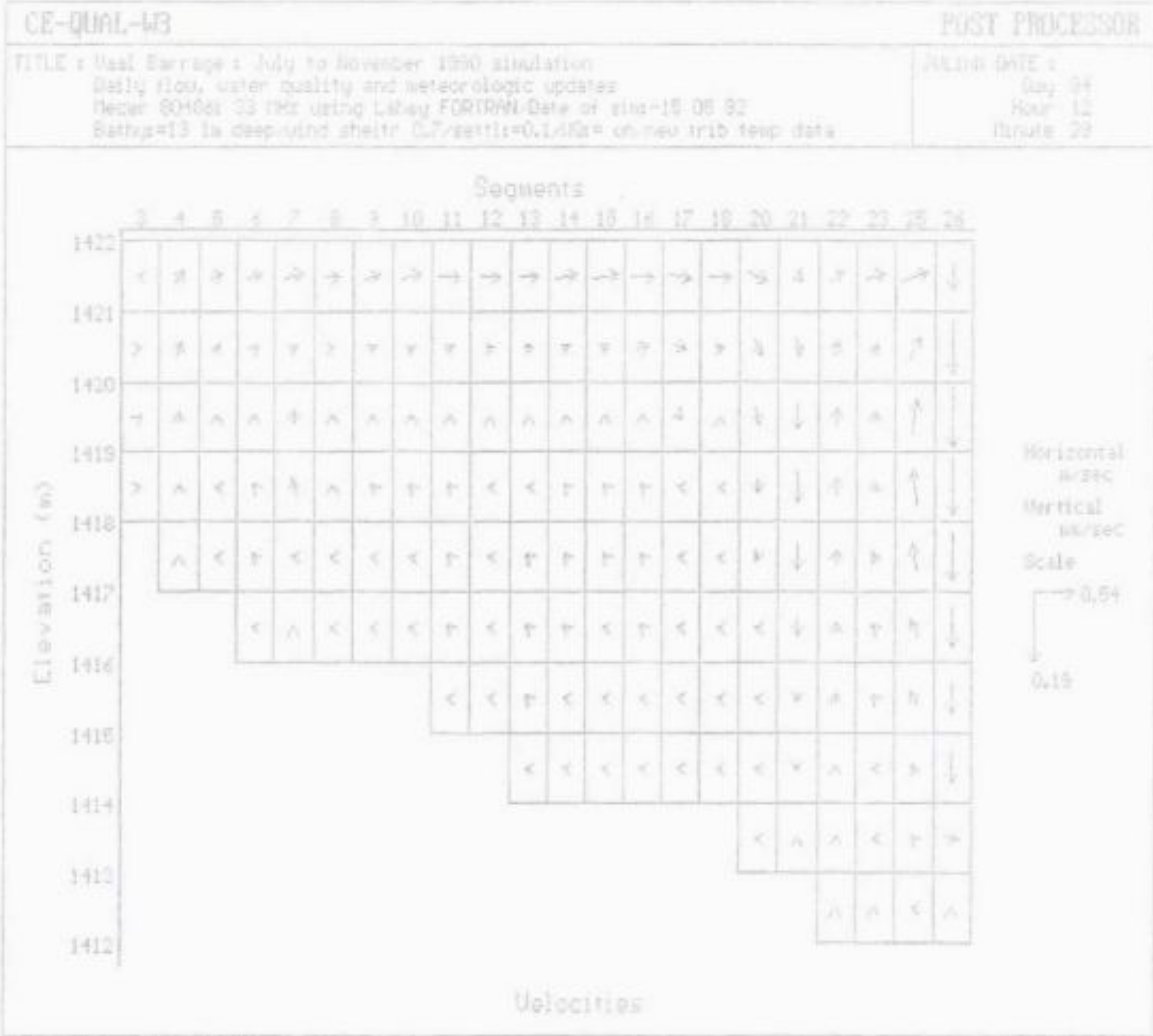

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Figure A4.6.70

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 38

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

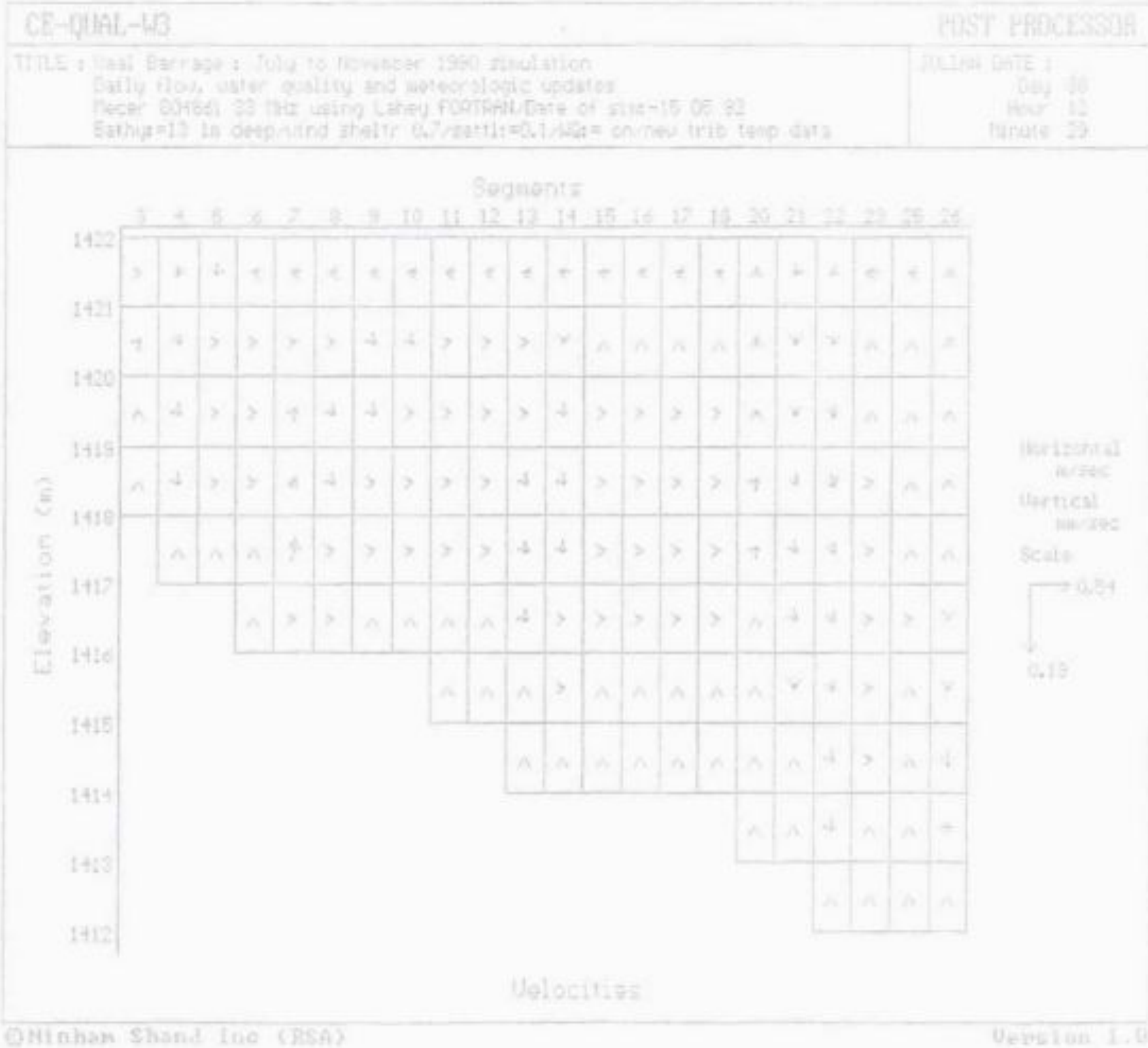


Figure A4.6.71

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 52

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

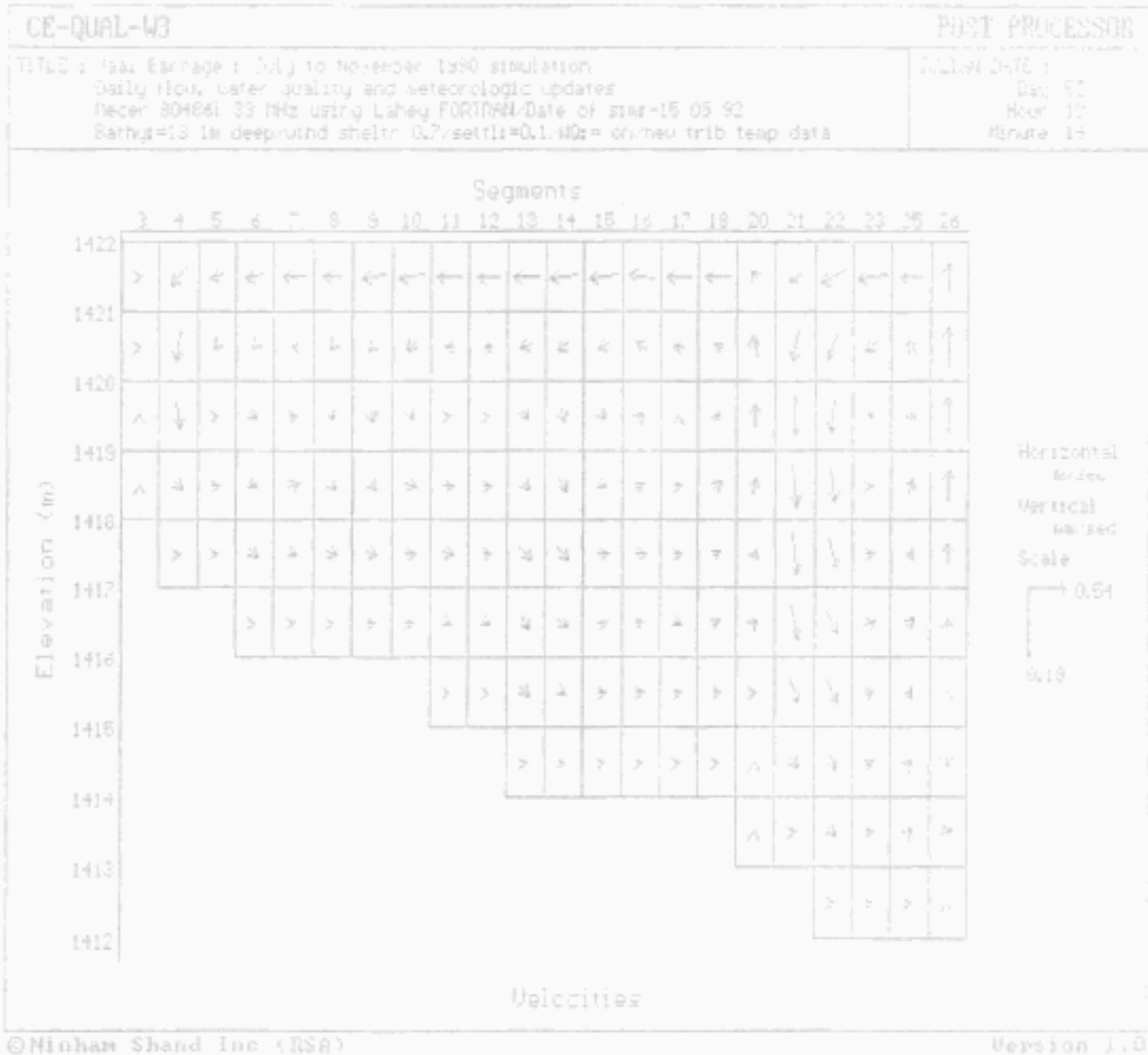


Figure A4.6.72

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 59

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

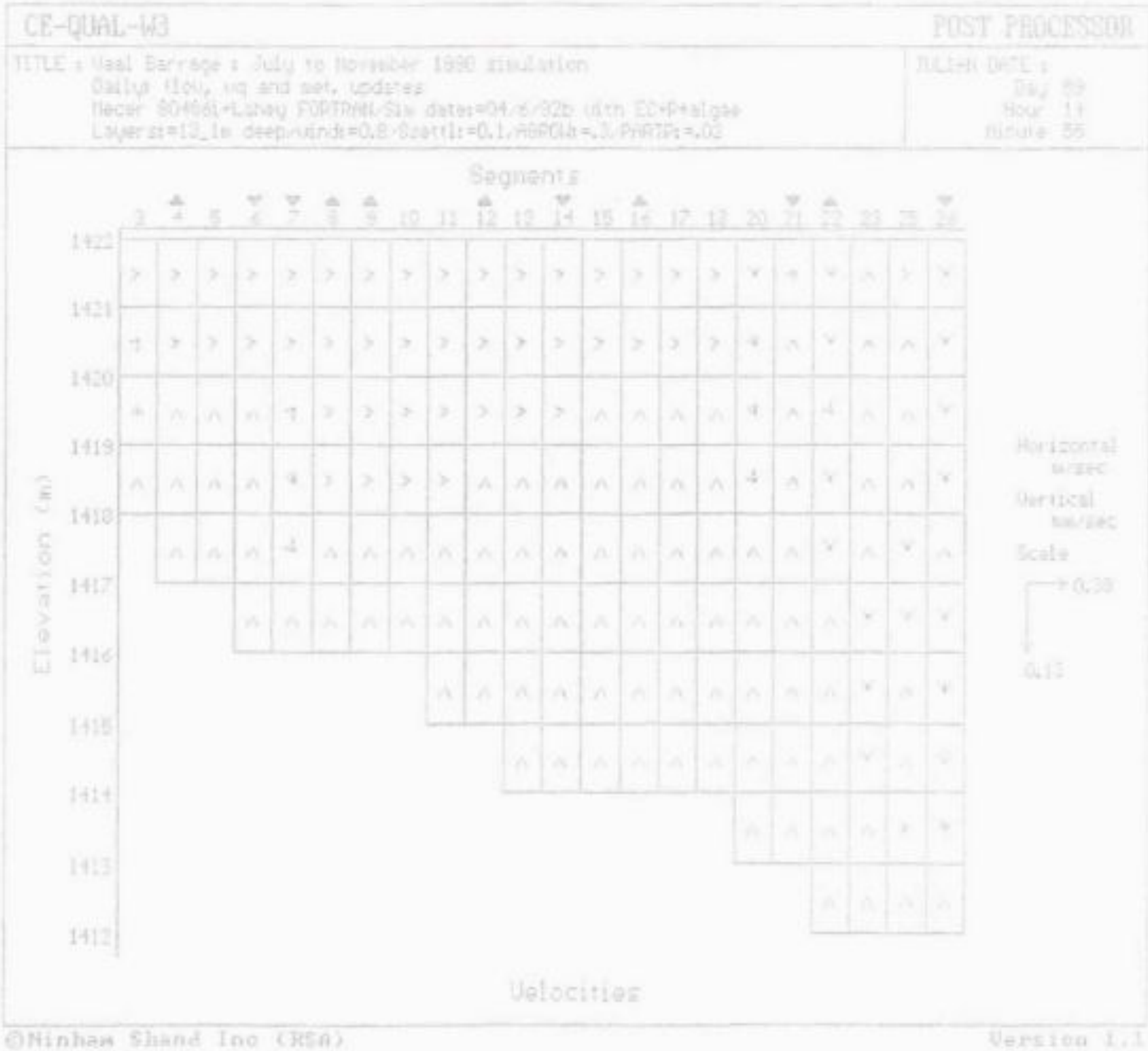


Figure A4.6.73

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 67

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

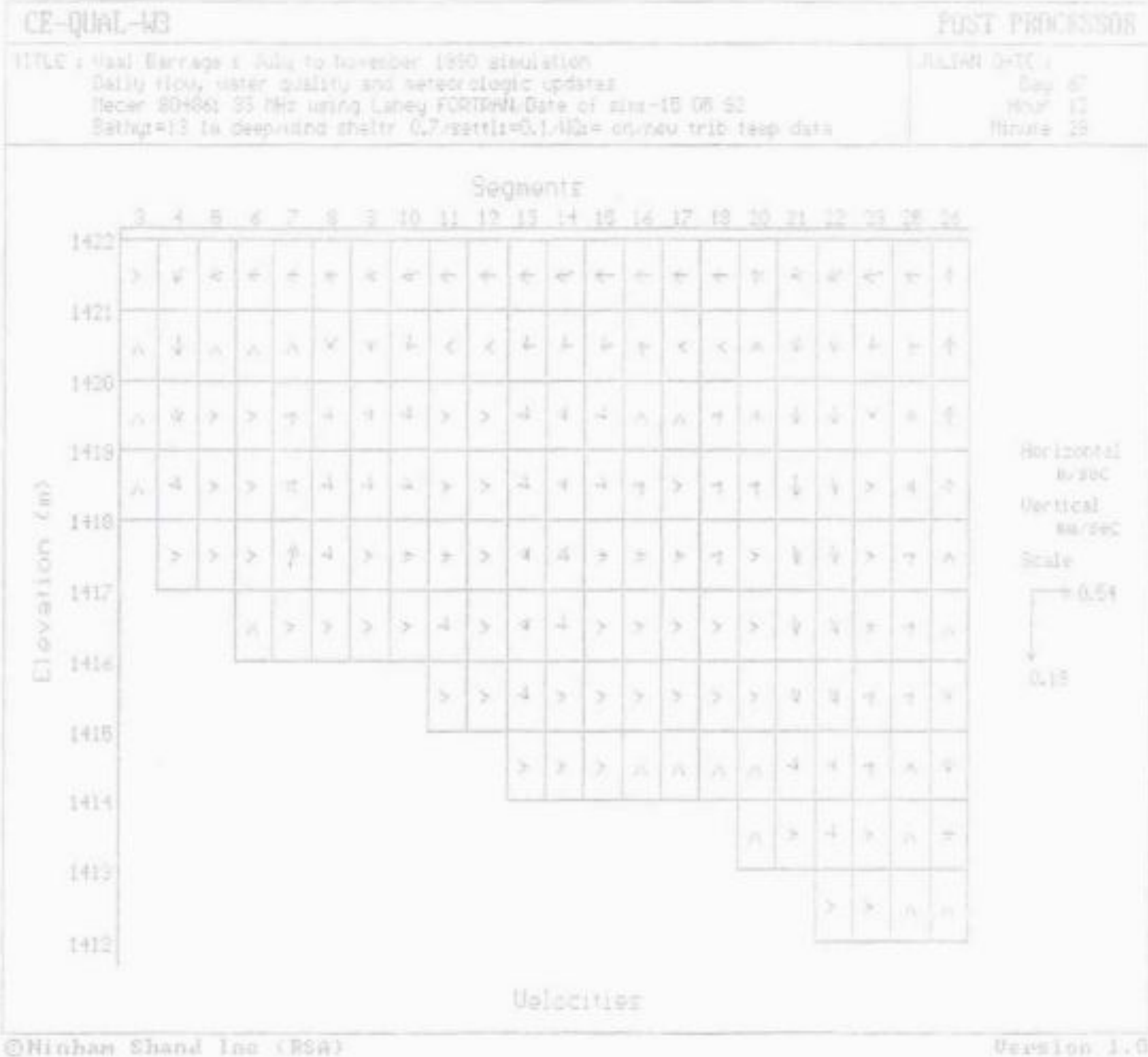


Figure A4.6.74

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 81

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

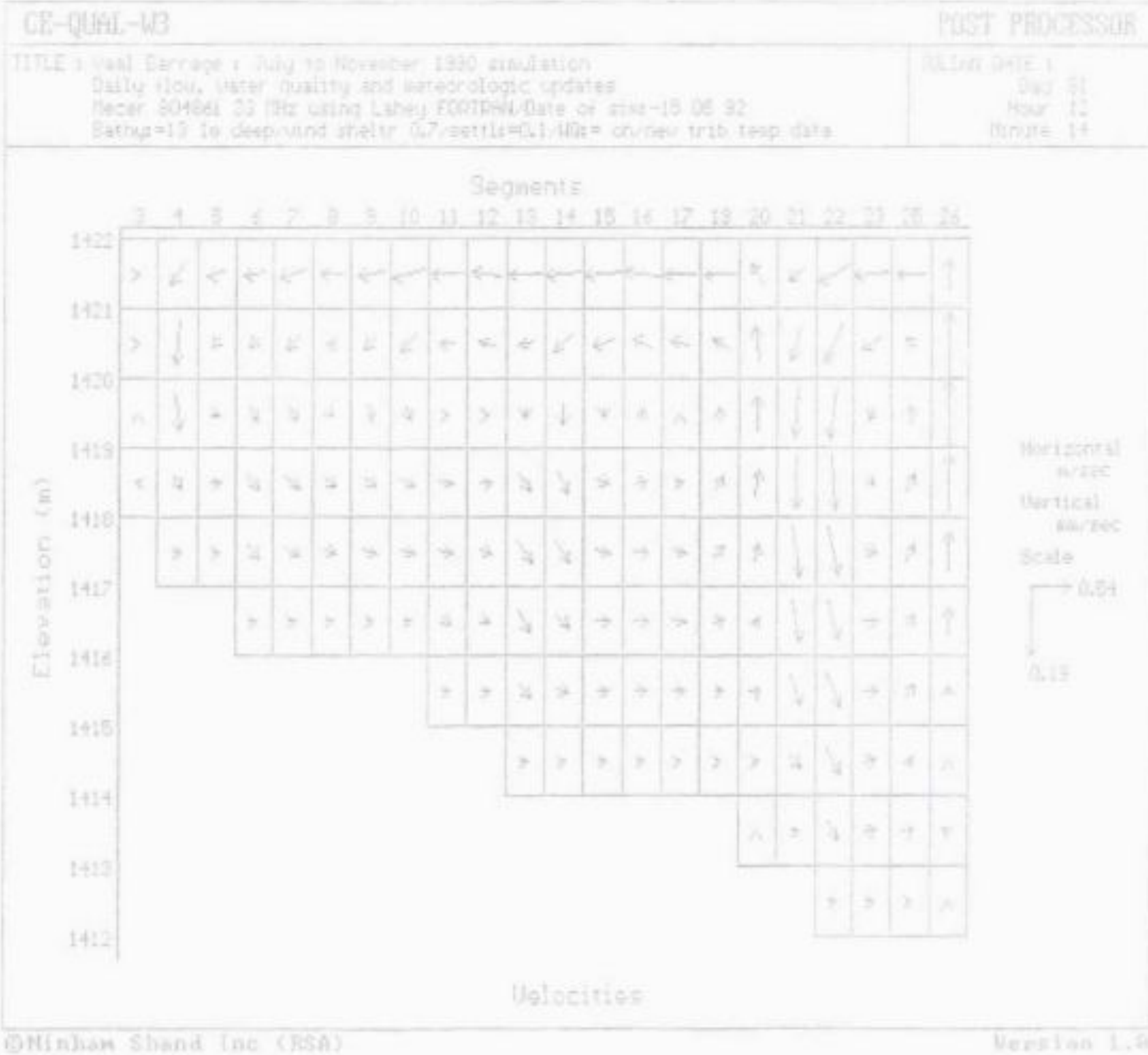


Figure A4.6.75

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 92

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

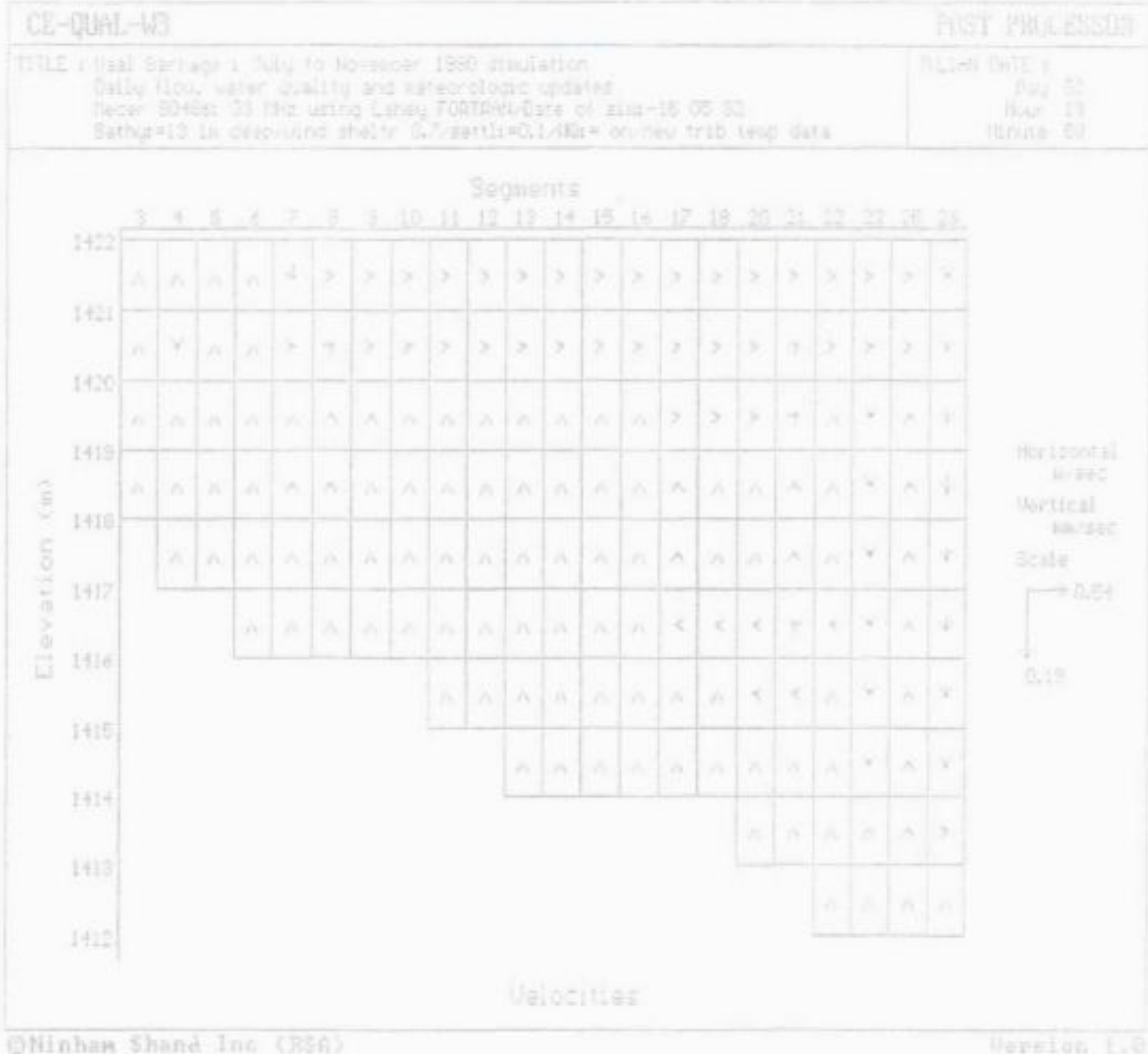


Figure A4.6.76

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 101

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

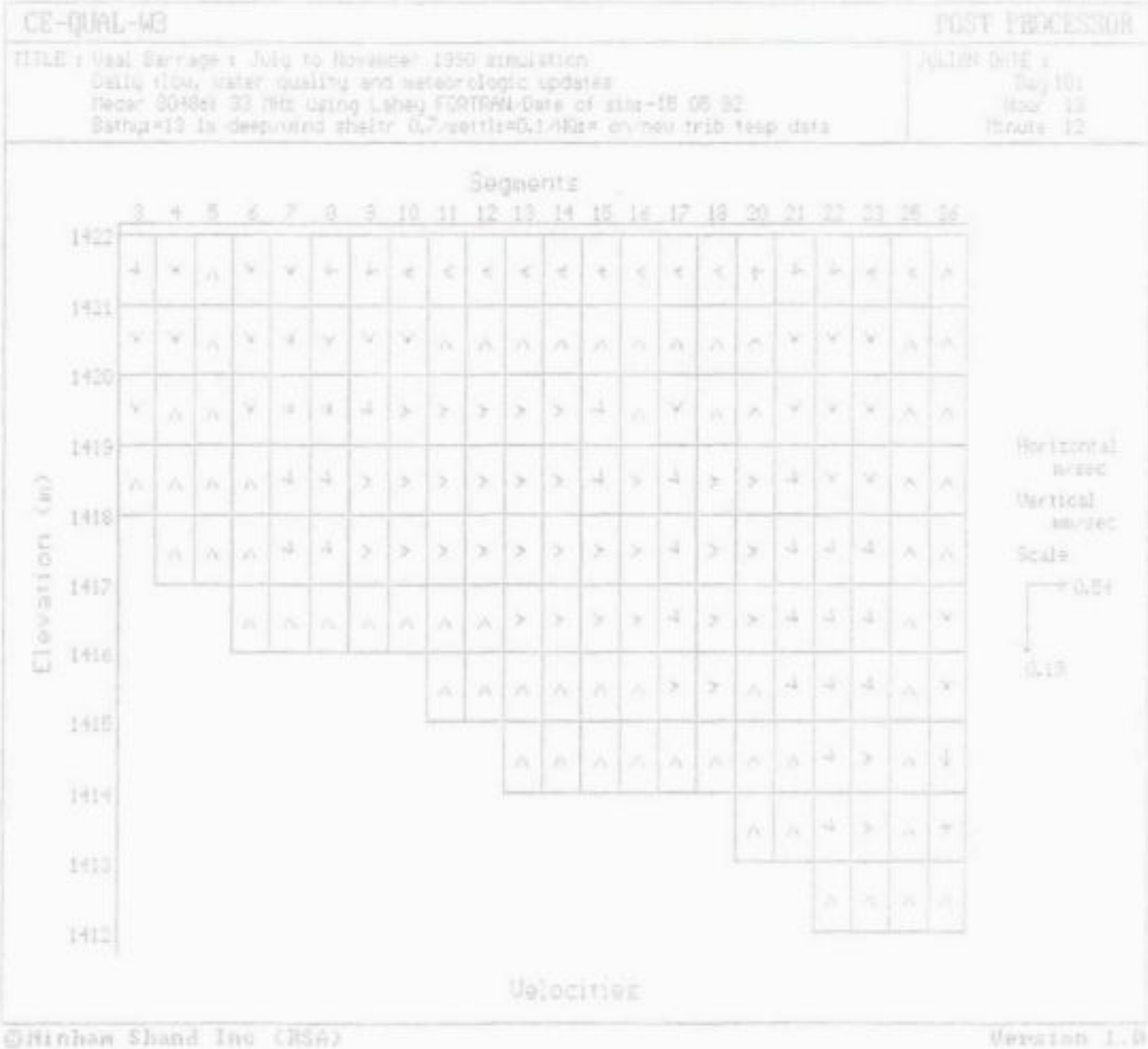


Figure A4.6.77

Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 109

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴

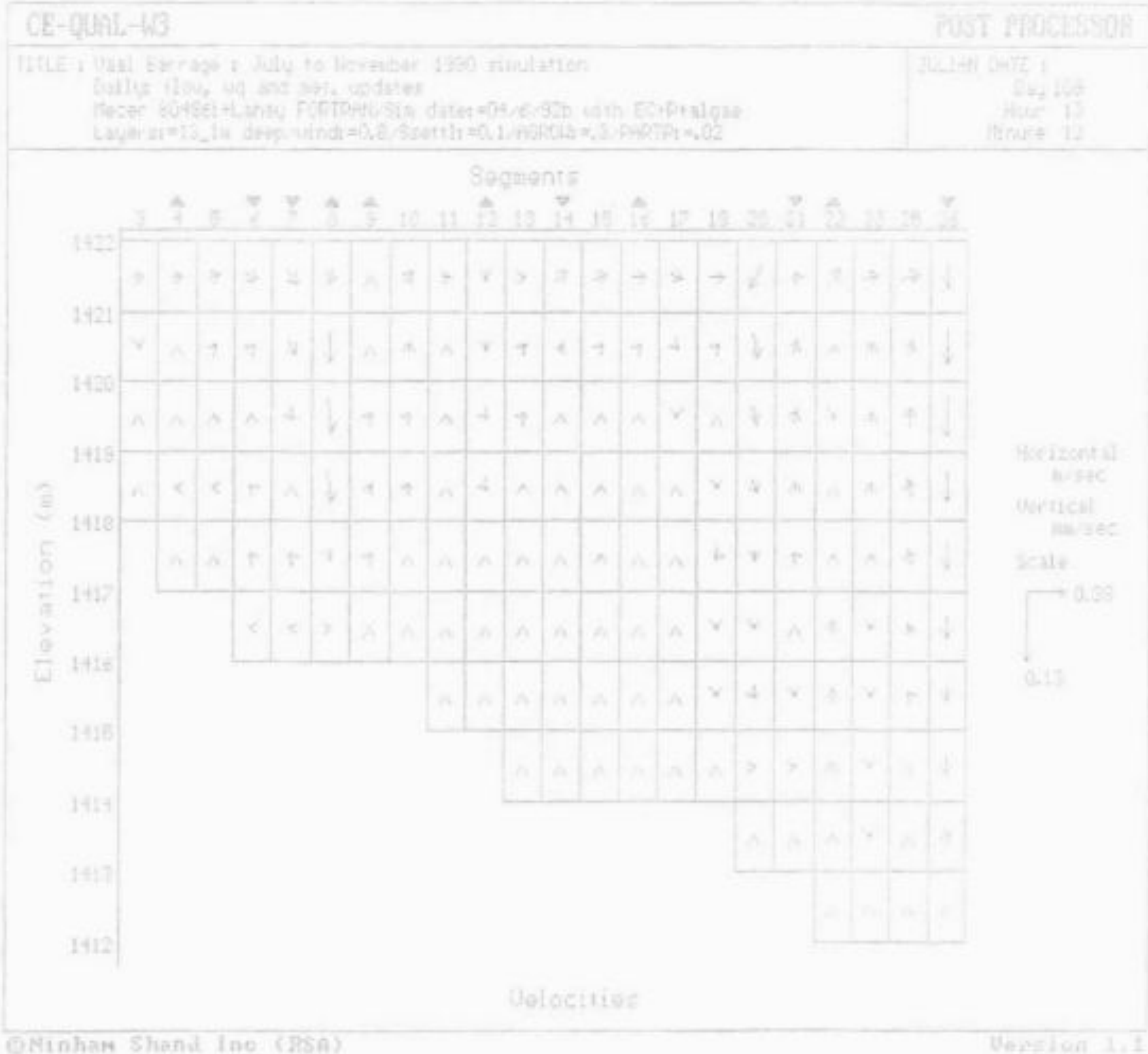


Figure A4.6.78

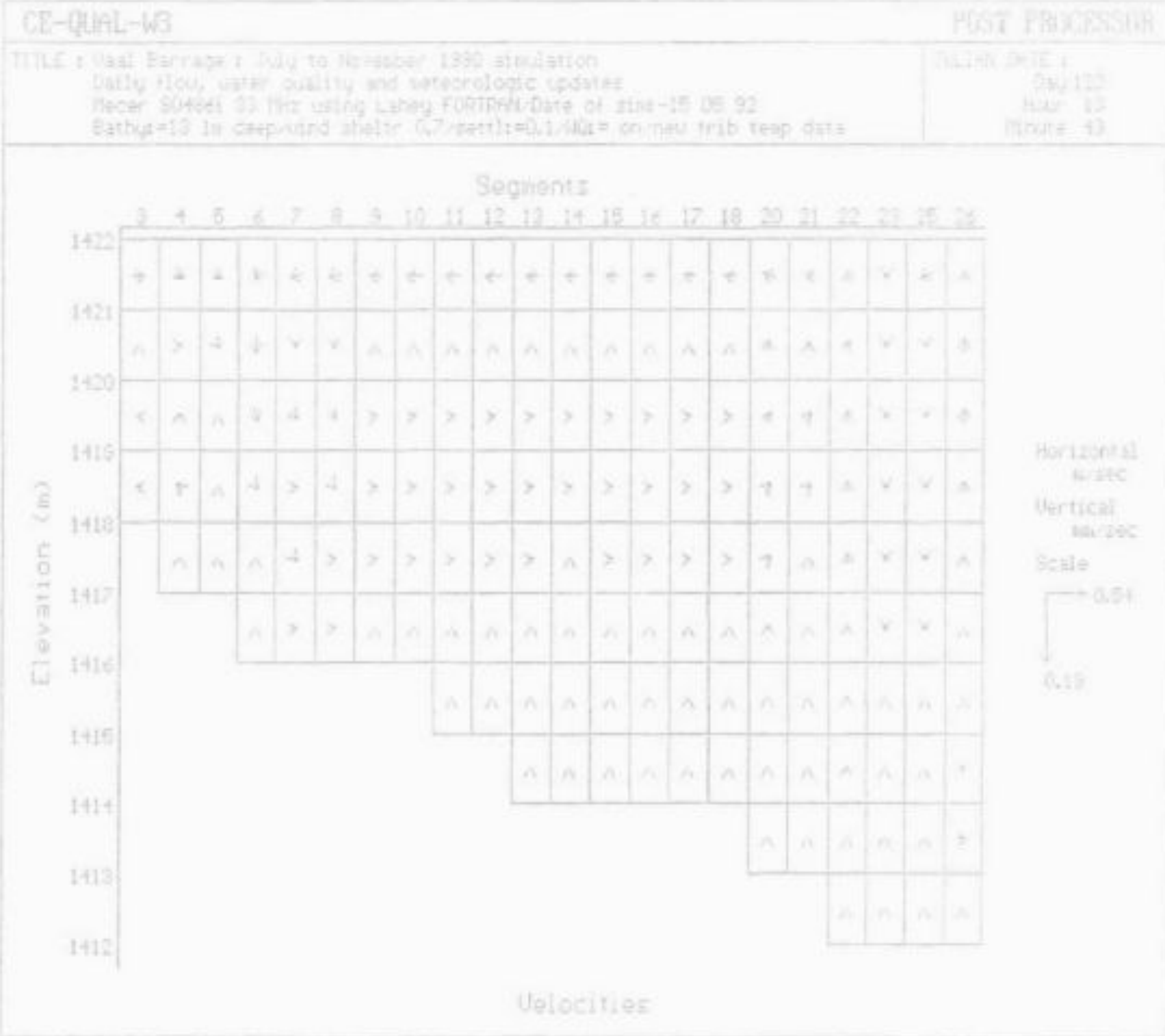
Two-dimensional plot showing the simulated horizontal & vertical movement of water in Segments 3 through to 26 in the Vaal Barrage.

Day number: 123

Beginning of release from Vaal Dam: Day 21

Horizontal scale: m/s
Vertical scale: mm/s

Inflow: ▾
Withdrawal: ▴



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Version 1.0

CHAPTER 5
APPLICATION OF WASP

by
A J Bath and G Basson

Contents: Page:

5.1 GENERAL DESCRIPTION OF WASP

WASP4 (Water quality Analysis Simulation Program) is a hydrodynamic and water quality model developed by the US Environmental Research Laboratory, Athens, USA. Version 4.2 is a dynamic two-dimensional compartment modelling system designed to analyze a variety of water quality problems in a diverse set of water bodies. WASP4 simulates the transport and transformation of conventional and toxic pollutants in the water column and benthos of reservoirs, rivers and estuaries. The WASP4 modelling system covers four major subjects: hydrodynamics, conservative mass transport, eutrophication - dissolved oxygen kinetics, and toxic chemical-sediment dynamics. The WASP4 modelling system consists of two stand-alone computer programs, DYNHYD5 and WASP4. These programs can be run together, or separately. The hydrodynamic program DYNHYD5, simulates the movement of water and the water quality program, WASP4, simulates the movement and interaction of pollutants within the water. The latter program is supplied with two sub-models capable of simulating two of the major classes of water quality problems:

EUTRO4	simulates conventional pollution (dissolved oxygen, biochemical oxygen demand, nutrients and eutrophication), and
TOXIC	simulates toxic pollution (organic chemicals, heavy metals and sediment interactions).

5.2 COMPUTER REQUIREMENTS OF WASP

The documentation of WASP gives computer run times for a number of test files used on a Compaq 386/20 computer (using DOS 3.3, 640 k bytes RAM, a 20 megahertz clock, and a maths numerical co-processor). These run times were compared with run times on a MECER 386/33 (using 4 Megabytes extended RAM, and maths co-processor). Implementation of the DYNHYD5 test file gave the following run times for the Compaq and Mecer computers:

Computer:	Compaq 38/20	Mecer 386/33
Run time:	3,30 minute	2.00 minute

The DYNHYD5 test file covers a simulation period of 2 days, which is short in comparison with the simulation of Roodeplaat dam and the Vaal Barrage which use 100 and 138 days, respectively. The run time for these simulations was found to be dependent on the length of simulation period and number of segments. Table 5.1 shows the run times produced for the South African data sets, using DYNHYD5. Table 5.1 shows that a 386 or 486 computer must be used to reduce computational run times, especially when the model simulation period covers more than one month.

TABLE 5.1 TYPICAL COMPUTER RUN TIMES FOR DYNHYD5

Computer	System	Number of segments	Number of days	Run time (minute)
286/20	Vaal Barrage	50	31	450
386/33	Vaal Barrage	50	31	30
386/33	Vaal Barrage	15	138	100
386/33	Vaal Barrage	11	138	85
386/33	Roodeplaat dam	7	100	40
386/33	Roodeplaat dam	5	100	30

5.3 IMPLEMENTATION OF DYNHYD5 - THE HYDRODYNAMIC FLOW SIMULATION MODEL

5.3.1 General

The program DYNHYD5 is an updated version of the Potomac Estuary hydrodynamic model DYNHYD2, developed in 1979. The model solves the one-dimensional equation of continuity and momentum for a branching or channel-junction (link-node) computational network. The results are stored as a disk file for later use by the water quality program (EUTRO4 and TOXIC). The computational network consists of links which act as channels conveying water and nodes which act as junctions storing water (see Figure 5.1).

Junctions in DYNHYD5 are equivalent to segments in the water quality model and the channels correspond to segment interfaces. The junctions and segments in the two models should be compatible, although the same numbering need not be used in the quality model. Upstream and downstream boundary junctions are not used in the quality model.

In summary, input parameters for the hydrodynamic model DYNHYD5 include:

- Junction parameters : initial surface elevation, surface area and bottom elevation
- Channel parameters : length, width, hydraulic radius, channel orientation, initial velocity and Manning's roughness coefficient
- Flow parameters : inflows and outflows can be specified as constant, or time variable
- Wind parameters : wind speed and wind direction
- Rain and evaporation : net evaporation per day (The following equation was found to give accurate results for the Roodeplaat simulation: Evap(net) = [S-pan evap + rain]*0,83-rain).

MODEL NETWORK

LINKS (CHANNELS) - CONVEY WATER

NODES (JUNCTIONS) - STORE WATER

AT EACH TIME STEP:-

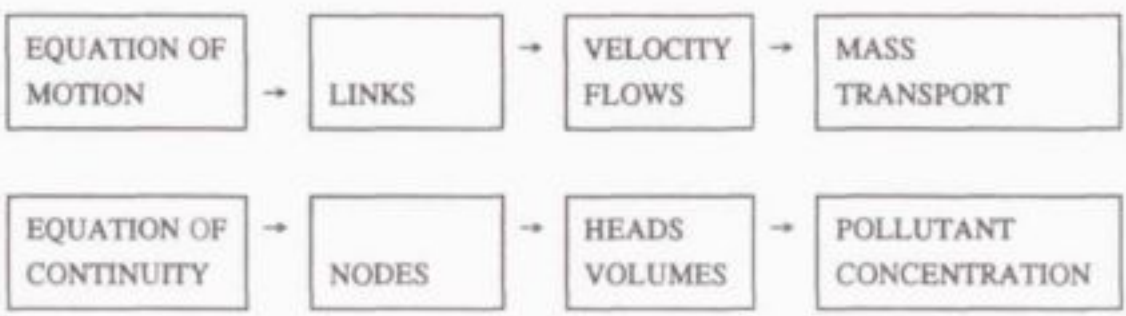


Figure 5.1 Model network showing links and node structure used in WASP.

5.3.2 Data acquisition for DYNHYD5

WASP4 was run on the Vaal Barrage and Roodeplaat Dam. These water bodies were selected because they exhibit longitudinal gradients in water quality between the point of inflow and the dam wall. The simulations were divided into two sections. Firstly, the simulation of the hydrodynamics using DYNHYD5 and secondly, the simulation of water quality using EUTRO4. This section describes the input data requirements of DYNHYD5.

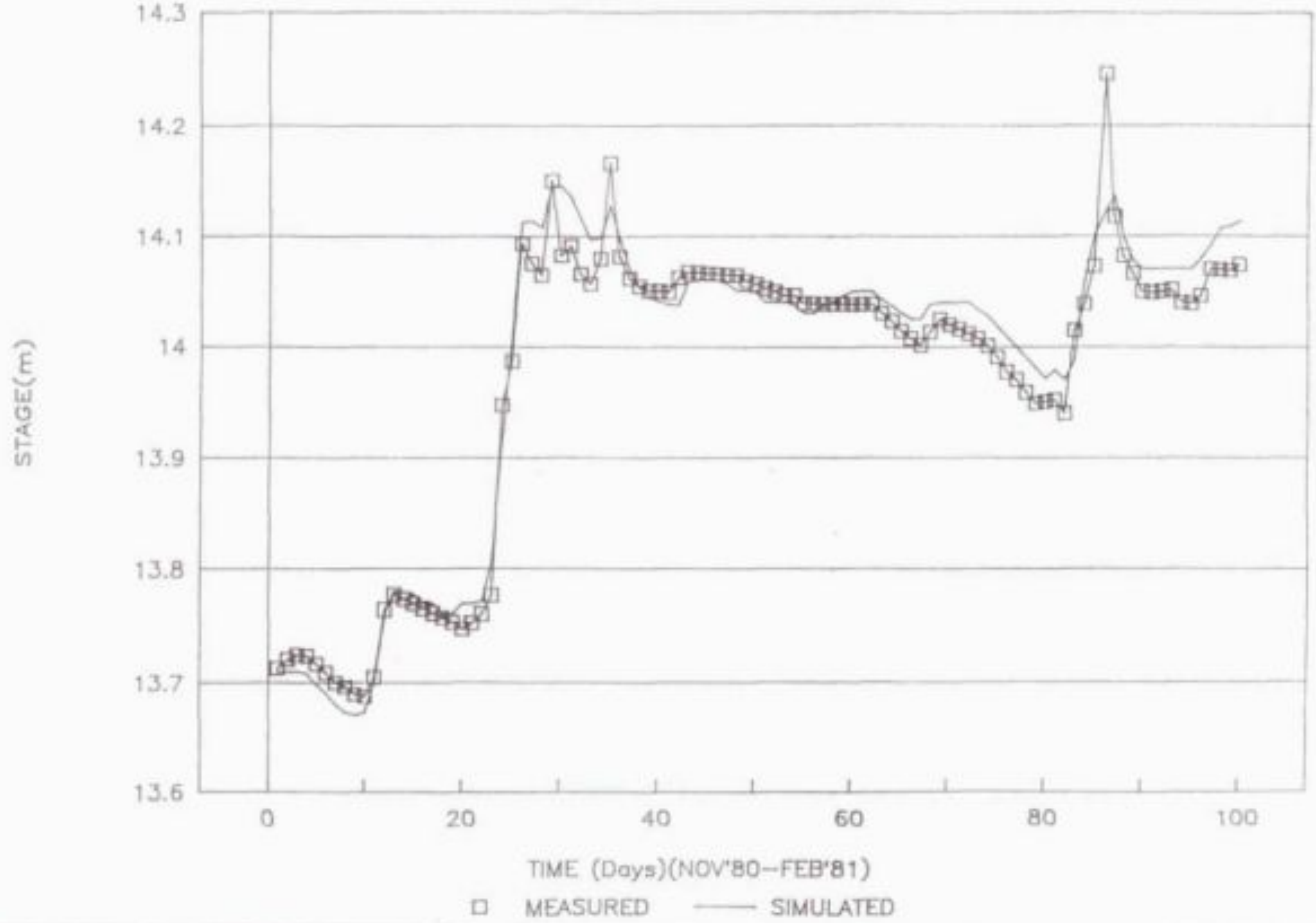
> **Roodeplaat Dam** The hydrological data for Roodeplaat Dam taken from the files used in the MINLAKE simulation. In addition, evaporation data was collected from the Department of Water Affairs and Forestry (DWA&F). A period of 100 days was chosen for the simulation period, starting on 1 November 1980.

> **Vaal Barrage simulation** The data set for the simulation period 1 July 1990 to 15 November 1990 (138 days) was obtained from the DWA&F and the Rand Water Board (RWB). The inflows, outflows and abstractions from the system and meteorological data are shown in Table 5.2.

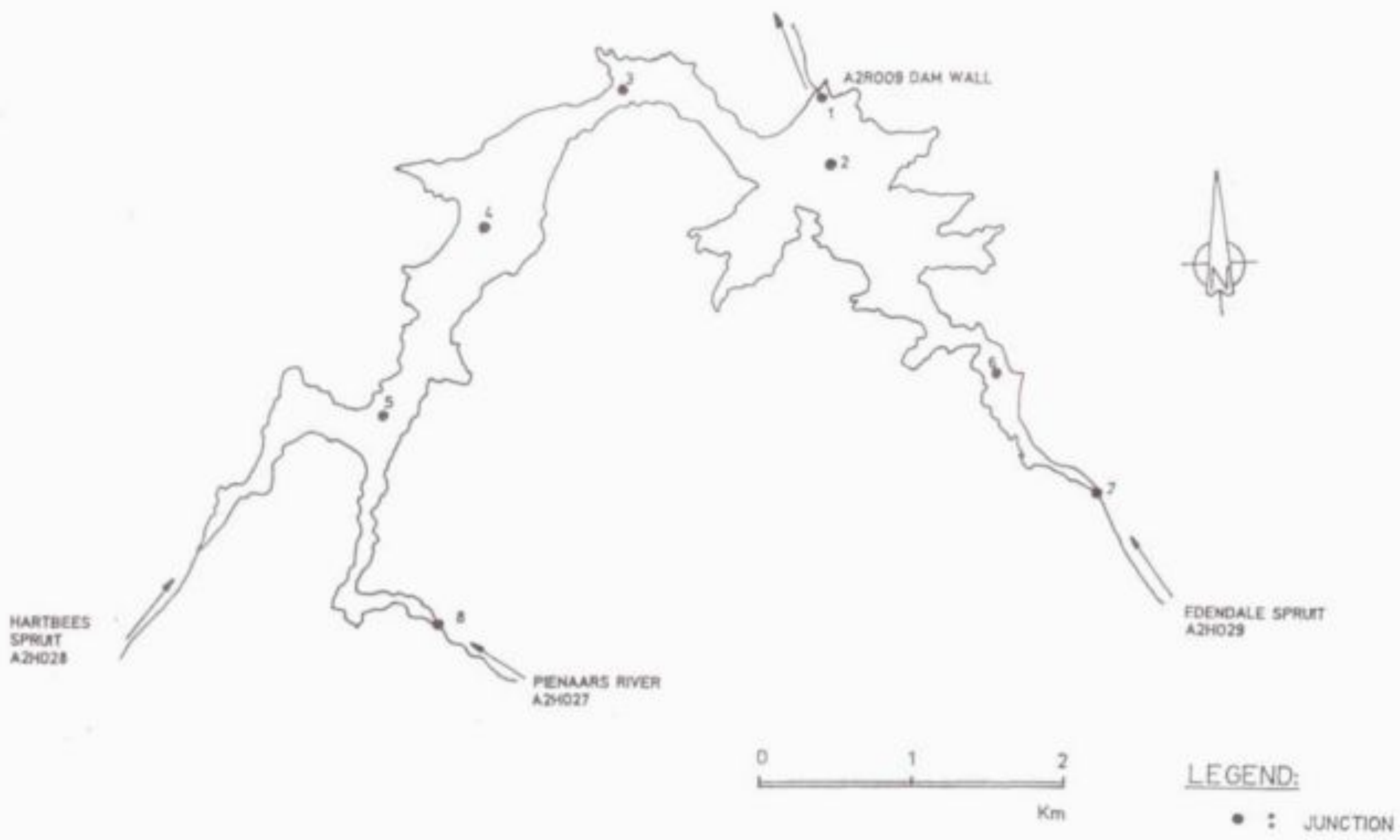
5.3.3 Roodeplaat Dam DYNHYD5 simulation

Figure 5.2 shows the simulation of the hydrodynamics of Roodeplaat Dam during the period of 100 days starting on 1 November 1980. A 6 junction layout was originally used, it was felt necessary to add an additional junction in the main basin (near the dam wall) which would give a better presentation of the measured flows in the reservoir layout. The layout of the chosen network of junctions and channels is shown in Figure 5.3. When DYNHYD is linked to the quality model, the upstream and downstream boundary junctions are not used, and therefore the quality model will consist of (at least) 5 surface segments. The hydrographic survey (DWA&F, 1979) of the dam basin was used to calculate surface areas, depths, volumes and channel widths. Conclusions from the Roodeplaat Dam verification exercise are:

- The model simulates accurately the hydrodynamics, but the model is sensitive to evaporation data used in the simulation (see Figure 5.4),
- The wind, under normal average daily conditions, does not have a major influence on the hydrodynamics of the system (Figure 5.5),
- The simulation of the rate of change of water level is dependent on the accuracy to which the total volume of the reservoir and inflows are estimated.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Simulated and measured stage levels for Roodeplaat Dam for the period November 1980 to February 1981.	FIGURE 5.2



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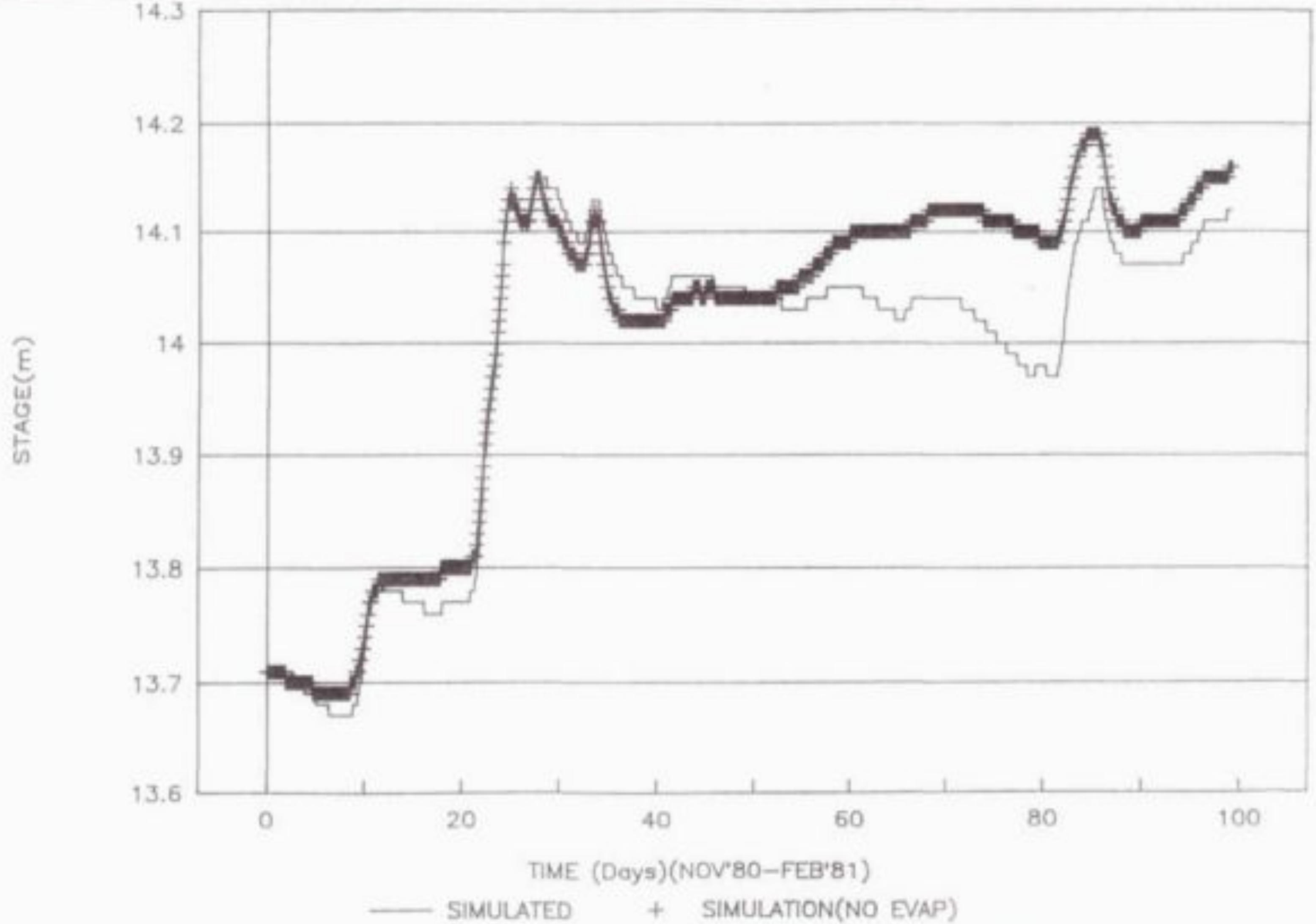
Roodeplaat Dam - Junction layout used for hydrodynamic simulations using DYNHYD5 (WASP)

FIGURE

5.3



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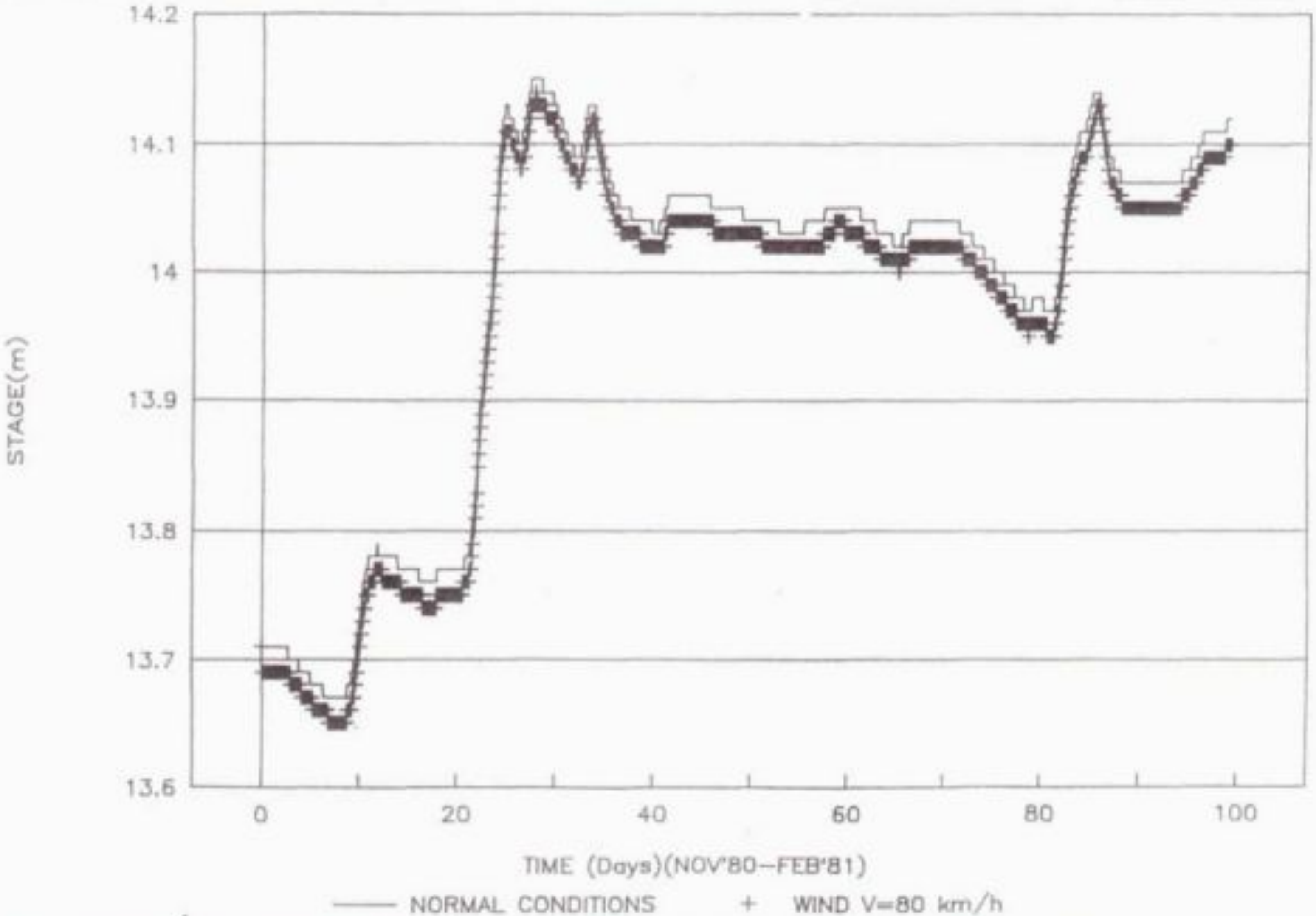
Effect of evaporation on the simulated stage level of Roodeplaat Dam. Simulated levels are predicted using WASP (DYNHYD) for the period November 1980 to February 1981.

FIGURE 5.4



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WASP simulations using measured wind velocity and wind velocity of 80km/hour for Roodeplaat Dam.

FIGURE 5.5

TABLE 5.2 : VAAL BARRAGE - DYNHYD5 INPUT DATA SET

Description		Source of data:	Data type	Figure No(*)
Barrage inflows from Vaal Dam	Vaal bank weir Engelbrechts drift weir	DWA&F RWB	Av. Daily Av. Daily	5.10
Abstractions u/s of Lethabo weir	Lethabo Eskom Iscor	DWA&F DWA&F DWA&F	Daily Daily Daily	
Inflows d/s of Lethabo weir	Klip Klip Taaibos Riet Suikerbosrand Suikerbosrand	RWB DWA&F RWB RWB RWB DWA&F	Av. Daily 06h00 Av. Daily Av. Daily Av. Daily 06h00	5.6 5.7
Abstractions d/s of Lethabo weir	Iscor Eskom Pump 1 Pump 2 Pump 3 USCO Vereeniging Mun Vereeniging Est TOSA	DWA&F DWA&F DWA&F DWA&F DWA&F DWA&F DWA&F DWA&F DWA&F	Monthly Monthly Daily Daily Daily Monthly Monthly Monthly Monthly	
Outflows from the Barrage	Barrage Lindeque Drift	RWB RWB	Av. Daily Av. Daily	5.8
Stage data	Barrage Lethabo weir	RWB RWB	Every gate change 06h00	
MET data	Rain Evaporation	Weather Bureau & DWA&F	Daily Daily	

(*) Graphs presentation showing comparison between different sources of flow data. u/s = upstream. d/s = downstream. MET = meteorological. Av. = average.

5.3.4 Vaal Barrage DYNHYD5 simulation

Model simulations were performed on the Vaal River between the Barrage and Lethabo weir, a distance of 50 km. A number of factors influenced the accuracy of the simulations of the Vaal Barrage:

(1) Continuous flows measurements at Lethabo weir were not available. Only stage readings taken at 6h00. Inflow into the system from Vaal Dam is gauged approximately 30 km upstream of Lethabo weir at Engelbrechts Drift (operated by RWB) and Vaal Bank (operated by DWA&F). To verify the water balance for the upper Barrage, a computer spreadsheet program was used to compare the rate of inflow and outflow on a daily basis.

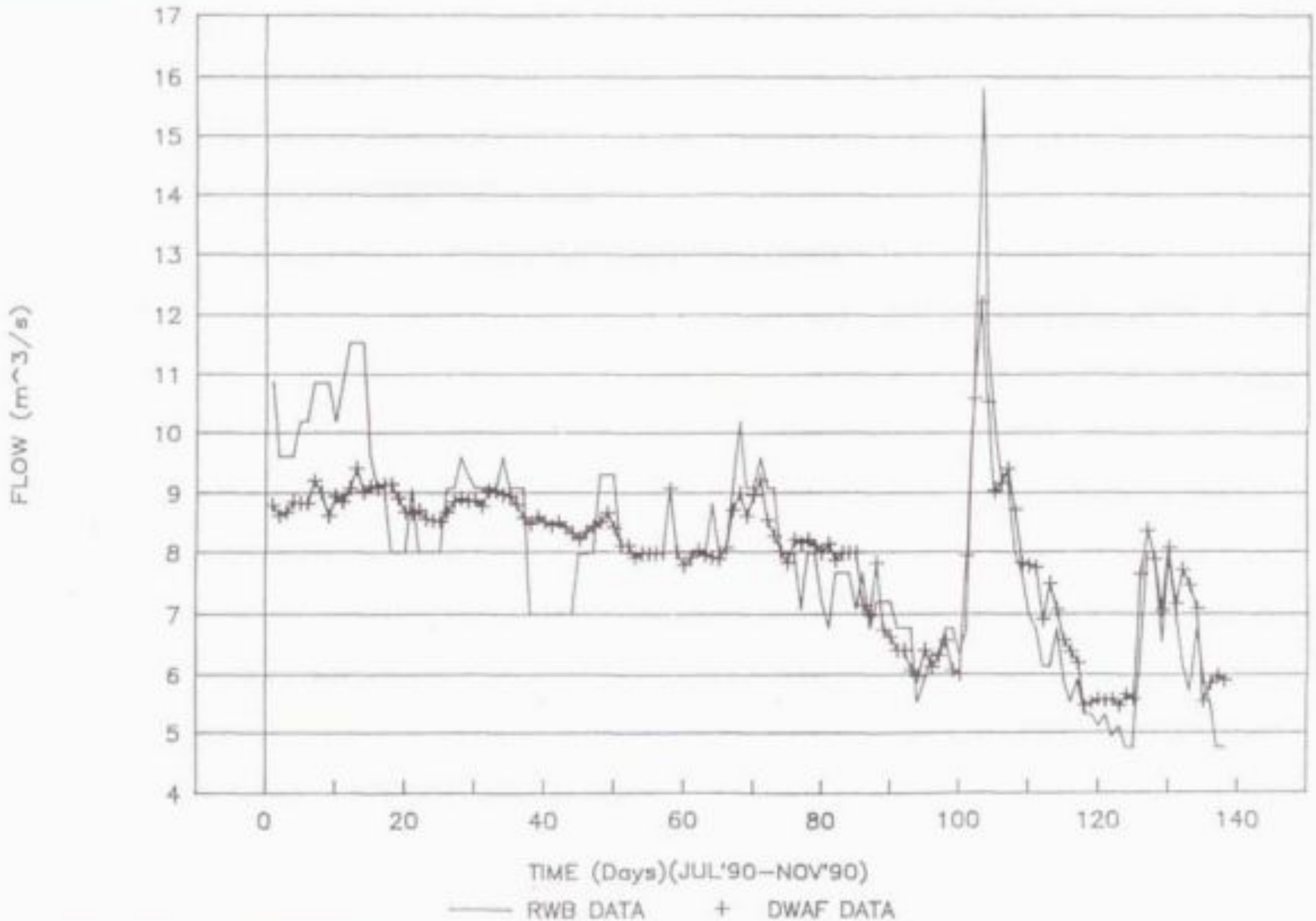
(2) Total monthly abstraction data were available for a number of users (refer to Table 5.2). Daily abstraction rates were calculated from monthly totals.

(3) Comparison between DWA&F and RWB inflow data for the Klip River, Suikerbos River and Barrage outflows shows large discrepancies (See Figures 5.6, 5.7 and 5.8). A number of simulations were performed on WASP to determine which inflow data gave the most satisfactory correlation between measured and simulated data.

(4) A hydrographic survey carried out by DWA&F (1978) was used to provide cross-sectional data at 5 to 10 km intervals. Difficulties were experienced in establishing the correct volume of the Vaal Barrage system. For the simulation, average depths were interpolated for the junctions using the DWA&F survey, while surface areas were calculated using 1:10 000 orthophoto maps. The water volumes for the Riet, Loch Vaal, Suikerbos, Klip and Taaibos Rivers were also included to improve the accuracy of the hydrodynamic flow system.

(5) The water consumption of riparian owners was not known and assumed to be small compared with other abstractions from the system and not included in the model simulations.

A number of network layouts were used to simulate the hydrodynamics of the system. These layouts ranged from 51 to 12 junctions. A network with 16 junctions (see Figure 5.9) was



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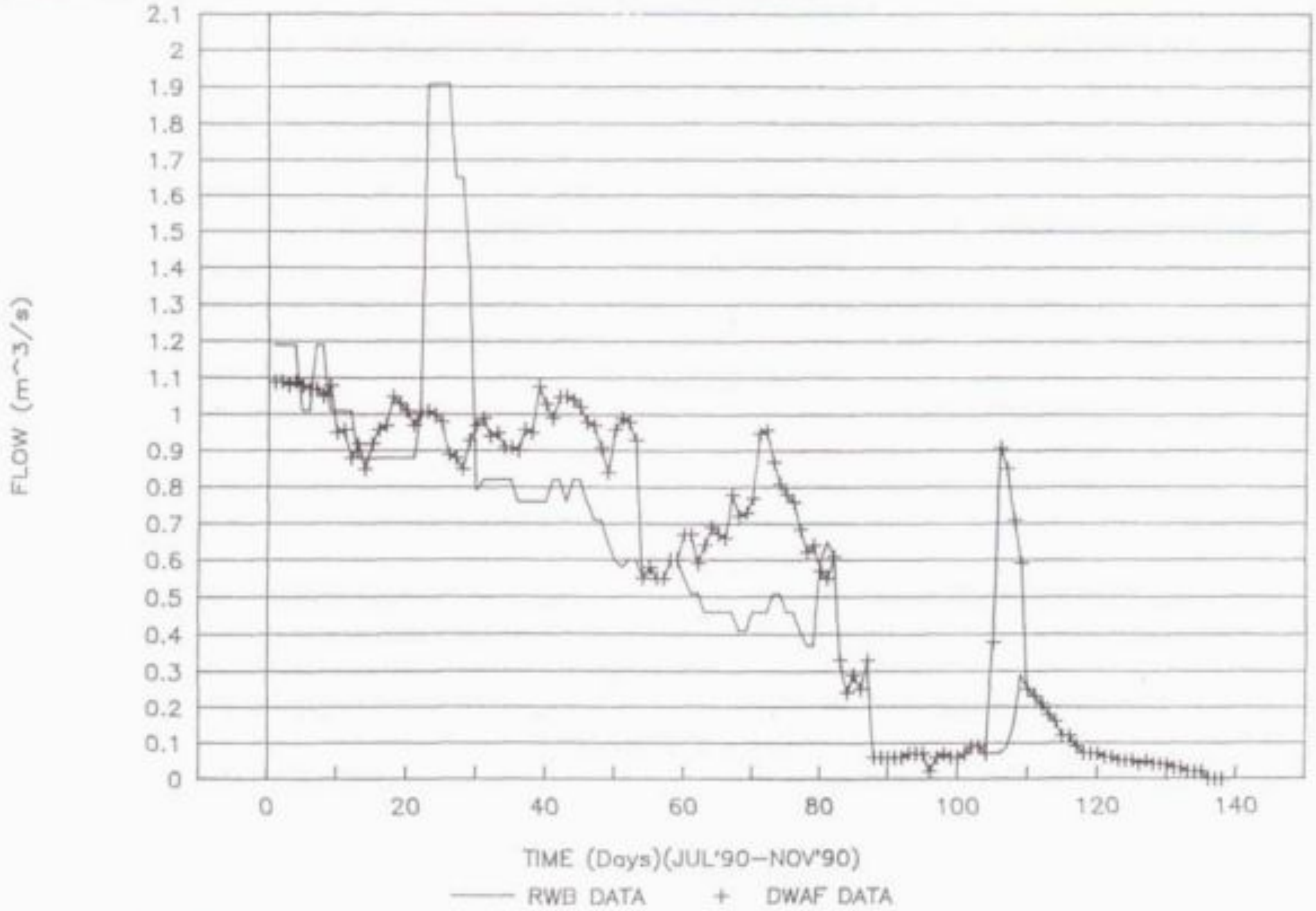
Measured hydrographs for the Klip Spruit using data from the Rand Water Board and Department of Water Affairs.

FIGURE 5.6



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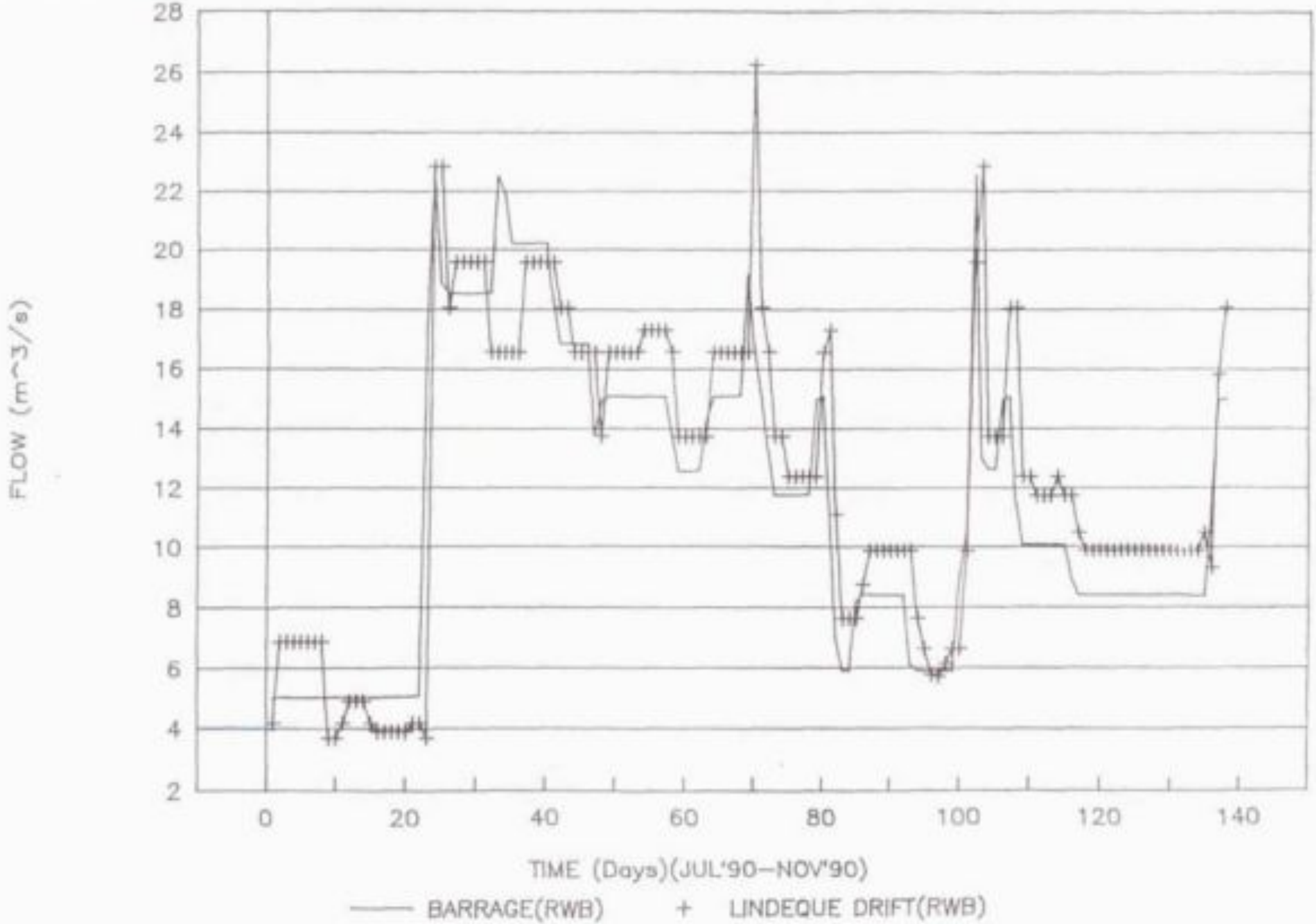
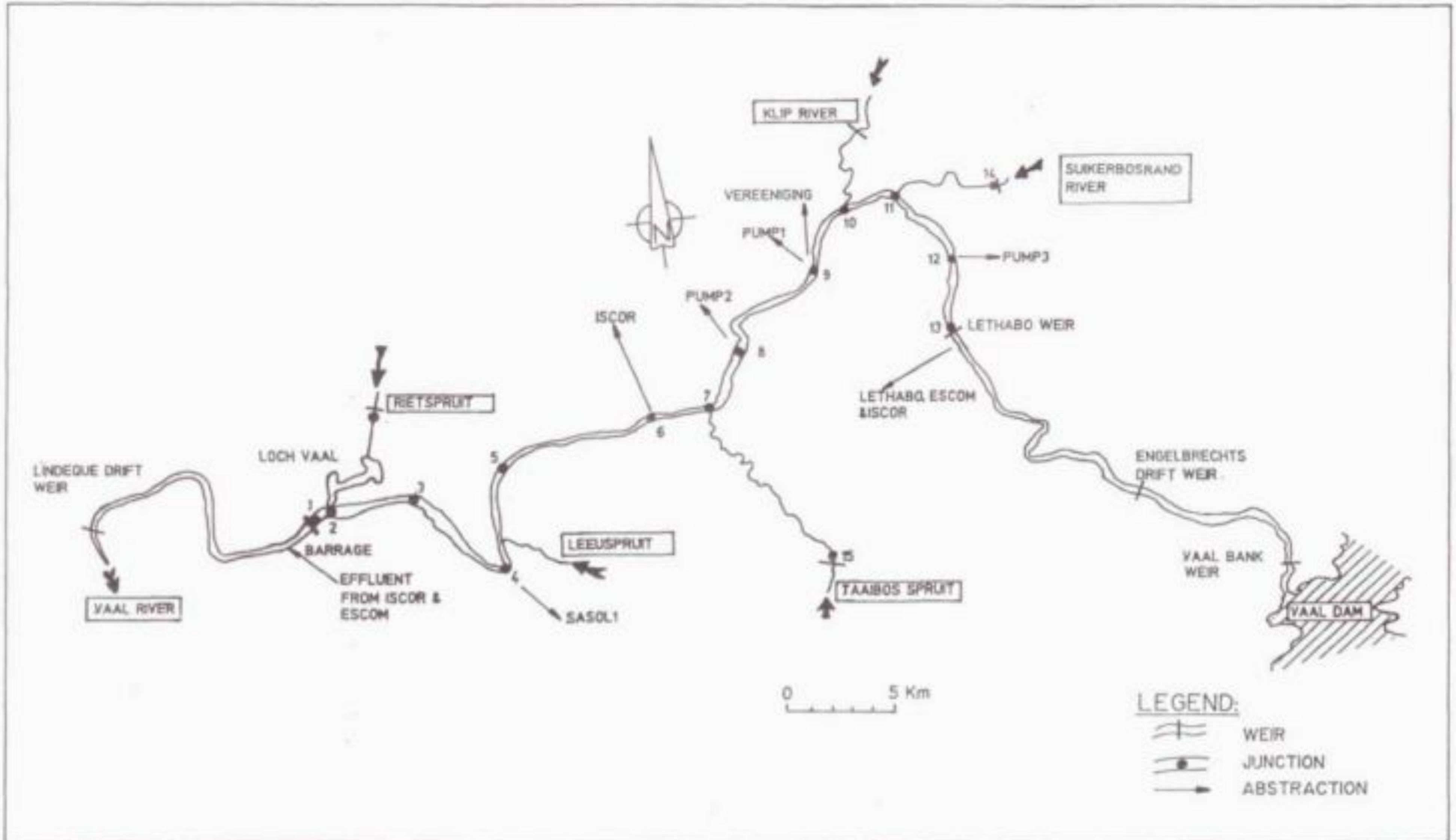
Measured hydrographs for the Suikerbos Spruit using data from the Rand Water Board and Department of Water Affairs.

FIGURE 5.7



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Measured hydrographs for the Vaal Barrage and Lindeque Drift (Rand Water Board).	FIGURE 5.8



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Vaal Barrage - Junction layout used for the hydrodynamic simulations using DYNHYD5 (WASP)	FIGURE 5.9

eventually chosen because it included the tributary volumes and a minimum number of junctions in the Vaal river, which reduced computer run time. The best correlation between measured and simulated water levels at the Barrage was obtained by using a combination of inflows and outflows described below (see Figures 5.10 and 5.11):

- **Inflows**: Vaal bank data (DWA&F) for full record.
  Although there was good correlation between Vaalbank and RWB data the DWA&F data were used because the rating curve of the weir had been recalculated recently.

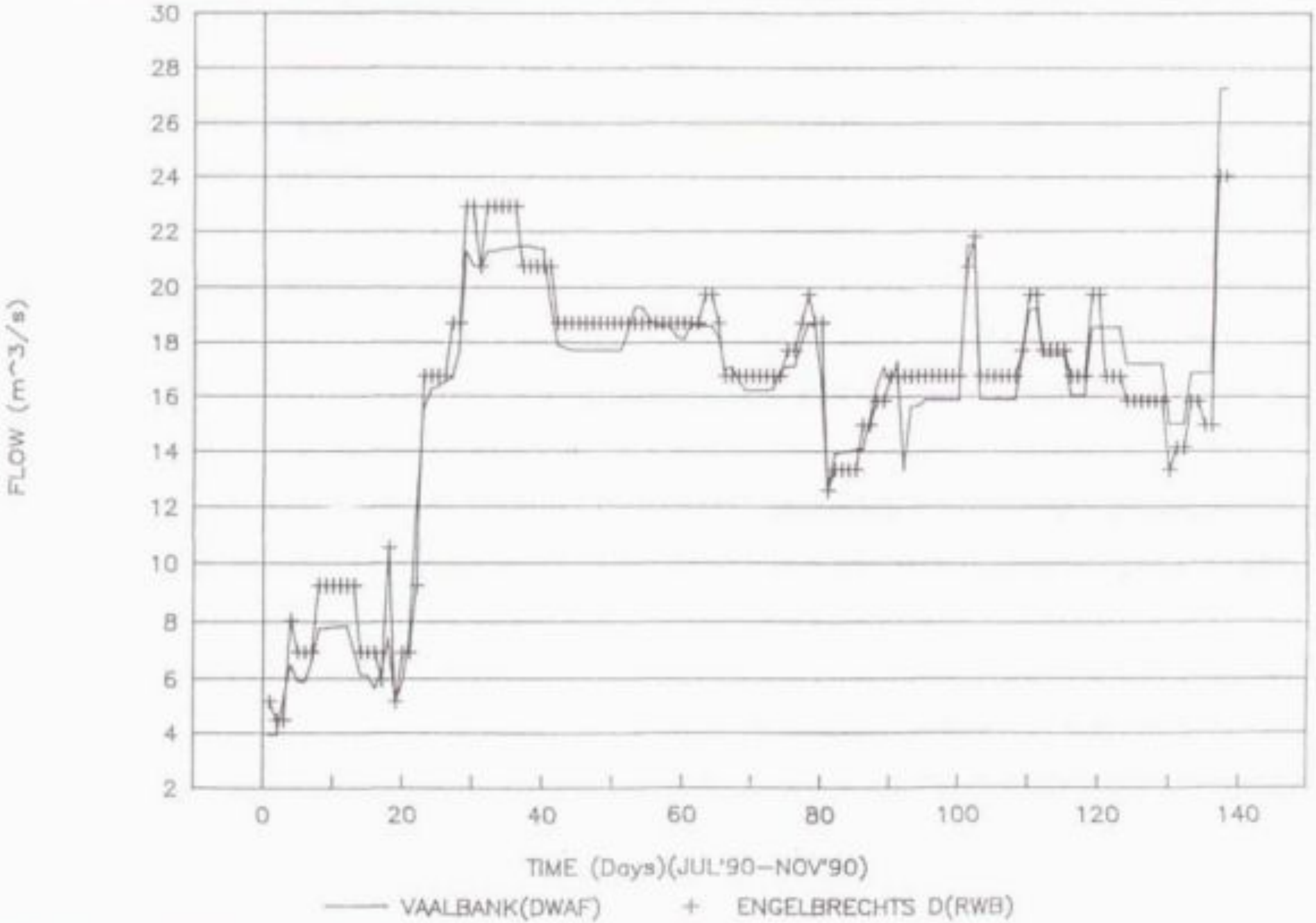
- **Inflows**: Day 0 to 54: Klip (DWA&F)
  Day 55 to 138 : Klip (RWB)
  Although data measured at 6h00 were available from DWA&F, the RWB data seemed to over- and underestimate the actual flows up to day 54. For the last part of the record, there was a good correlation between RWB and DWA&F data and therefore the calculated average daily data of RWB were used.

- **Inflows**: Suikerbos (DWA&F) for total period of simulation.
  Although the flow rates for the simulation period were less than 2 cumec, the peak discharges, given by the DWA&F gave improved simulation results compared with RWB data.

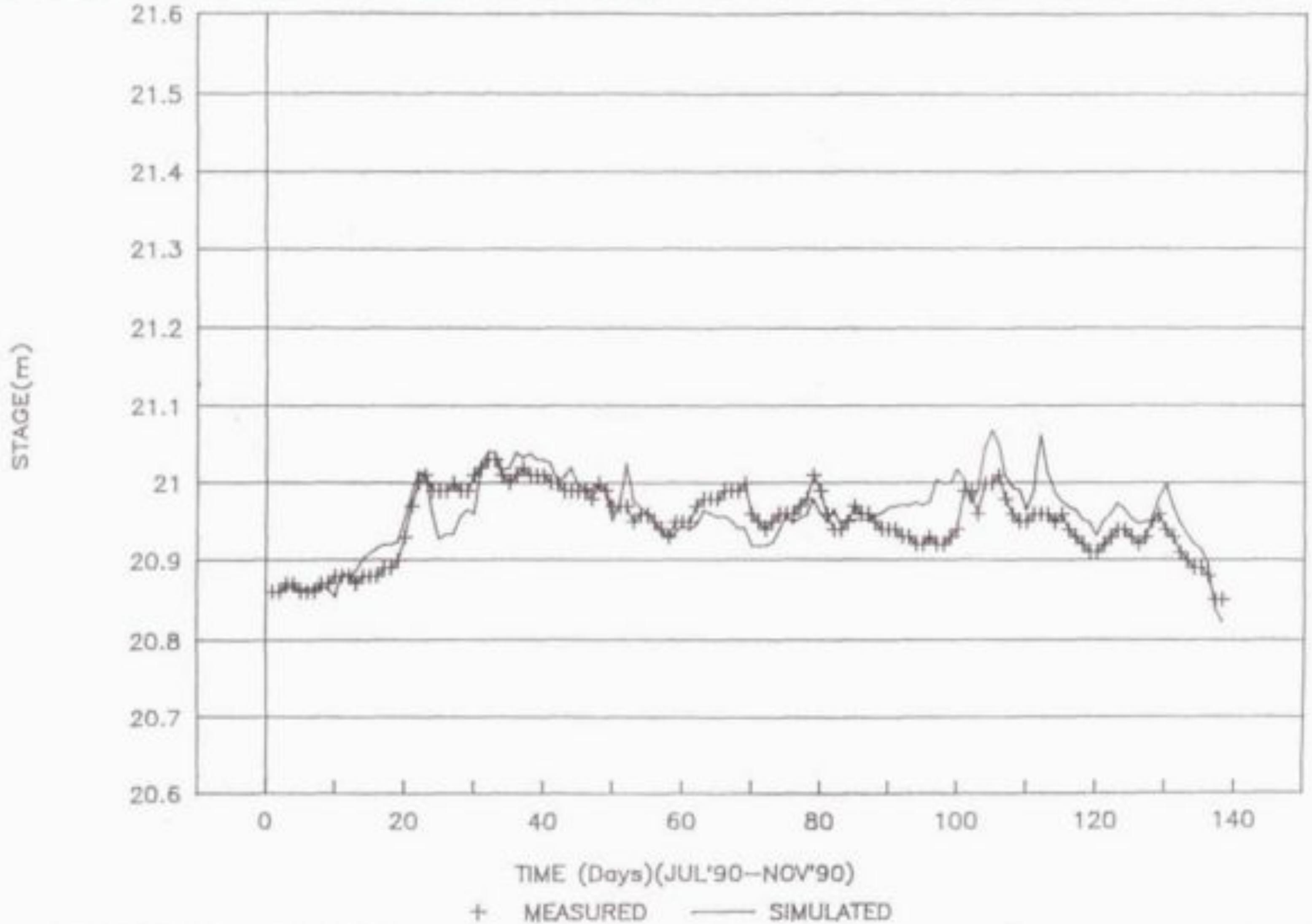
- **Outflows**: Day 0 to 40 : Barrage flows
  Day 41 to 138 : Lindeque weir flows (lagged - 1 day)
  with the peak on day 69 adjusted from 26,26 cumec to 21 cumec, which was equivalent to the Barrage peak flow.

Using Barrage outflows, the first part of the simulation period was simulated accurately which confirmed the accuracy of the chosen junction volumes. Prior to day 40, the flows were approximately ± 1.5 cumec greater than measured at Lindeque weir. After Day 40, the peaks and low flows were found to correspond less well with the stage values gauged at the Barrage.

Although effluent from Iscor and Eskom was discharged into the river between the Barrage and Lindeque drift and further riparian abstractions and evaporation are unknown, the low flows gauged at Lindeque drift were more accurate than the flow calculations at the Barrage. The reason being was the Barrage uses an approximate rating curve for the gate openings.



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Comparison of the measured hydrographs for Vaalbank Weir and Engelbrecht's Drift.	FIGURE 5.10



UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Comparison of the measured and simulated stage readings for the Vaal Barrage. Simulated readings derived from WASP for the period July to November 1990.	FIGURE 5.11

5.3.5. Summary of the DYNHYD5 simulations

The DYNHYD simulations for both Roodeplaat Dam and Vaal Barrage provide the following information.

- Relatively good correlation with field stages at the Barrage was possible when an understanding of the system was developed. To obtain satisfactory simulation of the hydrodynamics of the Vaal Barrage, detailed work must be carried out to assess relative accuracy of the various inflow data sets.

- The large discrepancies between flow data from different sources for the Vaal Barrage should be investigated. It may be necessary to recalculate the rating curves, especially for higher flows. A stage level recorder could also be installed at the Lethabo River weir and flank walls constructed on the broad crested weir to improve flow estimation during periods of low and medium flow. If this station could be included in the telemetric system of DWA&F, the operation of the Vaal Barrage System could be improved during low and medium flow conditions. This may also assist DWA&F in the application of the blending options used in the Vaal Barrage to manage the total dissolved salts concentration.

- The calibrated model can be used as a valuable tool to evaluate the accuracy of inflow and outflow hydrograph data which may prove a valuable tool when verifying the calibration of the gauging facilities.

- A large proportion of the time was spent working on DYNHYD was used in the evaluation of input data sets. Spreadsheets and graphical presentation packages were essential tools in this regard.

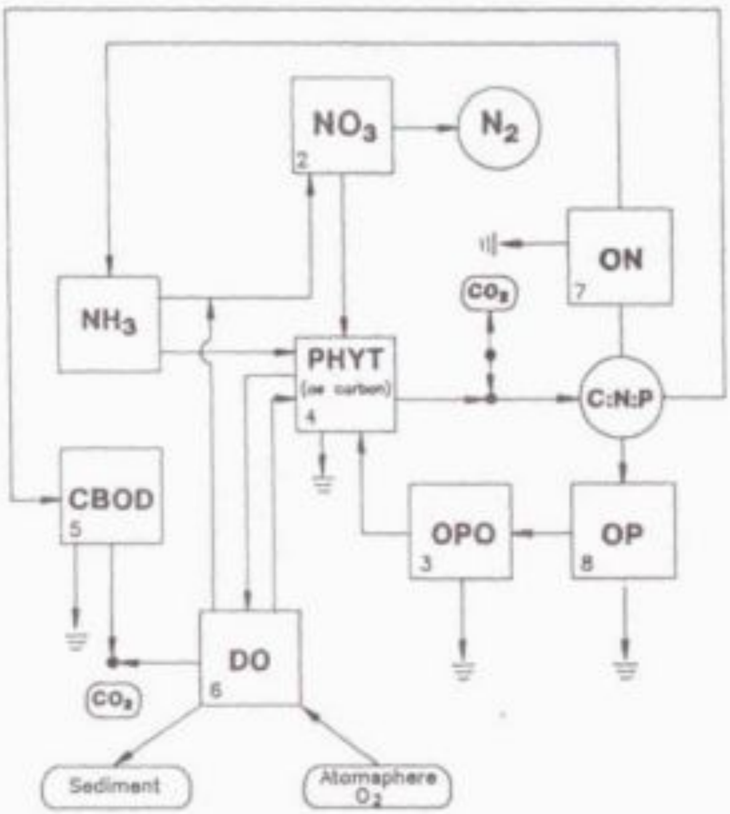
5.4. ROODEPLAAT DAM WASP (EUTRO4) SIMULATIONS

5.4.1 General

The eutrophication model, EUTRO4, is a simplified version of the Potomac Eutrophication Model, PEM (Thomann and Fitzpatrick, 1982). Numerous processes are associated with the eutrophication state of a water body, see Figure 5.12. EUTRO4 has been developed so that the operator can select the level of complexity required to simulate water quality. For example, in the simulation of DO and BOD, it is possible to bypass certain calculations and just simulate the variables of interest. The model deals with six levels of complexity, namely (1) Streeter-Phelps, (2) Modified Streeter-Phelps, (3) Full linear DO balance, (4) Simple eutrophication kinetics, (5) Intermediate eutrophication kinetics, and (6) Intermediate eutrophication kinetics with benthos interactions. EUTRO4 simulates the transport and transformation reactions of up to eight state variables. For modelling purposes, they are considered as four interacting systems: phytoplankton kinetics, the phosphorus cycle, the nitrogen cycle, and the dissolved oxygen balance. The general WASP mass balance equation is solved for each state variable and includes subroutines which accommodate for transformations as well as sources and sinks of nutrients, such as the benthic interactions.

The EUTRO4 data input file includes the following cards

- **Simulation control parameters (card A):**
  - number of segments in the network
  - number of model chemical systems
  - simulation control flags
  - time step selection
  - print intervals
  - linkage control with DYNHYD
- **Exchange coefficients (card B):**
  - number of exchange fields
  - mixing lengths
  - exchange areas between segments
  - dispersion coefficients
- **Volumes (card C)**
  - constant volumes or adjusted volumes
  - bed volume options
  - segment orientation and location
  - hydraulic coefficients



NINHAM SHAND	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Generalised schematic of the processes associated with the eutrophic state of a water body.	FIGURE 5.12

segment volume

- **Flows (card D)**

  flow rates between segments

  segment pair numbers

  sediment transport rate options

  precipitation and evaporation data

- **Boundary conditions (card E)**

  For each chemical system the boundary concentrations are specified.

- **Waste loads (card F)**

  quantified loads entering water body

  segments receiving loading

- **Environmental parameters (card G)**

  a number of "multipliers" are specified to convert between different units

  links time functions (in card I) with specific segments

- **Constants (card H)**

  nitrification rate

  temperature coefficients

  denitrification rate

  growth rates for algae

  other bio/chemical rate constants

- **Time functions (card I)**

  time series of data for:

  - temperature
  - solar radiation
  - fraction of sunlight
  - wind velocity
  - extinction coefficient
  - ammonia flux from bed
  - herbivorous zooplankton population
  - salinity

- **Initial concentrations (card J)**

  specifies the chemical concentration for each segment for each chemical system.

The above mentioned cards are linked into a single input data file which is read by the program at the beginning of the run stream. Verification of the input data file is only possible by running the model. The model gives error messages should formatting problems be detected in the input file. The format of the input data file is complex, and a pre-processor should be developed to assist in writing and verifying the input file.

To verify the installation of EUTRO4, test data files provided with the model were run. All test files were found to operate correctly and give the correct output. Once EUTRO4 had been tested, the next task was to undertake a verification exercise of the water quality model on Roodeplaat Dam.

5.4.2 Roodeplaat Dam EUTRO4 simulation

In the above sections, a description is given of the verification for the hydrodynamic model DYNHYD for Roodeplaat Dam. The water quality data set used in the EUTRO4 simulations was the same one used for MINLAKE, see Chapter 3. Considerable effort was required to reformat the input data to a form acceptable by WASP. A number of segment configurations were tested in order to carry out a simple eutrophication simulation for the reservoir, the following segment configurations were used.

Number of segments:	**Results:**
8	The model gave erroneous output for the volumetric components of the reservoir (volume, flow velocity and depth).
9	Difficulties were experienced in calibration of the water quality simulations.
12	Adjustment of the volumetric characteristics of the reservoir caused the model to crash.
4	Runs but not possible to link with DYNHYD, calibration of the water quality components caused the model to become numerically unstable.

A number of simulations were performed using the segment configurations listed above and shown in Figure 5.13. None of the simulations gave satisfactory output in terms of the water quality of Roodeplaat Dam. The manual and documentation for WASP were not adequate to identify the problems. Contact was made with the developers of the model in the United States who stated that WASP version 6.22 was superseded by version 6.3. Version 6.3 was tested and gave similar problems as described above.

5.5 CHANGES TO SOURCE CODE

A number of changes had to be made to the WASP hydrodynamic program, DYNHYD5, to increase the time period of simulations, the number of segments in a system, and format of the input data file. The Lahey Fortran compiler F77L was used to compile the source code for this purpose.

5.6 CONCLUSIONS AND RECOMMENDATIONS

The hydrodynamic model, DYNHYD, provided good simulation results for Roodeplaat Dam and the Vaal Barrage. The water quality model, in contrast, provided a series of problems. The errors were traced to the source code but sufficient time was not available to undertake a detailed analysis of the code. It is recommended that the model is retested once new source code and documentation are available.

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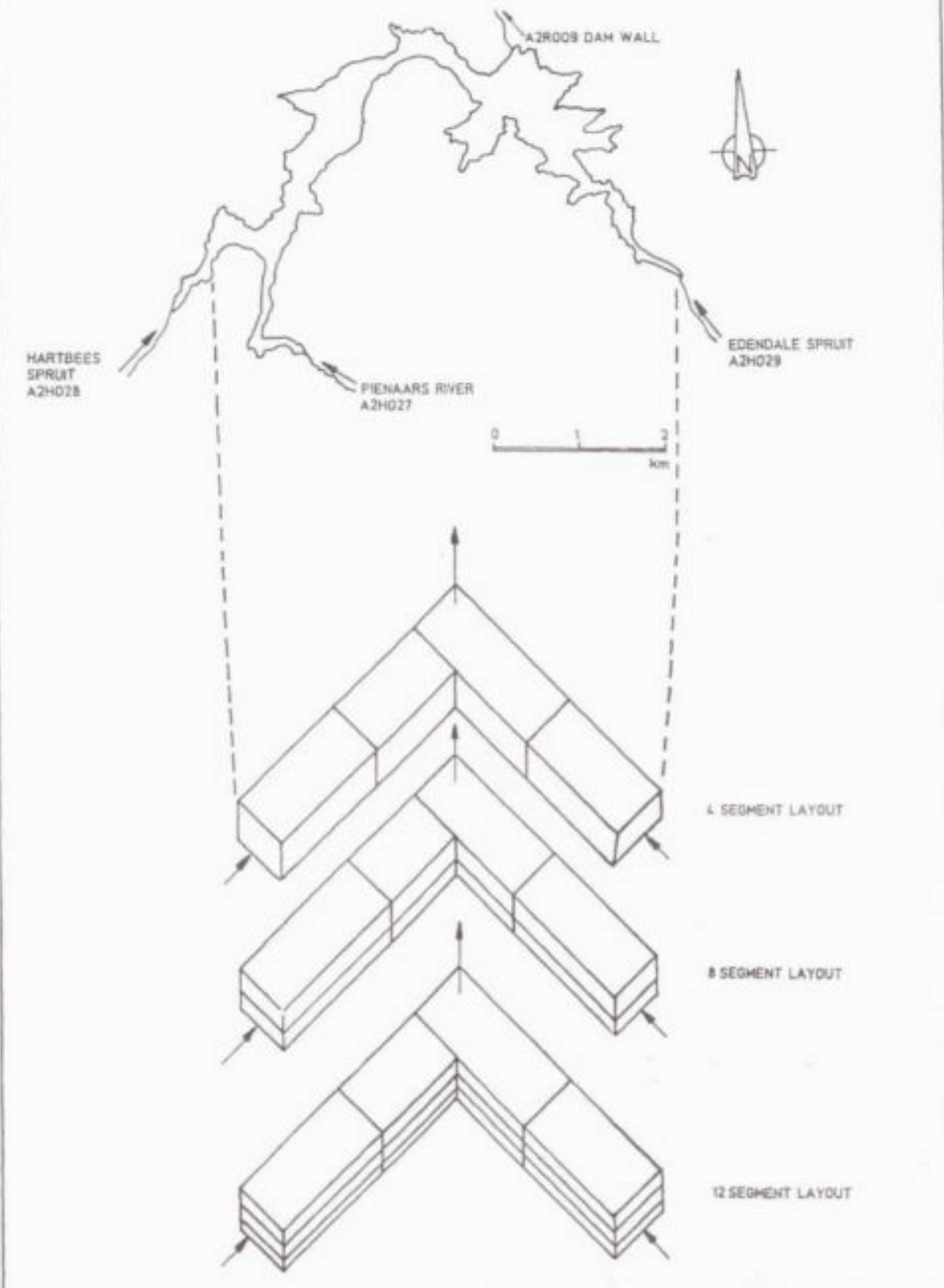


	UNIVERSITY OF CAPE TOWN	WATER RESEARCH COMMISSION	Segment configurations used for the simulation of the water quality of Roodeplaat Dam using WASP version 4.22.	FIGURE 5.13

CHAPTER 6

GENERALISED CONCLUSIONS

Contents: Page:

6.1 INTRODUCTION

The purpose of this chapter is to draw together and generalise the detailed conclusions from the individual model application chapters. For this integration process we have used the original project aims presented in Chapter 1 as a guide, but we also kept general modelling interests in focus. For detailed conclusions on a particular model or reservoir application the reader is referred to the respective chapters. It must also be stressed that, owing to the explorative and non-exhaustive nature of this study, our stated conclusions are necessarily of a provisional nature.

6.2 PREDICTIVE ABILITY

In this sub-section the term "predictive ability" is used in the context of iterative comparisons between model simulation outputs and observed in-dam data. It should be noted that conventional split-sample tests consisting of calibration followed by independent verification of predictive ability was not possible given the explorative nature of the study.

6.2.1 Water Balance

Against a background of variable degrees of effort for calibration and interpretation, all four models implemented - DYRESM, MINLAKE, CE-QUAL-W2, WASP - maintained appropriate mass balances in their respective case studies.

6.2.2 Thermal and Hydrodynamics

Against a background of variable degrees of effort for calibration and interpretation the following three models showed acceptable predictive ability of the thermal and hydrodynamics (in terms of profiles) in their respective case studies : DYRESM, MINLAKE, CE-QUAL-W2.

6.2.3 Conservative Water Quality

The following two models were verified successfully for TDS profiles : DYRESM and CE-QUAL-W2. (This feature was not investigated in depth in the MINLAKE component of the project as the focus of this component lay elsewhere.)

6.2.4 Non-conservative Water Quality

The only model that displayed reasonable verification success for non-conservative water quality parameters - suspended solids, phosphate, algal biomass - was CE-QUAL-W2. This finding might be an artefact of the available database, as the case study for MINLAKE was based on synthetic suspended solid time series for the inflowing streams to Roodeplaat Dam and might not be an adequate test for MINLAKE's capability. (See conclusions below regarding respective calibration efforts required for this purpose.)

6.2.5 Role of Calibration

Calibration requirements vary in sympathy with the range of processes that a particular model is geared to simulate :

- DYRESM - thermal and hydrodynamics : no calibration
- MINLAKE - thermal and hydrodynamics : no calibration
  - water quality : extensive calibration

- CE-QUAL-W2 - thermal and hydrodynamics : modest calibration
  - water quality : extensive calibration
- WASP - hydrodynamics : modest calibration.

No conclusions could be drawn regarding the transferability of model parameter values from one reservoir to another.

6.2.6 Hydrometeorological Database

Hydrometeorological databases for the three impoundments studied - Roodeplaat Dam, Hartbeespoort Dam and Inanda Dam - were found to suffer from a range of inadequacies and extensive use had to be made of data collected at stations remote from the dams. Provisionally, it appears that, of all the input data types concerned, the highest requirement for accuracy and representativeness of data lies with daily wind-run, daily inflow quantity and daily inflow quality data.

6.2.7 In-reservoir Database

Three requirements are relevant for the in-reservoir database which serves to verify a model's adequacy for water quality management :

- observations of a suitable range of water quality variables at weekly to quarterly intervals : at least temperature, EC, suspended solids, phosphates, nitrates, algal indices;
- observations of the chosen variables at a number of representative points across the reservoir basin : at least three points chosen to expose longitudinal variation and to include the main body of water; and

- observation of the chosen variables at a suitable number of depths at each observation point : at least three depths at each point - one each in the epilimmion, the metalimmion and the hypolimmion.

Of the three impoundments studied, only the data set for Inanda Dam met all three requirements adequately. The Vaal Barrage data set was adequate in terms of the particular goals of that investigation, but not in the general terms stated above.

6.3 ADAPTATION OF SELECTED MODELS

6.3.1 Algorithm Modifications

All four models required various degrees of modification to certain process algorithms and/or to improve their versatility. Details are provided in the specific model chapters. Some of the modifications that appear to be required fell outside the scope of this study and/or the expertise of the project team.

6.3.2 Model Structure Modifications

An important modification to DYRESM by the model's developers became available and was successfully implemented during the course of the study : the bubble plume dynamics utility, useful for testing destratification options.

6.3.3 Input/output Modifications

In terms of user-friendliness for both input preparation and output display/manipulation the models can be ranked as follows, from high friendliness to low friendliness : DYRESM; MINLAKE; CE-QUAL-W2; WASP.

On the input side, much effort had to be expended during this project to improve the CE-QUAL-W2 and WASP input framework. On the output side, friendly specialist output display software was developed during this project for each of DYRESM, MINLAKE and CE-QUAL-W2. Details appear in the respective model application chapters.

6.4 CASE STUDIES OF WATER QUALITY MANAGEMENT

Although each model application can be viewed as a "case study" in its own right and has led to detailed conclusions as reported in each relevant chapter, this sub-section deals only with the two cases where a water quality management action was simulated, namely :

- hypothetical destratification of Roodeplaat Dam by air bubble plume action; and
- blending of Vaal Barrage contents by low-salinity releases from Vaal Dam.

6.4.1 Destratification

The technical feasibility of destratification by aeration of a typical dam in the summer rainfall zone, Roodeplaat Dam, has been demonstrated and broadly quantified by simulation with DYRESM. Optimisation approaches for both layout design and operation of the aerator have also been indicated.

6.4.2 Blending

The two-dimensional nature of the translation of the low-salinity release water through the Vaal Barrage has been demonstrated by simulation with CE-QUAL-W2. The consequent distribution of non-conservative water quality constituents throughout the Barrage has also been highlighted.

CHAPTER 7

GENERALISED RECOMMENDATIONS

Contents: Page:

7.1 INTRODUCTION

Highly detailed recommendations conclude the respective model application chapters, which, for reasons of economy, are not repeated here. Instead, this chapter offers a broad overview to give the reader a sense of the nature of the detailed recommendations. We also emphasise certain crucial aspects relating to this level of modelling and databases in general, for notice by the research planning/funding and water management fraternity in South Africa.

7.2 SPECIFIC TO THIS PROJECT

The generalised conclusions in Chapter 6 and the detailed conclusions in the respective model application chapters confirm that this project has largely succeeded in its goal to explore the "applicability of hydrodynamic reservoir models for water quality management in stratified water bodies in South Africa". Time and budget constraints meant that certain research tasks could not be exhaustively completed. We therefore recommend extensions to this project to complete the following research tasks:

- Implementation of the new versions of the DYRESM model, ie. DYRESM-2D and DYRESM-WQ, with the present project databases to evaluate these models and their application.

- Further study of the water quality aspect of MINLAKE, to evaluate its predictive capacity, incorporate sediment-phosphorous interaction and pH simulation, and verify the formulations for nitrogen limited growth in order to simulate algal succession.

- Definitive sensitivity analyses of all selected models to identify the significance of model parameters and processes.

- Use of CE-QUAL-W2 and the DYRESM suite for specific water quality management studies on Inanda Dam, Vaal Barrage and Hartbeespoort Dam.

7.3 MODELLING IN GENERAL

The data intensity of physically-based, time series-driven models, such as those investigated in this project, is often of concern to water resource managers because of the consequent cost and time implications. We believe that our elementary case studies on destratification of Roodeplaat Dam and freshening releases into Vaal Barrage illustrate the worth of this level of modelling. This work confirms the promise shown in earlier simulation studies by Ninham Shand Inc. (1989) on salinity management of Laing Dam. It is unlikely that the detailed findings which such water quality management studies are required to yield could be achieved with steady-state models or rule-based approaches.

In recognition of water resource managers' legitimate concerns about data intensity on the one hand and the shortcomings of South African monitoring systems for this purpose on the other hand, we recommend that the selected models should be tested under reduced data input, such as smoothed weekly, monthly or seasonal values for the hydrometeorological input data. Such a study should assist in:

- establishing whether the intensity of data requirements of the models can be reduced without serious loss of performance,

- establishing if site-specific hydrometeorological data are essential, or whether regional data will suffice for certain input requirements, and

- identifying the significance of model variables, parameters and processes.

Future studies should lead to a specification of how model results can be used to manage water quality. If this link between model output representativeness and management benefits can be clearly made, it would aid assessment of how much money should be spent on the data monitoring network.

7.4 DATA IN GENERAL

We recommend that a shortlist of reservoirs be compiled where intensive water quality management is expected in the future and that a monitoring strategy be devised to accommodate the primary input requirements of hydrodynamic models such as those implemented in this project.

In such a strategy particular attention should be accorded to the following:

- **Wind data** : Since the wind speed is of major significance in all the selected models, careful attention should be given to the placement of wind measuring stations where possible. Periods of wind measurement should be undertaken at a height of 10 metres in order to validate the conversion of wind measured at other heights. Similarly, over water wind speeds should be measured where possible and compared with that measured over land, so that these locational effects may be quantified. It is also recommended that further research be undertaken into the over land to over water and height conversion of wind speeds.

- **In-reservoir profiles** : Key water quality variables which should be given high priority include:
  - suspended solids (and occasional fall velocities)
  - Phosphorous (soluble ortho and total)
  - Nitrogen-species (nitrate and ammonia)
  - Algal biomass, chlorophyll-a, and dominant algal species
  - Dissolved oxygen and water temperature
  - Total coliform
  - TDS and electrical conductivity

  Ideally, such variables should be measured regularly at discrete intervals throughout the depth profile. However, as a minimum data requirement, samples should be taken at the surface, mid-depth (metalimnion) and bottom waters (hypolimnion) at weekly to quarterly intervals, depending on the season. The sampling points should be positioned along the length of a water body so that longitudinal gradients in water quality can be evaluated. Single measurements taken of the surface water at the dam wall provide no useful information on longitudinal and vertical gradients. The sampling methods used in Inanda Dam by Umgeni Water represent a near ideal water quality monitoring system.

- **Water quality of inflowing streams** : Key requirements here are daily to weekly measurements of:
    - temperature
    - TDS/EC
    - nutrients
    - suspended solids.

- **Reservoir modelling databank** : The establishment of such a databank at an appropriate institution, linked to the Computing Centre for Water Research (CCWR), should be part of the monitoring strategy.

ADDENDUM 1

AVAILABILITY IN SOUTH AFRICA OF DATA REQUIRED FOR WATER QUALITY MODELLING

by

A Venter, A Görgens, A Bath and G Marais

Contents

AD 1.1 INTRODUCTION

Water quality models require a number of input variables and constants that need to be measured. These can be divided into four groups: meteorological, river flow/water quality, in-dam water quality, and reservoir constants.

- Meteorological data are air temperature, precipitation, wind speed and direction, dew point temperature/humidity, hours of sunshine, and solar radiation (shortwave radiation.

- River flow/water quality data are daily flow rate, water temperature and concentrations of dissolved oxygen, inorganic sediment, TDS, phosphate, ammonia, nitrate, BOD, and others. In any particular application only those water quality variables that are of significance to the reservoir being studied need to be supplied.

- In-dam water quality data consists of depth profiles of water temperature and concentrations of dissolved oxygen, inorganic sediment, TDS, dissolved nutrients and algal concentration.

- Reservoir constants are area/depth ratios, height of reservoir discharges, daily reservoir depth (stage), and daily discharge volumes.

- With dynamic models, meteorological and river flow/water quality data need to be supplied on a daily basis. Depth profiles of reservoir water quality variables are needed at regular intervals. The intervals will depend on the magnitude of the changes in the variables, and may range from weekly to monthly to three-monthly intervals.

There has been an extensive program for monitoring meteorological and water quality variables, for a number of years, in South Africa. Various state departments, institutions and agencies, eg. the Weather Bureau, Department of Water Affairs and Forestry, CSIR, universities and municipalities, are involved in monitoring those variables appropriate to their needs. These data are not stored in a central data bank and for this reason data acquisition can be a prolonged and laborious process at times.

AD 1.2 METEOROLOGICAL DATA

The 'National Register for Weather, Climate and Atmospheric Numeric Data Sources' (CSIR 1985) lists various institutions that measure meteorological data, as well as the specific data that are measured. The most comprehensive data banks are those of the Weather Bureau (Department of Transport) in Pretoria, and the Department of Agriculture. Limited measurements of selected meteorological variables can be obtained from municipalities, airport authorities and other agencies.

AD 1.2.1 Weather Bureau

The Weather Bureau operates 2494 rainfall stations and 208 climate stations across the country. Rainfall stations, as their name implies, measure only precipitation. Climate stations provide a spectrum of measurements depending on the classification of the station, ie. first, second or third-order (CSIR, 1985):

- **First-order climate stations** are manned by either full-time personnel or part-time weather observers. Observations are made at least three times daily: at 8h00, 14h00 and 20h00 South African Standard Time, but most of the variables are recorded autographically. Below is a list of the variables monitored, with the number of stations, where these are measured, shown in brackets:

atmospheric pressure (105)	humidity (158)
evaporation (82)	sunshine hours (101)
solar radiation (12)	cloud cover (?)
wind speed and direction (21)	

- **Second-order climate stations** are manned by volunteer observers. Air temperature measurements are made daily at 08h00 and 14h00. Humidity, sunshine hours and rainfall are recorded autographically.

- **Third-order climate stations** are manned by volunteer observers. Air temperature and rainfall are measured daily at 08h00.

A computerised listing of all climate and rainfall stations is available from the Weather Bureau. Data from these stations are available on computer print-outs or on floppy disks.

AD 1.2.2 Department of Agriculture

The Department of Agriculture has approximately 250 agro-climate stations throughout the country (CSIR, 1985). All stations record rainfall and air temperature at 08h00 daily. Where funds permit, stations are upgraded to include the measurement of evaporation, sunshine hours, wind speed, humidity and solar radiation.

The Department of Agriculture has computerised all historic and present data and these are available on an online databank. The databank also contains rainfall data as measured by the Weather Bureau, and evaporation data measured by the Department of Water Affairs and Forestry. Data can be obtained by making a formal request to the Director of the Regional centres and/or Pretoria head office.

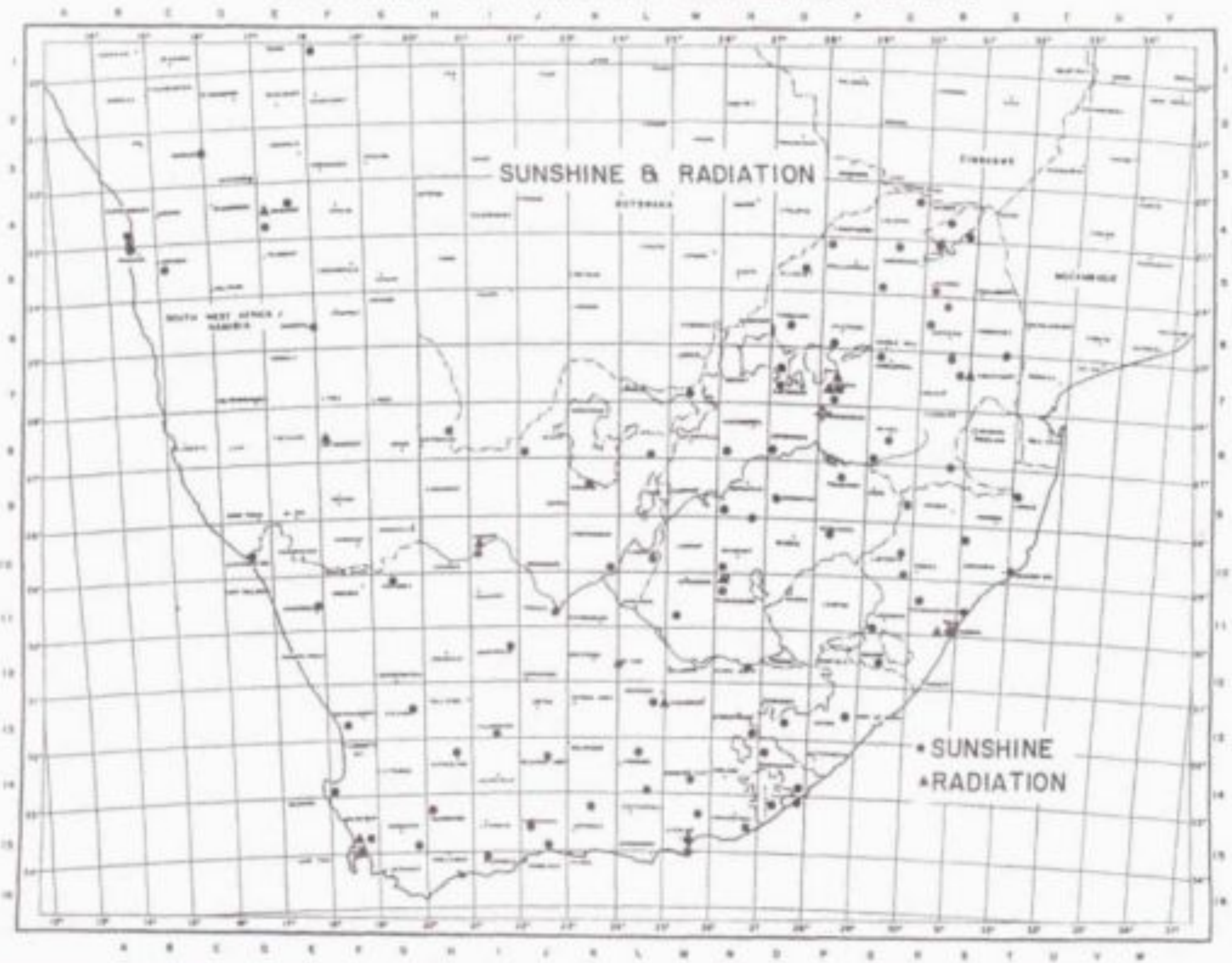
AD 1.2.3 Other sources of meteorological data

Various other institutions, eg. municipalities and airports, carry out measurements of specific meteorological variables of importance to their function. For example, the Division of Water Technology has meteorological data on Hartebeespoort Dam, while the Hydrological Research Institute (Department of Water Affairs and Forestry) has meteorological data on Roodeplaat Dam. The sources for the data sets are listed in the National Register mentioned earlier.

AD 1.2.4 Data utilisation

Only a few of the meteorological monitoring stations provide a complete set of data required for modelling purposes. For example, two variables of prime importance to modelling, are solar radiation and wind speed/direction; the Weather Bureau measures solar radiation at only 12 stations, and wind speed/directions at only 21 stations. A map indicating the locations where solar radiation is monitored, is shown in Figure AD 1.1. Evidently the distributions are sparse, so that almost invariably, when solar radiation and wind speed/direction at a particular site are to be estimated, interpolation is required. Interpolation of solar radiation can give reasonably acceptable data sets, but with regard to wind speed, aerial topography and the general greater variability of the wind pattern will result in estimates of relatively low reliability. Measurements from second and third order climate stations, agricultural stations, and various other agencies, even though partial, might be of assistance in checking, indirectly, estimates of other variables made from first order station data.

DEPARTMENT OF TRANSPORT - S.A. WEATHER BUREAU



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Map indicating sampling locations for sunshine and solar radiation measurement

FIGURE AD 1.1

AD 1.3 RIVER WATER QUALITY AND FLOW RATE DATA

AD 1.3.1 Water quality data

River water quality is monitored mainly by the Department of Water Affairs and Forestry. Local and regional authorities such as municipalities and regional waterboards (eg. Umgeni water in Natal) operate monitoring programs in specific localities/areas.

Sample collection, as done by the Department of Water Affairs and Forestry, commenced during the 1950's and routine sampling at a large number of sites was initiated during the early 1970's. Currently, most of the registered sampling sites in a country-wide monitoring network are sampled routinely for a variety of water quality variables, at intervals which vary from daily to weekly to monthly (DWAF, 1991). These variables are listed in Table AD 1.1.

TABLE AD 1.1 : WATER QUALITY VARIABLES MONITORED BY THE DEPARTMENT OF WATER AFFAIRS AND FORESTRY IN RIVERS AND RESERVOIRS

CHEMICAL VARIABLES	PHYSICAL VARIABLES	
Rivers and Reservoirs	Rivers	Reservoirs
pH	Conductivity	Conductivity
Calcium	Water temp.	Water level
Magnesium		Sampling depth
Potassium		Water temp.
Sodium		
Chloride		
Fluoride		
Silicon		
Sulphate		
Total Phosphorus (as P)		
Ortho-phosphate (as P)		
Ammonium (as N)		
Nitrate plus Nitrite (as N)		
Total Kjeldahl Nitrogen (as N)		
Dissolved organic carbon (as C)		
Total alkalinity ($H_2CO_3^*$alkalinity)		
Total dissolved salts (TDS)		

Historically, not all of these variables have been measured at all the measuring sites. An important variable, often omitted at specific sites, is river water temperature. It should also be noted that local and regional authorities often monitor a more extensive set of variables.

The various sites where sampling is undertaken by the Department of Water Affairs and Forestry are listed in a technical document entitled 'TR 146 - Water Quality Data Inventory', published by the Department of Water Affairs and Forestry in 1991 (DWAF, 1991). This document also provides sampling site locality maps, and sampling site information. Sampling site information is presented in the form of an information sheet for each site (*cf.* Figure AD 1.2)

The data acquired from the various sampling sites are stored in the Hydrological Information System (HIS) on a mainframe computer of the Department of Water Affairs and Forestry in Pretoria. Data can be obtained by direct access to the database on the main frame computer for users in possession of the required access codes. Data can also be obtained by writing to the Director General, Department of Water Affairs and Forestry, Private Bag X313, Pretoria, 0001. The format in which the data are required must be specified. Data are available in the following formats (DWAF, 1991):

- Printouts (hard copies)
- Magnetic tapes (must be supplied)
- Floppy disks (must be supplied)

AD 1.3.2 River flow rate data

River flow rate data are monitored by the Department of Water Affairs and Forestry. Information on flow rate measuring sites can be obtained from technical document, TR 146, described in the previous paragraph (DWAF, 1991). Alternatively, the various flow rate measuring sites are listed in a document entitled 'List of Hydrological Gauging Stations - July 1990', published by the Department of Water Affairs and Forestry (DWAF, 1990). River flow rate data are stored in the Hydrological Information System on the main frame computer of the Department of Water Affairs and Forestry in Pretoria. The procedure for obtaining data is the same as that for river water quality data.

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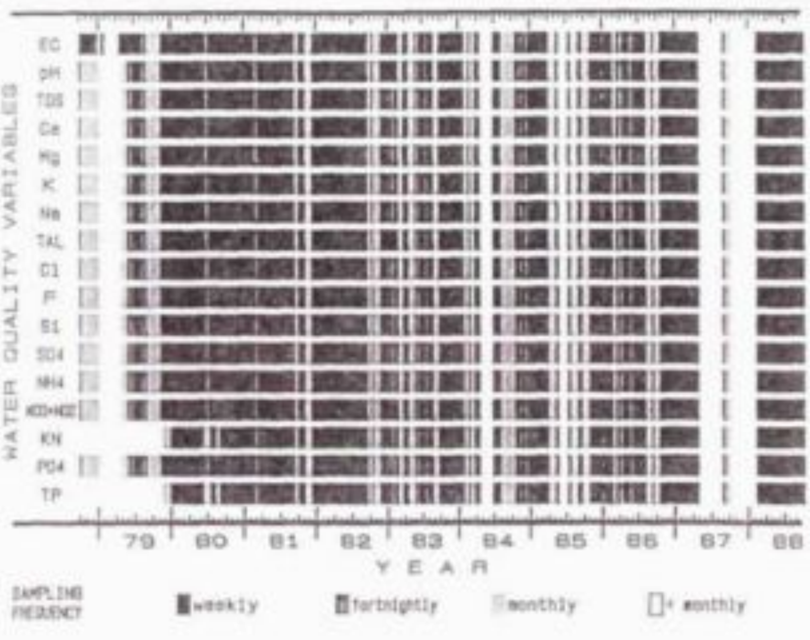
HARTEBEES SPRUIT AT KAMEELDRIFT



OLD STATION NUMBER	: A2H28

LOCATION

LATITUDE AND LONGITUDE	: 25 39'03" 28 19'10"
TERTIARY DRAINAGE REGION No.	: 123

DESCRIPTION OF CATCHMENT

CATCHMENT AREA (km^2)	: 161
CALCULATED MEAN ANNUAL RUNOFF (10^6 m^3)	: 9
MAIN TRIBUTARIES UPSTREAM	: --
MAIN RESERVOIRS UPSTREAM	: --

DESCRIPTION OF MONITORING STATION

TYPE	: GAUGING WEIR
AUTOMATIC FLOW RECORDER (Y/N)	: Y

SAMPLING

DATE OF FIRST SAMPLE ANALYSED	: 67/05/10
DATE OF LAST SAMPLE ANALYSED	: 89/08/29
TOTAL NUMBER OF SAMPLES ANALYSED	: 2315
CURRENT SAMPLING FREQUENCY (Daily, Weekly, Monthly, Quarterly)	: W

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Information sheet with sampling site information

FIGURE AD 1.2

AD 1.4 RESERVOIR WATER QUALITY

Surface sampling of reservoirs is done routinely by the Department of Water Affairs and Forestry as part of its country-wide monitoring network described in Section AD 1.3. However, for modelling of water quality, depth profiles of water quality variables are essential. (Depth profiles specific to the reservoir are needed to start the simulations, calibrate and verify the model, and to check model performance under inputs provided. Profiles at monthly intervals are adequate.) Depth profile measurements are not undertaken routinely. Depth profiles on specific dams appear to be taken only if research is being undertaken on the reservoir(s) by research institutions, or if a specific water quality problem is being monitored:

- In the late seventies a study of the water quality and limnological characteristics involving 21 South African reservoirs was commissioned by the Water Research Commission and The National Institute for Water Research (CSIR). The reservoirs that were sampled, the sampling period, and frequency of sampling are indicated in Table AD 1.2. A great number of water quality variables were sampled, but mostly at the surface. Depth profiles were taken on only two variables, water temperature and dissolved oxygen. The unprocessed data are available in hard copy from the Water Research Commission and the Division of Water Technology, CSIR (Walmsley and Butty, 1980).

- The Division of Water Technology at the CSIR has done extensive research on Hartbeespoort Dam; depth profiles of several water quality variables were measured over extensive periods. Data are available on floppy disk.

TABLE AD 1.2 : RESERVOIRS SAMPLED, SAMPLING PERIOD AND FREQUENCY IN A STUDY OF 21 RESERVOIRS

RESERVOIR	STUDY PERIOD	SAMPLING FREQUENCY
Bospoort	Aug 77 - Jul 78	Fortnightly
Bronkhorstspruit	Aug 77 - Jul 78	Fortnightly
Buffelspoort	May 75 - May 76	Weekly
Lindleyspoort	May 75 - May 76	Weekly
Loskop	Aug 77 - Jul 78	Fortnightly
Olifantsnek	Aug 77 - Jul 78	Fortnightly
Rust der Winter	Aug 77 - Jul 78	Fortnightly
Tonteldoos	Jan 76 - Jan 77	Weekly/fortnightly
Doringpoort	Aug 77 - Jul 78	Fortnightly
Bloemhof	Sep 77 - Oct 78	Monthly
Rietvlei	Jan 76 - Jan 77	Weekly
Roodeplaat	Dec 77 - Dec 78	Fortnightly
Albert Falls	Nov 77 - Nov 78	Fortnightly
Hazelmere	Nov 77 - Nov 78	Fortnightly
Henley	Nov 77 - Nov 78	Fortnightly
Midmar	Nov 77 - Nov 78	Fortnightly
Nagle	Nov 77 - Nov 78	Fortnightly
Vernon Hooper	Jan 76 - Jan 77	Fortnightly
Bridle Drift	Aug 77 - Aug 78	Fortnightly
Laing	Nov 77 - Nov 78	Fortnightly
Nahoon	Aug 76 - Aug 77	Weekly/fortnightly

- The Hydrological Research Institute at Roodeplaat Dam, which forms part of the Department of Water Affairs and Forestry, has made extensive measurements on Roodeplaat Dam. Data from monthly surface measurements of the chemical variables, listed in Table AD 1.1, are available on floppy disk. Monthly depth profiles of reservoir temperature and dissolved oxygen are also available, but these profiles are measured only down to the thermocline.

- The Rand Water Board routinely measures depth profiles of several water quality variables in the Vaal Dam system.

- Umgeni Water routinely monitors depth profiles of an extensive set of variables.

- Data can also be obtained from various universities conducting research on specific reservoirs. The Hydrological Research Institute (Department of Water Affairs and Forestry) at Roodeplaat Dam may know whether or not research data exist for a specific reservoir.

AD 1.5 RESERVOIR CONSTANTS

For modelling purposes the following data on the physical structure of the reservoir are required: Area/depth ratios, height of reservoir discharge, reservoir water level (stage), and daily discharge volume. These data are available from the Department of Water Affairs and Forestry.

AD 1.6 CONCLUSIONS

Data sets developed by the various agencies are usually designed with specific objectives in mind. Data sets developed by the Weather Bureau and Department of Water Affairs and Forestry would be comprehensive as it is accepted that their data are to be utilised by users with disparate objectives. However, even with these, it is possible that new objectives can be identified which require information not within the set being measured. For modelling hydrodynamic and water quality behaviour the data sets from the Weather Bureau and The Department of Water Affairs and Forestry are deficient, either in the omission of a particular variable or because they do not have the required density of measurement demanded for adequate developing and checking of models.

The main deficiency in reservoir water quality data is that all the variables required in the depth profiles are not measured. Usually only water temperature and dissolved oxygen are profiled. In some instances, for example Roodeplaat Dam, these variables are only measured down to the thermocline.

Considering the meteorological data, measurement of the surface wind speed is at a 1.8 m height above ground level instead of 10 m as is used in most other countries. Not only do different models require wind speed measurements at different heights, some models require wind speed to be measured over land, while others require wind speed to be measured over the water surface. Most of the modern hydrodynamic models indicate that the modelled response is very sensitive to wind speed. It is very important therefore that the measured wind speeds are in compliance with model requirements. Two different methods for adapting wind speed with height, as well as a method for adapting wind speed measured over land to wind speed over water, are discussed in Addendum 2.

Although complete or near complete data sets are available at a restricted number of locations, often these locations will be relatively far removed from the water bodies being studied. Locations generating partial data sets are more widely distributed, but these may be of little help if the data set does not contain variables that have a substantive influence on the hydrodynamic and water quality behaviour of the water body.

In a number of instances, the format in which the data sets of particular variables is presented is not user-friendly, so that specific individual sets require considerable manipulation to convert to a format that is compatible with modelling requirements. There appears to be a need to standardise the data presentation from various agencies into a mutually agreed format.

The units of measurement by different agencies have also been found to be different: The Weather Bureau presents solar radiation in $(\text{Mjoule/m}^2)*100$, whereas the Department of Water Affairs and Forestry (HRI at Roodeplaat Dam) presents solar radiation in Watt-hr/m^2. It would be an advantage if all measurements were done according to agreed (SI) units. As it is, considerable confusion can be generated, requiring unnecessary effort to convert standard units of measurement to the non-standard unit expressions often used in models developed in different countries.

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ADDENDUM 2

WIND SPEED MEASUREMENT

by

A Venter and G Marais

Contents

AD 2.1 INTRODUCTION

Wind speed is a function of height, as well as of surface roughness. Two formulae are generally used to adapt wind speed measurements with height: the Power Law formula and the Logarithmic formula. Wind speed measured over land can be adapted to wind speed over water at the same height by using a relationship between the fetch and the roughness factors for land and water surfaces.

AD 2.2 THE POWER LAW

The power law was first used in 1880 to describe the change in wind speed with height (Bruetsaert, 1970). The power law was derived empirically and gives a good approximation of the variation of wind speed with height, provided the terrain is horizontally homogeneous (Ciria, 1971). According to the power law (Le Gourieres, 1982):

$$\frac{V}{V_o} = \left(\frac{H}{H_o}\right)^n \qquad (1)$$

V_o	=	measured wind speed at height H_o
V	=	wind speed at height **H**
n	=	a constant dependent upon roughness of terrain

Different values of n for different terrains is given in Table AD 2.1.

TABLE AD 2.1 : VALUES OF THE POWER LAW EXPONENT *n* FOR VARIOUS TERRAINS (CIRIA, 1971)

Type of terrain	*n*
Water surface, eg. oceans and lakes	0.14
Open terrain with few obstacles, eg. desert or open grass	0.16
Terrain uniformly covered with obstacles 10 to 15 m in height, eg. small towns, small fields with bushes trees and hedges.	0.28
Terrain with large and irregular objects, eg. centres of large cities, very broken country with many tall trees.	0.40

In the Power Law (Equation 1), the value of n is constant for a given application. However, the value of n has been found to change with height (Geiger, 1965), therefore the Power Law only gives an approximation of the wind profile. Conditions under which the Power Law will give realistic results can be summarised as follows (CIRIA, 1971):

> "Provided the terrain is reasonably level, and of sufficiently uniform surface roughness to allow a state of dynamical equilibrium to be established between the drag and the stirring action of the surface and the steady flow at high level determined by the isobar map,the variation of mean wind speed with height in neutral stability (high wind) conditions can be satisfactorily represented by a simple power law."

If a model is sensitive to wind speed, the Power Law is likely to be inadequate.

AD 2.3. THE LOGARITHMIC LAW

The Logarithmic Law is based on Prandtl's Logarithmic Law that states that the flow of air over a surface, ie. wind speed over a certain terrain, is expressed by (Simiu and Scanlan, 1986):

$$V = \frac{u_*}{k} \ln(\frac{H}{z_o}) \qquad (2)$$

V = wind speed at height H above the surface

u_* = wind shear velocity

k = Von Karman's constant (0.4)

z_o = roughness length

The shear velocity is indicative of the amount of turbulence and its value is independent of height for a given profile. The roughness length is a function of the roughness of the surface and is also independent of height for a given profile. It is determined empirically and has the dimensions of length, thereby expressing the roughness of the terrain as a numerical value. Different values of the roughness length for different terrains are given in Table AD 2.2.

Using Prandtl's law as a basis, the variation of wind speed with height for a given terrain can be expressed as:

$$\frac{V}{V_1} = \frac{\ln(\frac{H}{z_o})}{\ln(\frac{H_1}{z_o})} \qquad (3)$$

V_1 = wind speed measured at height H_1

V = wind speed at the required height H

z_o = roughness length (from Table AD 2.2)

TABLE AD 2.2 : VALUES OF SURFACE ROUGHNESS LENGTH z_o IN THE LOGARITHMIC LAW (SIMIU AND SCANLAN, 1986)

Type of surface	z_o (cm)
Sand	0.01 - 0.1
Snow surface	0.1 - 0.6
Mown grass (~0.01 m)	0.1 - 1
Low grass, steppe	1 - 4
Fallow field	2 - 3
High grass	4 - 10
Palmetto	10 - 30
Pine forest (mean height of trees: 15 m; one tree per 10 m^2)	90 - 100
Sparsely built-up suburbs	20 - 40
Densely built-up suburbs, towns	80 - 120
Centres of large cities	200 - 300

AD 2.4 ADAPTING WIND SPEED FROM LAND TO WATER SURFACE

Apart from the height where wind speed is required, it is also important to determine whether a particular model requires wind speed to be measured over land, or at the water surface. Some models, eg. MINLAKE, incorporate the adjustment of wind speed from land to water surface, whereas other models, eg. DYRESM, require the user to adapt the wind speed as part of the meteorological data.

The relationship between wind speed over land and wind speed over water, at the same height, is expressed by (Ford and Stefan, 1980):

$$V_w = V_{10} \frac{\ln\frac{H}{z_2} \ln\frac{z_b}{z_1}}{\ln\frac{H}{z_1} \ln\frac{z_b}{z_2}} \qquad (5)$$

V_w	=	wind speed at the water surface ($m.s^{-1}$)
V_{10}	=	wind speed measured over land at a height of 10 metres
z_2	=	surface roughness of the water (~ 0.0001 m)
z_1	=	surface roughness of the land in metres (from Table AD2.2)
z_b	=	equivalent boundary layer over the water

The equivalent boundary layer over the water is expressed by (Elliot 1958):

z_b	=	$0.86(\text{Fetch})\ z_1^{0.23}$
z_b	=	equivalent boundary layer over water
Fetch	=	fetch of the wind over the water surface *(m)*
z_1	=	surface roughness of the land *(m)*

AD 2.5 REFERENCES

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