VALIDATION OF THE MODIFIED MINLAKE MODEL ON ROODEPLAAT DAM

A Venter • CE Herold

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VALIDATION OF THE MODIFIED MINLAKE MODEL ON ROODEPLAAT DAM

FINAL REPORT

to the

WATER RESEARCH COMMISSION

by

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"Validation of the modified Minlake model on Roodeplaat Dam"

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

Mr H M du Plessis	Water Research Commission (Chairman)
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EXECUTIVE SUMMARY

BACKGROUND

Eutrophication has been identified as a serious water quality problem in South Africa. Selection of the most appropriate management techniques to decrease the negative impact of eutrophication, as well as prediction of the effectiveness of possible treatment options, is difficult because the interactions between the processes that cause eutrophication are very complex. Also, as each impoundment is unique in the way it will react to the various factors that contribute to eutrophication, a management strategy that was effective at one impoundment may not be effective at another, i.e. each impoundment must be evaluated in its own right.

AIMS OF STUDY

The aims of the project were as follows:

1. To validate the MINLAKE reservoir water quality model with regard to its ability to predict the trophic response of a reservoir to:

   - hydrological and climatic conditions different from those for which the model was calibrated
   - altered nutrient inputs.

2. To evaluate the confidence with which the MINLAKE model can be used by water managers to predict the results of management options.

LEVEL OF STUDY

The study has been carried out at a low cost reconnaissance level.

THE MODIFIED MINLAKE MODEL

Valuable information about the trophic behaviour of a particular impoundment can be obtained by simulating the hydrodynamic and water quality behaviour of the impoundment with the aid of a mathematical model. One such a model is the modified MINLAKE model. It is a one-dimensional water quality model that was originally developed at the University of Minnesota in the USA. The model has been extensively applied to various lakes and impoundments in the northern USA. However, the northern USA has a cold temperate climate, whereas the climate in South Africa is warm temperate to subtropical. Thus the original model had to be modified before it could simulate the water quality of a typical South African reservoir (Roodeplaat Dam near Pretoria). The modifications relate mostly to the climatic differences. For instance, the higher water temperature of dams situated in a warm temperate climate causes biological rates such as bacterial decomposition of organic matter to increase. This results in more rapid hypolimnetic oxygen depletion (and thus greater internal cycling of nutrients) than would be the case for a dam with a similar concentration of organic matter, but situated in a cooler region (Henderson-Sellers 1984). The aerobic/anaerobic state of the water therefore affects a great number of in-dam processes. In fact, according to Mortimer (1942) dams where the hypolimnion becomes anaerobic should be considered fundamentally different from dams where the hypolimnion does not become anaerobic. The original MINLAKE model did not make provision for the effect of the aerobic/anaerobic state of the water on process rates, probably because this affect was not considered important in the cold temperate climate where the model was developed. However, it was not possible to simulate the water quality behaviour of Roodeplaat Dam until the original MINLAKE model had been modified to take cognisance of the affect of the aerobic/anaerobic state of the water on process rates (Venter 1996).

The modified MINLAKE model not only provides for the effect of the aerobic/anaerobic state of the water on process rates, it also is the only one-dimensional water quality model that has been calibrated on a South African impoundment and that can simulate algal succession (Venter 1996). Hence it has the potential to be used as a tool in assessing the effectiveness of treatment options aimed at changing blue-green algal dominance to dominance by green algae. However, the model needed to be validated before it could be used to predict future events. The need for validation stems from the following:

- Impoundments are not static and the complexity of the processes is such that if a model is formulated to mimic the dynamic state of an impoundment in detail, the resultant model must of necessity be complex. The greater the complexity of a model, the greater is the inherent uncertainty associated with the predictions (Jorgensen 1980). Thus the mathematical representation of some processes that are regarded as relatively static (or less dynamic) such as for instance, sediment nutrient release rate, are simplified by the use of constants and/or calibration coefficients. Though the simplified expression may mimic the process adequately over the short term, there may be long term changes in the process that may invalidate the simplified expression because of the constants that were used.

- There is an inherent uncertainty, or error, associated with the calibration coefficients that have to be specified during calibration of the model. If a calibrated model is used to predict future events, these uncertainties are propagated as a certain degree of error, or uncertainty in future predictions. There is thus no guarantee that the validity of a model extends beyond the data set against which it has been calibrated, until knowledge is obtained as to how errors of estimation of calibration coefficients affect the model predictions about the future behaviour of an impoundment.

SELECTION OF STUDY CATCHMENT

Validation studies are often prohibited because of the time and money involved, as well as scarcity of data. An ideal opportunity for validation of the MINLAKE model was presented by the extensive data record that existed for Roodeplaat Dam. The record at this dam also provided a unique opportunity to evaluate the effect of the reduction in inflow phosphate load following the introduction of the 1 mg phosphate standard, and whether the model would have been able to predict the outcome of this particular management option correctly.

DATA COLLECTION AND PROCESSING

The daily data required to run the modified MINLAKE model were collected and assessed. In some instances, the data base was surprisingly good. Minimum infilling of river inflow water quality data had to be done. Meteorological data presented the biggest problem. Although the required data were available, it was of poor quality and extensive infilling of meteorological data was required. The quality of in-dam data was good, as sampling was done on a regular basis in the epilimnion as well as the hypolimnion, thereby enabling comparison of simulated and observed results at various depths in the impoundment.

SELECTION OF VALIDATION PERIOD

After assessment of the data it was decided that the most suitable validation period would be October 1988 to January 1990, a period of 15 months. The databases required by the model were constructed, and, where infilling of data was necessary, the methodology that was developed during calibration of the model was followed.

CONCLUSIONS

The model simulated the hydrodynamic behaviour of Roodeplaat Dam during the validation period well. The validation results also showed that the model was able to predict the degree of change in phosphate concentration that occurred from the calibration to the validation period as a result of implementation of the 1 mg phosphate standard. Prediction of the degree of change in chlorophyll-a concentration, as well as ammonia and nitrate concentration, was less successful. This significantly decreases the potential use of the model to predict future trophic conditions in an impoundment.

The poor performance of the model in predicting the trophic response of the reservoir to the change in nutrient input rate is thought to be attributable to the simplistic modelling of sediment nutrient release rate. However, the possibility of an incorrect combination of coefficients selected for other model parameters cannot be ruled out. For instance, none of the coefficients relating to simulation of the nitrogen budget had been determined for Roodeplaat Dam, thus values from literature studies had to be substituted. It is possible that these values are not the optimal values for Roodeplaat Dam.

RECOMMENDATIONS

Model applications

Although the model cannot be used to predict *future* trophic conditions, it still has many other uses. For instance, one of the greatest strengths of the modified MINLAKE model is its use to determine the relative importance of the various factors that may limit current algal growth in a particular impoundment (Venter 1996). This can assist the water manager to make an informed decision as to the treatment method that would be most appropriate and cost-effective. The model can also be used as an aid to determine the relative importance of the pollution loads that enter the impoundment, and to show to what extent the current water quality in the reservoir will be altered by changing loads from these sources. The possibility and effectiveness of improving water quality by switching between water sources, altering release patterns, or importing better quality raw water, as well as the best time to import raw water, can also be evaluated with the aid of a model such as the modified MINLAKE model.

The model can also be effective in assisting in the setting of water quality standards. Some reservoirs are able to tolerate a higher pollutant load than others, and thus the trophic response of a reservoir should serve as a measure for setting water quality guidelines for the inflowing rivers. The trophic response of a reservoir is best determined by using a model such as the modified MINLAKE model, which takes account of all the main factors that affect the trophic response of the reservoir.

Monitoring of water quality and meteorological data is very expensive. Hence the frequency of measurement should be reduced to the minimum necessary for the efficient operation of a reservoir. Monitoring programmes can be designed and optimised by the use of an appropriate water quality model. The relative importance of different water quality and meteorological variables can be determined with the aid of the model. For instance, during calibration of the MINLAKE model it was found that the effect of wind on the behaviour of the impoundments is much more significant than the effect of radiation or humidity. The cost effectiveness of the monitoring programme can be further increased by using the model to determine the optimum monitoring frequency, and in the case of reservoir profile data, optimum depth of measurement.

From the above it can be concluded that, although the model cannot be used with confidence to predict the future behaviour of an impoundment, there still is significant scope for using a model such as the modified MINLAKE model for a multitude of practical applications.

Further research

The following further research is recommended allow the Minlake model to be used with greater confidence.

1. Investigations are required to gain a better understanding of both the short and long term processes governing nutrient release and uptake by sediments under local conditions.

2. The constant rate sediment release algorithms used in the MINLAKE model need to be replaced by a more appropriate sub-model capable of simulating the dynamics of the processes involved.

3. Further work is required to better determine the most appropriate ranges and combinations for the host of model calibration values, especially the values relating to nitrogen simulation.

1. INTRODUCTION

1.1 Background

In this study eutrophication is defined as the enrichment of a water body with nutrients such as phosphates and nitrogen, resulting in excessive algal growth. Eutrophication has been identified as a serious water quality problem in South Africa (DWAF 1985).

A number of processes can contribute to excessive algal growth in an impoundment. These processes are affected by nutrient concentration, light, water temperature, meteorological factors such as wind speed, and morphological factors such as the size, shape and depth of the impoundment. The interaction between the processes are very complex, making the selection of the most appropriate management technique to decrease excessive algal growth, as well as prediction of its effectiveness, very difficult.

The water quality manager can obtain valuable information about the trophic behaviour of a particular impoundment by simulating its hydrodynamic and water quality behaviour with the aid of a mathematical model. One such a model is the one-dimensional modified MINLAKE model. The original MINLAKE model was developed by the St Anthony's Falls Hydraulic Laboratory at the University of Minnesota, USA (Hanson *et al* 1987, Riley 1988). During a previous Water Research Commission project (Venter 1996) it was found that, because of climatic differences between Minnesota (cold temperate climate) and South Africa (warm temperate/subtropical climate), the water quality part of the model had to be modified before it could simulate the water quality behaviour of a typical South African impoundment (Roodeplaat Dam near Pretoria). The modifications related mainly to the effect of the aerobic/anaerobic state of the water on the rates of a number of processes that take place in an impoundment. (For instance, the rate of denitrification is must faster under anaerobic conditions). The original MINLAKE model did not make provision for simulation of the effect of both aerobic and anaerobic conditions during the simulation period, probably because this effect is not very pronounced in the colder climate where the model was developed, whereas anaerobic conditions develop more readily in impoundments situated in a warm climate. The process of denitrification also was not included in the original model. Denitrification has a pronounced effect on the nitrogen budget of South African impoundments (Ashton 1981). Once these shortcomings had been rectified, the model was well able to simulate the water quality behaviour of Roodeplaat Dam.

The modified MINLAKE model is the only one-dimensional water quality model, calibrated on a South African impoundment, that can simulate algal succession (Venter 1996). Thus it has the potential to be used as a tool in assessing the effectiveness of treatment options aimed at changing blue-green algae dominance to dominance by green algae. However, neither the modified MINLAKE model, nor any other water quality model being used in South Africa, has been validated, and a model should be validated before it is used to predict future events. The need for validation is twofold:

- Impoundments are not static and the underlying processes are complex. The model formulations required to mimic the dynamic the dynamic state of an impoundment in detail therefore must of necessity be complex. The greater the complexity of a model, the greater is the inherent uncertainty associated with the predictions (Jorgensen 1980). Thus the mathematical representation of some processes that are regarded as relatively static (or less dynamic) such as for instance, sediment nutrient release rate, are simplified by the use of constants. However, even though the simplified expression may mimic the process adequately over the short term, there may be long term changes in the process that may invalidate the simplified expression because of the constants that were used.

- During calibration of a model, several calibration coefficients have to be specified. The values of these coefficients are determined by field measurements, or else taken from the literature. If a calibrated model is used to predict future events, the inherent errors associated with field measurements, and the uncertainty associated with literature values, are propagated forward as a degree of uncertainty, or error in the predictions. Some calibration coefficients may have a large degree of uncertainty which may not be visible during the calibration period, but may become important during future predictions, because of changing conditions. This would produce model predictions with a wide range of uncertainty, greatly reducing confidence in model output and hence the usefulness of the model. There is therefore no guarantee that the validity of a model extends beyond the sample data set against which it has been calibrated, until knowledge is obtained as to how errors of estimation of calibration coefficients affect the model predictions about the future behaviour of a impoundment. During model validation, the values of the coefficients specified during calibration are retained, but the model is run with a set of input data for a time period that is sufficiently removed from the calibration period to ensure different hydrological and climatic or nutrient input conditions from those for which the model was calibrated.

Validation studies are often prohibited because of the time and money involved, as well as scarcity of data (Orlob 1983). An ideal opportunity for validation of the MINLAKE model was presented by the extensive data record that existed for Roodeplaat Dam (see Figure 1.1). The record at this dam also provided an unique opportunity to evaluate the effect of the reduction in inflow phosphate load following the introduction of the 1 mg phosphate standard, and whether the model would have been able to predict the outcome of this particular management option correctly.

Successful validation of the model would greatly extend its usefulness, resulting in a model that can be used with confidence by water managers to:

- evaluate the effectiveness of different management techniques; and
- compare different treatment options aimed at maintaining or improving future water quality.

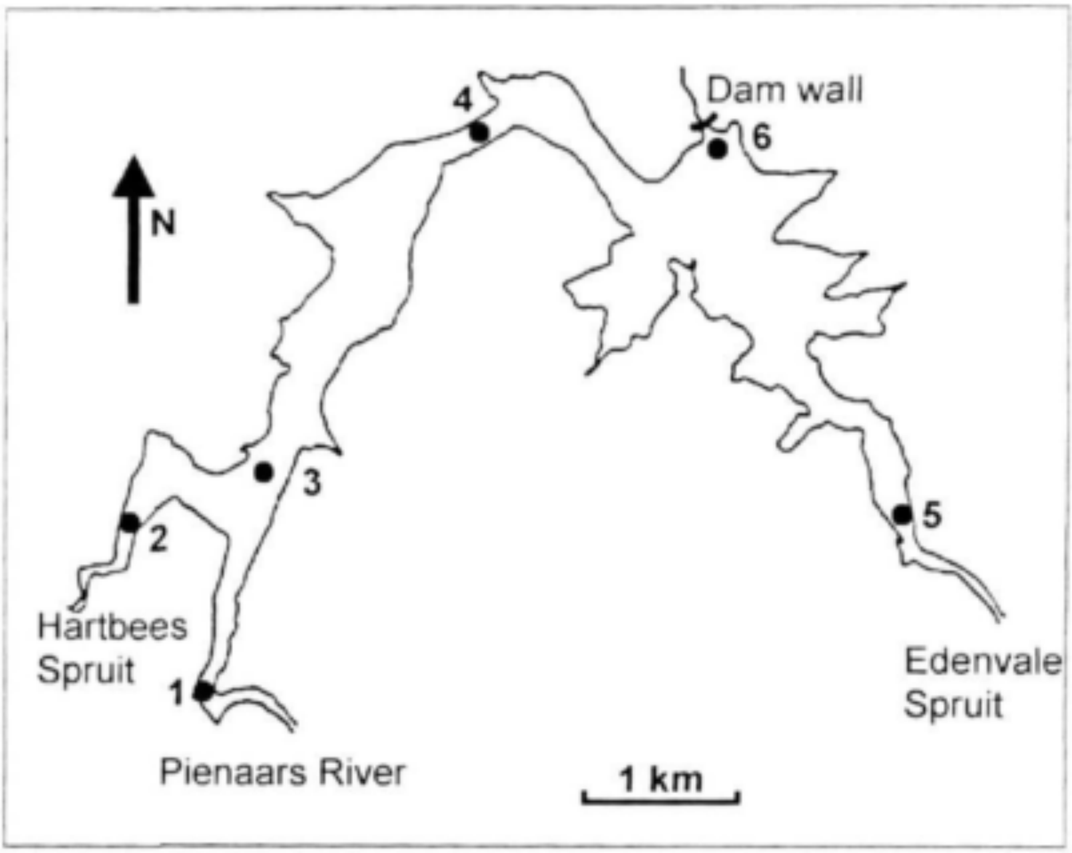

Figure 1.1
Map of Roodeplaat Dam indicating monitoring points and rivers flowing into the dam

1.2 Aims of study

The aims of this study were to:

1. validate the modified MINLAKE reservoir water quality model with regard to its ability to predict the trophic response of a reservoir to:

   - hydrological and climatic conditions different from those for which the model was calibrated; and
   - altered nutrient inputs.

2. evaluate the confidence with which the MINLAKE model can be used by water managers to predict the results of management options.

1.3 Approach

The first step was to select a suitable validation period. The MINLAKE model was calibrated for the period October 1980 to October 1982. The validation period must be sufficiently removed from the calibration period to enable testing of the stability of the model with regard to different meteorological and hydrological conditions.

After selection of a suitable validation period, the data required by the modified MINLAKE model was collected from various institutions, such as the Institute for Water Quality Studies at Roodeplaat Dam and the Weather Bureau. Selection of the validation period and collection of data are discussed in Chapter 2.

The original MINLAKE model requires data on a daily basis. Although it has been shown that the data output of the modified model is not significantly affected by changing the input frequency of some variables from daily to weekly or even monthly during calibration (Venter 1996), there was uncertainty as to whether the change in input frequency would be as insignificant when using the model for prediction of future conditions. Consequently, daily data were also used for validation of the model. Infilling of data had to be done as continuous daily time sequences were not always available. Infilling of data is discussed in Chapter 3.

The validation results are presented and interpreted in Chapter 4 in the form of time-series graphs, depth profiles, and duration curves. Conclusions and recommendations are given in Chapter 5.

2. DATA COLLECTION

2.1 Introduction

Before the data required to validate the MINLAKE model could be collected, a suitable validation period had to be selected. The MINLAKE model was originally calibrated on Roodeplaat Dam for the period October 1980 to October 1982. To validate of the model, one or more suitable periods had to be selected from among the following:

- A period prior to implementation of the 1 mg/l Phosphate Standard, but suitably removed from the calibration period, to test the stability of the model with regard to different meteorological and hydrological conditions.

- A period subsequent to implementation of the 1 mg Phosphate Standard to test the ability of the model to predict the effect of changing nutrient inputs on the trophic response of the reservoir.

- A period subsequent to commissioning of the Zeekoegat Waste Water Treatment Works discharging into the impoundment.

2.2 Selection of the validation period

The first step in selecting a suitable validation period was to asses the ortho-phosphate and chlorophyll-a concentrations in Roodeplaat Dam from 1980 (start of the calibration period) to present.

Surface ortho-phosphate concentrations as monitored near the impoundment wall in Roodeplaat Dam for the period April 1980 to December 1994 are shown in Figure 2.1. From this figure it is evident that there was a sharp decrease in surface ortho-phosphate concentration from about October 1984. However, this decrease cannot be attributed to implementation of the 1 mg/l Phosphate

Standard, as this standard was implemented in the Roodeplaat Dam catchment only in August 1988.

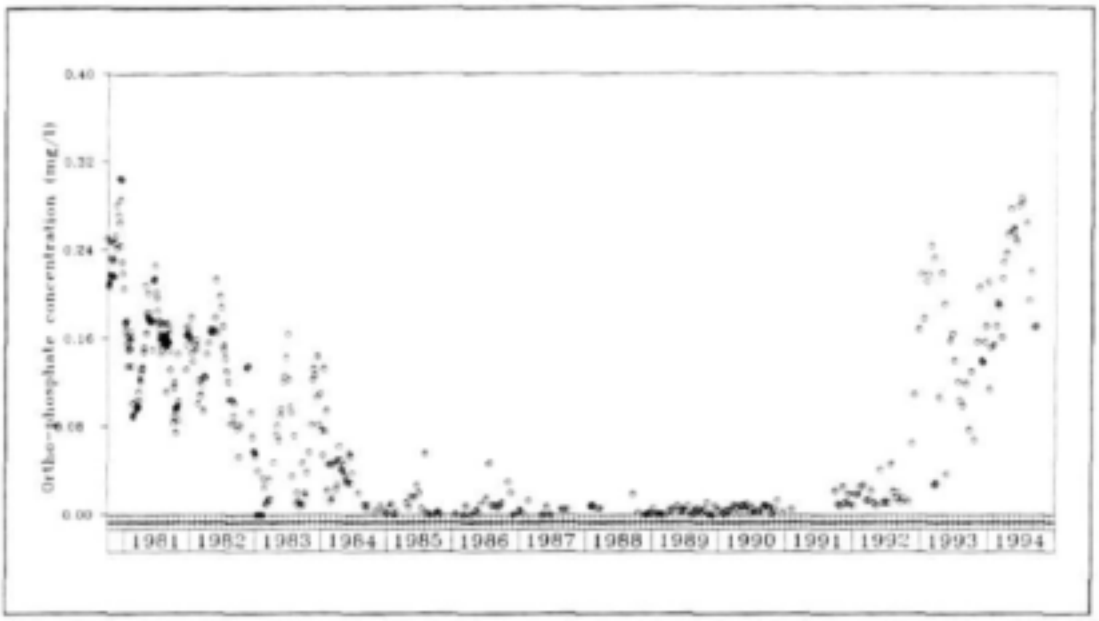

Figure 2.1
Time-series graph of surface ortho-phosphate concentration as measured in Roodeplaat Dam near the dam wall for the period October 1980 to September 1994

The effect of the Phosphate Standard is marked by a small reduction in the surface ortho-phosphate concentration from about October 1988 to 1991, compared with the period January 1985 to September 1988. Unfortunately data for the period October 1987 to September 1988 are scarce. From October 1991 onwards the concentration increased slightly, with a very significant increase from October 1992 onwards. This can probably be attributed to the commencement of discharge from the Zeekoegat Sewage Treatment Works directly into the Pienaars River limb of the impoundment near to the dam wall.

The surface chlorophyll-a concentrations as measured near the impoundment wall for the period January 1980 to December 1993 are shown in Figure 2.2.

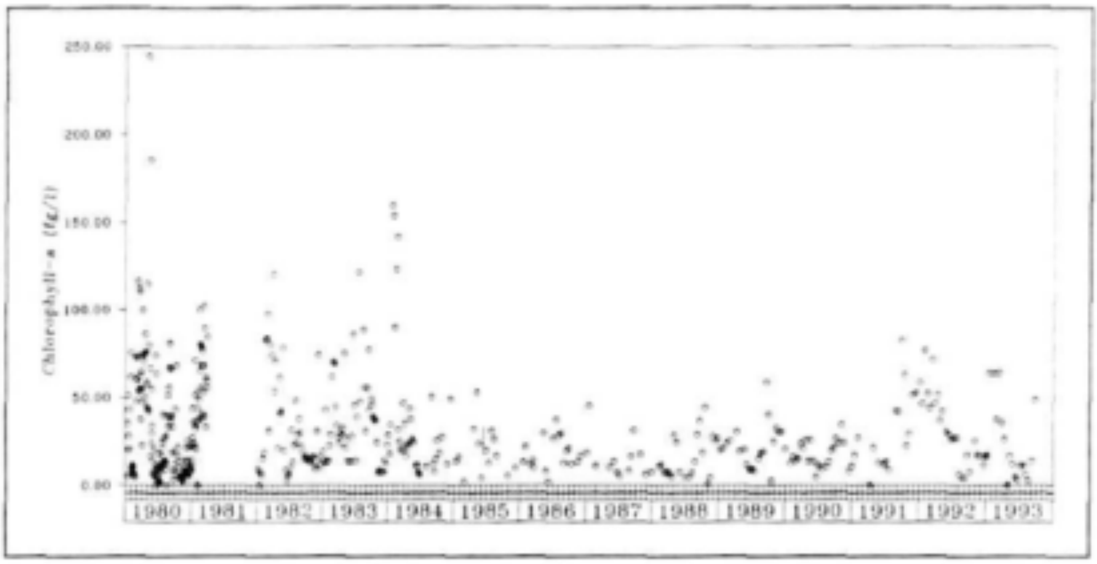

Figure 2.2
Time-series graph of surface chlorophyll-a concentration as measured in Roodeplaat Dam near the dam wall for the period January 1980 to December 1993

From examination of the changes in of surface ortho-phosphate and chlorophyll-a concentrations, and keeping in mind that the validation period must be sufficiently removed from the calibration period to ensure different meteorological and hydrological conditions, it was concluded that suitable simulation period(s) would have to be chosen from the period 1985 to 1994.

2.3 Data collection

The variables required by the MINLAKE model and the government departments and institutions from whom data were requested, are indicated in Table 2.1.

Table 2.1
Variables required by the MINLAKE model and the institutions where data were requested

Variable	Department
Meteorological data:	
Air temperature	IWQS, Weather Bureau
Humidity	IWQS, Weather Bureau
Precipitation	IWQS
Wind speed	IWQS, Weather Bureau
Wind direction	IWQS, Weather Bureau
Sun hours	IWQS
Radiation	IWQS
River water quality data:	
Flow	DWAF Hydrology
Water temperature	DWAF Hydrology
Ortho-phosphate	DWAF Hydrology
Ammonia	DWAF Hydrology
Nitrate	DWAF Hydrology
Dissolved oxygen	DWAF Hydrology
Reservoir profiles:	
Temperature	DWAF hydrology
Dissolved oxygen	DWAF hydrology
Ortho-phosphate	DWAF hydrology, IWQS
Ammonia	DWAF hydrology, IWQS
Nitrate	DWAF hydrology, IWQS
Chlorophyll-a	DWAF hydrology, IWQS
Other reservoir data:	
Water level	DWAF Hydrology
Daily discharge	DWAF Hydrology

NOTES:

IWQS : DWAF Institute for Water Quality Studies, Roodeplaat Dam.

DWAF Hydrology : Directorate of Hydrology, Department of Water Affairs and Forestry.

2.3.1 Meteorological data

Meteorological and river water quality data as listed in Table 2.1 are required on a daily basis. The availability of meteorological data is given in Table 2.2.

During calibration of the model, wind speed was identified as the driving force in the model, and consequently much time and effort was spent in infilling missing wind speed data. It was therefore very encouraging to find a virtually complete record of wind speed (and wind direction) as measured at Roodeplaat Dam for the period January 1985 to January 1990. The record for sunshine hours is also complete. Regarding the rest of the meteorological variables (air temperature, humidity, precipitation and radiation), no record of the data prior to January 1988 could be found. The data for the period March to August 1988 are also missing. However, the record for the period September 1988 to May 1990 is virtually complete, although there is a slight problem with air temperature and humidity data.

The MINLAKE model requires daily average values, whereas the records obtained from Roodeplaat Dam only contain single daily values monitored early in the morning, as well as minimum and maximum air temperatures. However, during calibration of the model it was found that the model is not very sensitive to sort term fluctuations in air temperature, and moderately sensitive to humidity data. Hourly data, as well as the averages for both humidity and temperature are available for Forum Building in Pretoria, and thus it will be possible to construct a suitable data base for Roodeplaat Dam from the data as measured at Roodeplaat Dam, and those measured at Forum Building.

2.3.2 River flow and water quality data

River water quality data are required for each of the three rivers flowing into Roodeplaat Dam. (Figure 1.1 is a map of Roodeplaat Dam, indicating the inflowing rivers and some monitoring points.) The availability of daily flow and river water quality data for the period 1985 to 1990 are indicated in Table 2.3.

Table 2.2
The availability of meteorological data for Roodeplaat Dam

MONTH	Temp.	Humidity	Precip.	Wind speed	Wind direction	% Sun	Radiation
1985							
1	xx	xx		*	*	**	xx
2	xx	xx		*	*	**	xx
3	xx	xx		*	*	**	xx
4	xx	xx		*	*	**	xx
5	xx	xx		*	*	**	xx
6	xx	xx		*	*	**	xx
7	xx	xx		*	*	**	xx
8	xx	xx		*	*	**	xx
9	xx	xx		*	*	**	xx
10	xx	xx		*	*	**	xx
11	xx	xx		*	*	**	xx
12	xx	xx		*	*	**	xx
1986							
1	xx	xx		*	*	**	xx
2	xx	xx		*	*	**	xx
3	xx	xx		*	*	**	xx
4	xx	xx		*	*	**	xx
5	xx	xx		*	*	**	xx
6	xx	xx		*	*	**	xx
7	xx	xx		*	*	**	xx
8	xx	xx		*	*	**	xx
9	xx	xx		*	*	**	xx
10	xx	xx		*	*	**	xx
11	xx	xx		*	*	**	xx
12	xx	xx		*	*	**	xx
1987							
1	xx	xx		**	**	**	xx
2	xx	xx		**	**	**	xx
3	xx	xx		**	**	**	xx
4	xx	xx		**	**	**	xx
5	xx	xx		**	**	**	xx
6	xx	xx		**	**	**	xx
7	xx	xx		**	**	**	**
8	xx	xx		**	**	**	**
9	xx	xx		**	**	**	**
10	xx	xx		**	**	**	**
11	xx	xx		**	**	**	**
12	xx	xx		**	**	**	**

continued...

Month	Temp	Humidity	Precip	Wind speed	Wind dir	% Sun	Radiation
1988							
1	**	**	**	**	**	**	**
2	**	**	**	**	**	**	**
3	31	31	31	**	**	**	**
4	30	30	30	**	**	**	**
5	31	31	31	**	**	**	**
6	30	30	30	**	**	**	**
7	31	31	31	**	**	**	**
8	31	31	31	**	**	**	**
9	**	**	**	**	**	**	27
10	**	**	**	**	**	**	**
11	**	**	**	**	**	**	**
12	**	**	**	**	**	**	**
1989							
1	**	**	**	4	4	**	**
2	**	**	**	**	**	**	**
3	**	**	**	**	**	**	**
4	**	**	**	**	**	**	**
5	3	3	3	**	**	**	**
6	**	**	**	**	**	**	**
7	**	**	**	**	**	**	**
8	**	**	**	**	**	**	**
9	**	**	**	**	**	**	xx
10	**	**	**	**	**	**	xx
11	**	**	**	**	**	**	xx
12	**	**	**	**	**	**	xx
1990							
1	**	**	**	**	**	**	xx
2	**	**	**	11	11	**	xx
3	**	**	**			**	xx
4	**	**	**			**	xx
5	**	**	**			**	xx

NOTES:

xx : Data exists for every day of the month as monitored at Forum building
** : Data exists for every day of the month as monitored at Roodeplaat Dam
Number : Number of days of missing data (three or more consecutive days)
Blank : The variable was not monitored

Table 2.3

The availability of flow and river water quality data

MONTH	FLOW			Temperature, PO_4, NH_4, NO_3, TDS			Chlorophyll-a, TSS, BOD		
	M27	M28	M29	M27	M28	M29	M27	M28	M29
1985									
1	**	(29)	(17)	**	8	**			
2	**	**	(16)	**	4	**			
3	**	**	(23)	**	**	**			
4	**	(29)	(30)	**	**	**			
5	**	(11)	(31)	**	12	**			
6	**	(30)	(30)	**	**	**			
7	**	(13)	(31)	**	6	**			
8	**	(24)	(31)	**	6	**			
9	**	(13)	(30)	**	5	**			
10	**	(28)	(30)	**	3	**			
11	**	(5)	(22)	7	16	8			
12	**	**	(22)	14	13	9			
1986									
1	**	**	(28)	8	15	3			
2	**	(8)	(28)	**	**	**			
3	**	(22)	(31)	**	**	**			
4	**	(11)	(30)	**	**	**			
5	**	(9)	(31)	**	20	**			
6	**	**	(30)	**	12	**			
7	**	**	(31)	**	**	**			
8	**	(7)	(31)	**	15	**			
9	**	(30)	(30)	3	**	**			
10	**	(16)	(21)	**	4	7			
11	**	**	(14)	**	4	14			
12	**	**	(13)	**	**	3			
1987									
1	**	**	**	**	**	**			
2	**	**	(8)	**	**	**			
3	**	**	(4)	**	11	5			
4	**	(3)	**	**	3	**			
5	**	(31)	**	**	**	10			
6	**	(30)	**	**	**	**			
7	**	(31)	**	**	**	**			
8	**	(25)	**	22	4	19			
9	**	**	**	25	29	20			
10	**	**	**	31	31	31			
11	**	**	**	30	30	30			
12	**	**	(5)	31	31	26			

continued....

Month	Flow			Temperature, PO_4, NH_4, NO_3, TDS			Chlorophyll-a, TSS, BOD		
	M27	M28	M29	M27	M28	M29	M27	M28	M29
1988									
1	**	(4)	(31)	31	27	**			
2	**	(17)	(29)	**	4	**			
3	**	**	(6)	**	4	**			
4	**	**	**	**	8	5			
5	**	**	**	**	**	6			
6	**	**	**	**	**	**			
7	**	**	**	**	**	**			
8	**	(10)	**	**	**	**			
9	**	(10)	(13)	3	**	**			
10	**	(11)	(31)	**	**	**			
11	**	(8)	(30)	**	3	**			
12	**	**	(31)	**	**	**			
1989									
1	**	(6)	(31)	**	**	**			
2	**	**	(13)	**	**	**			
3	**	**	(10)	**	3	7			
4	**	(7)	(30)	**	8	**			
5	**	**	(31)	**	**	**			
6	**	**	(4)	**	**				
7	**	**	**	**	**				
8	**	**	**	**	**				
9	**	(27)	(21)	**	3				
10	**	(21)	(31)	**	3				
11	**	(3)	(5)	**	**				
12	**	**	**	**	**				
1990									
1	**	**	**	No data until 2 Feb 1992					
2	**	**							
3	**	**							
4	**	**							
5	**	**							

NOTES:

(Number)	: Number of days with zero flow
Number	: Number of days of missing data (three or more consecutive days)
**	: Data exists for every day of the month
Blank	: The variable was not monitored
M27	: Pienaars River
M28	: Hartbeesspruit
M29	: Edendalespruit

A full record of daily river flow is available for all three rivers for the period 1985 to 1992. During 1985 and 1986 there was very little, if any flow in the Edendalespruit (M29 in Table 2.3). The flow in the Hartbeesspruit (M28 in Table 2.3) was also low during this period. During 1987 the flow increased, but the period from about October 1988 until the end of 1989 was again characterized by a very low flow in the Edendalespruit. The flows for the three rivers for the period 1985 to 1990 are compared in Figure 2.3, which shows that the flow into Roodeplaat Dam is dominated by the flow from Pienaars River (station M27 in Table 2.3), especially during low flow conditions.

Chlorophyll-a, BOD, and total inorganic suspended sediment (TSS) concentrations were not measured in any of the three rivers. During calibration of the model it was found that TSS concentration plays an important role in the simulation of algal kinetics, because of the effect of TSS concentration on the availability of under water light. TSS concentrations for the validation period therefore had to be synthesized, using the same method that was used during calibration of the model (Venter 1996).

Unfortunately water temperature, ortho-phosphate, ammonia, nitrate and total dissolved salts were not monitored for any of the rivers during the period August 1987 to January 1988, and again from January 1990 to February 1992 (Table 2.3). The missing data for August 1987-January 1988 are particularly unfortunate, as the MINLAKE model ideally requires the simulation period to start in September/October (the beginning of the stratified period). Apart from these periods, the water quality record for the Pienaars River is virtually complete. This is important, as previous studies have shown that Pienaars River is responsible for more than 70% of the ortho-phosphate load that enters Roodeplaat Dam. This dominance of the Pienaars River is also evident in Figures 2.4, 2.5, and 2.6, which comprise time-series graphs of the ortho-phosphate, ammonia and nitrate concentrations in the three rivers during the period January 1985 to December 1990.

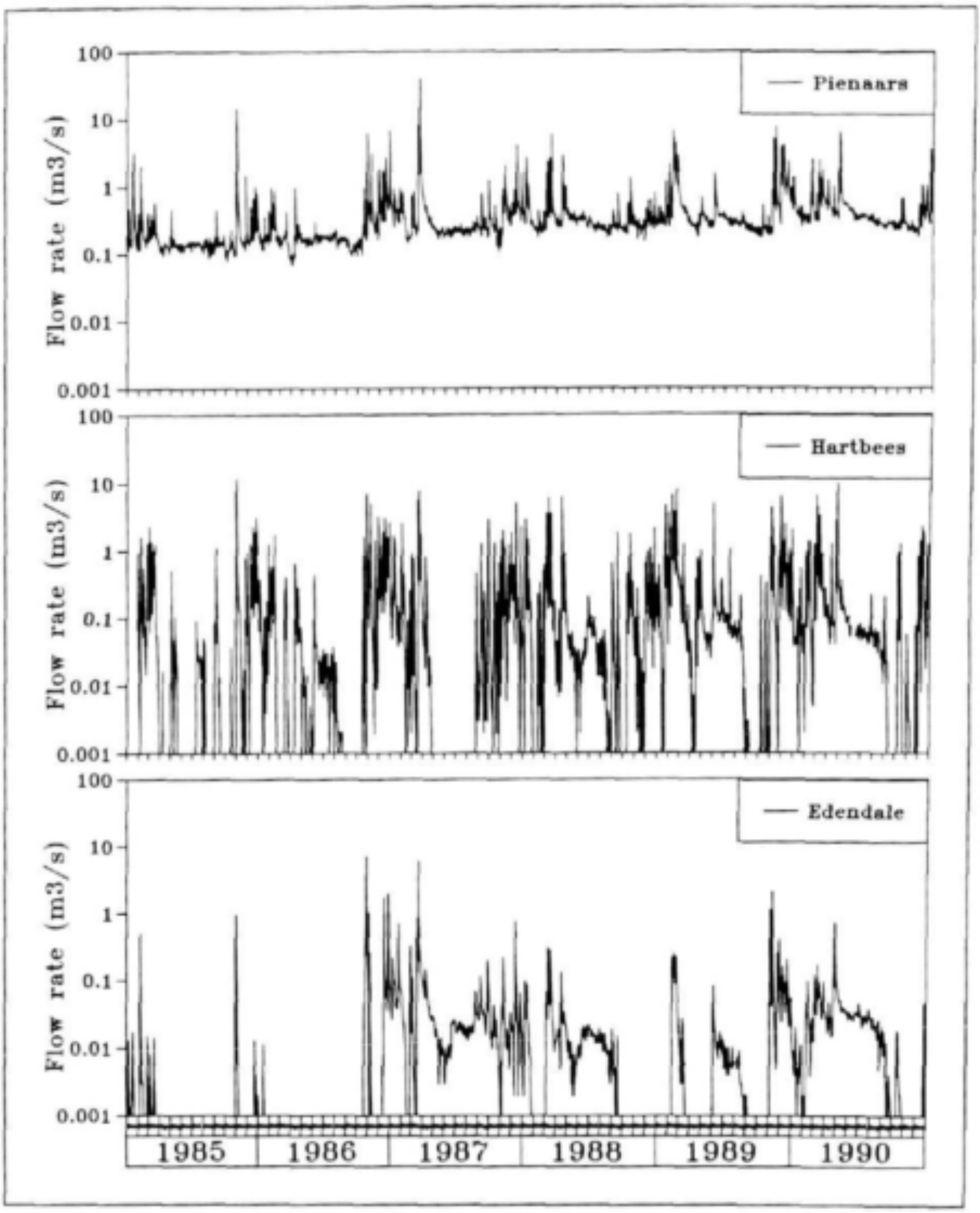

Figure 2.3
Time-series graph of flows as measured in Pienaars River, Hartbeesspruit and Edendalespruit

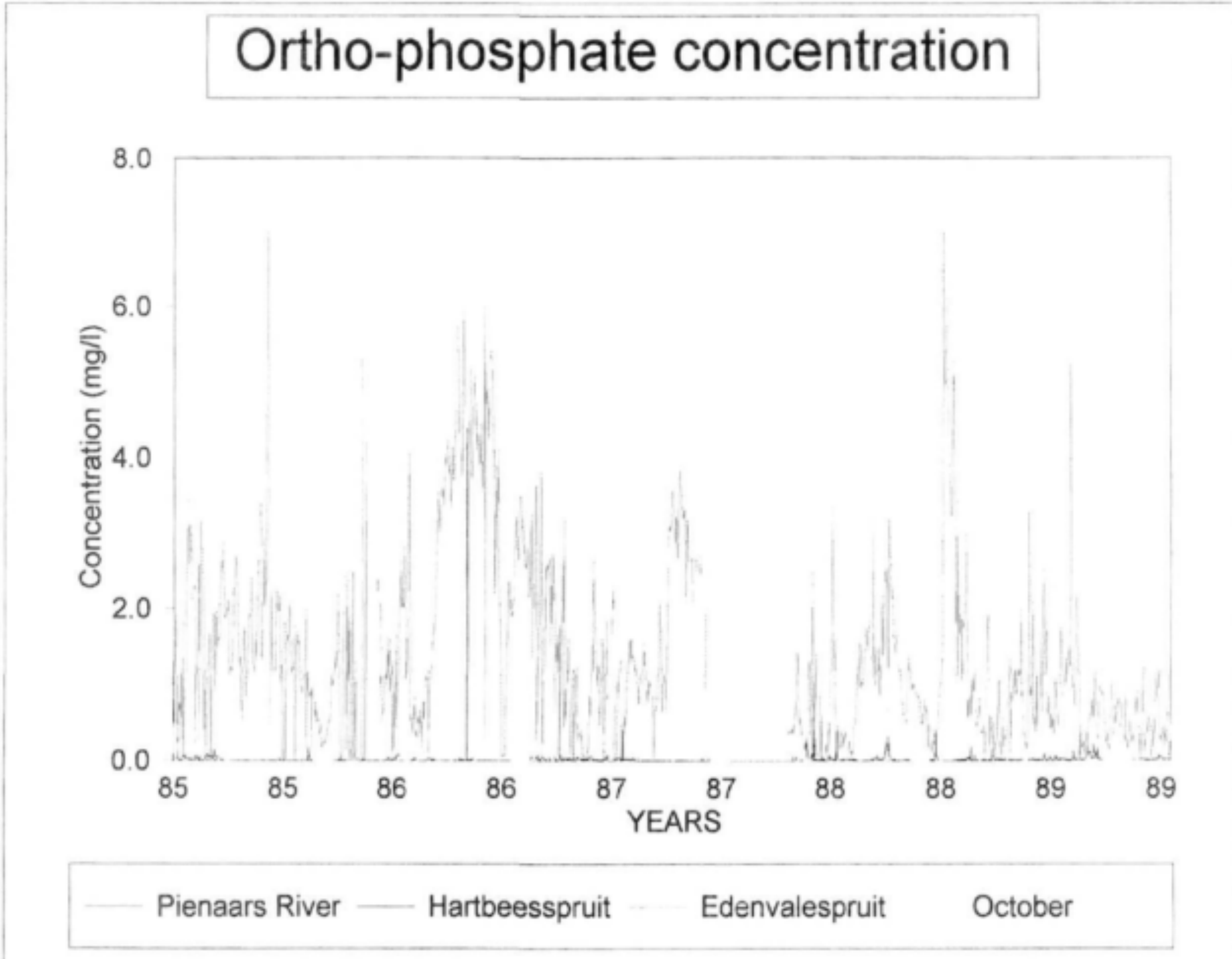

Figure 2.4 Time-series graph of ortho-phosphate concentrations as measured in Pienaars River, Hartbeesspruit and Edendalespruit

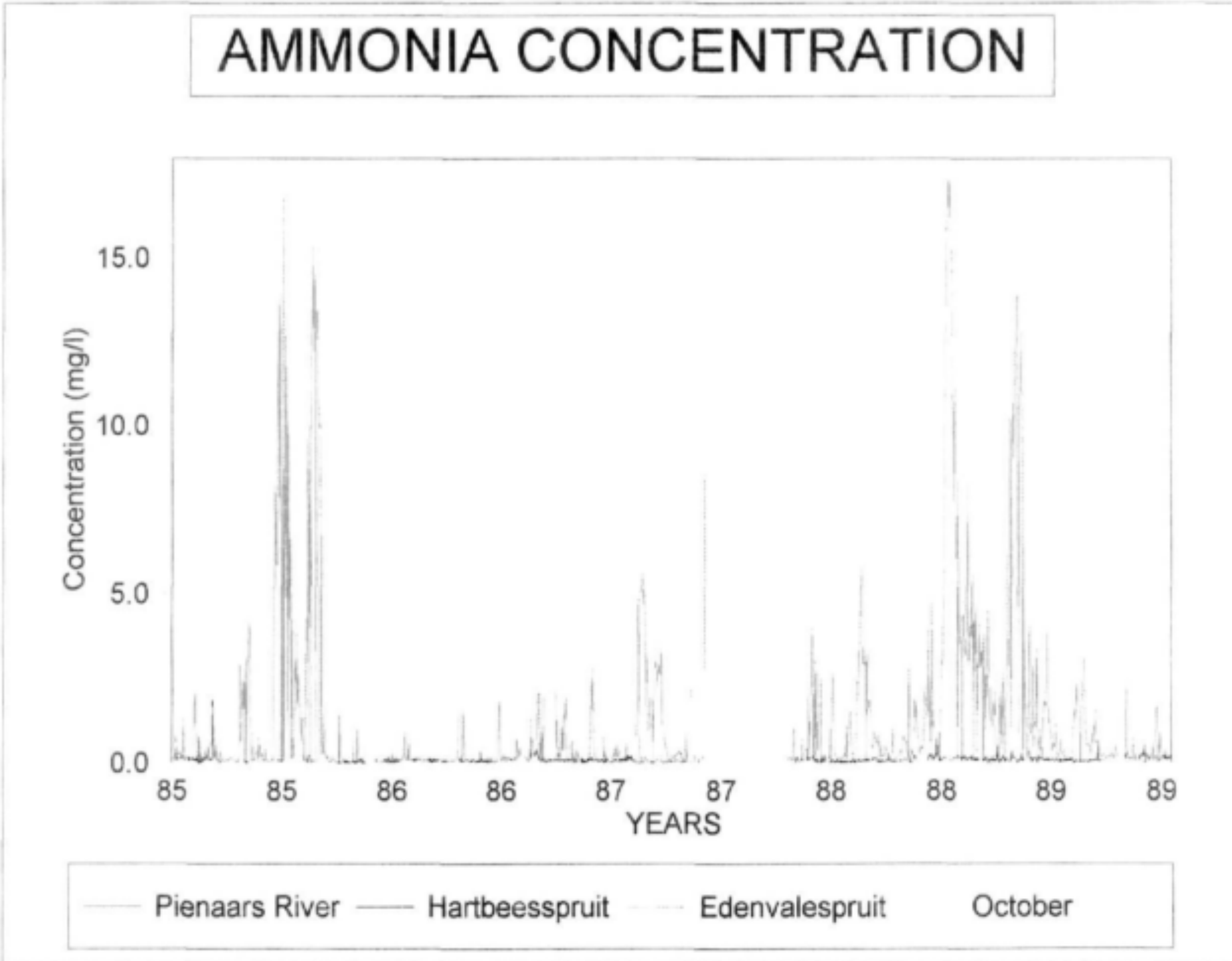

Figure 2.5 Time-series graph of ammonia concentrations as measured in Pienaars River, Hartbeesspruit and Edendalespruit

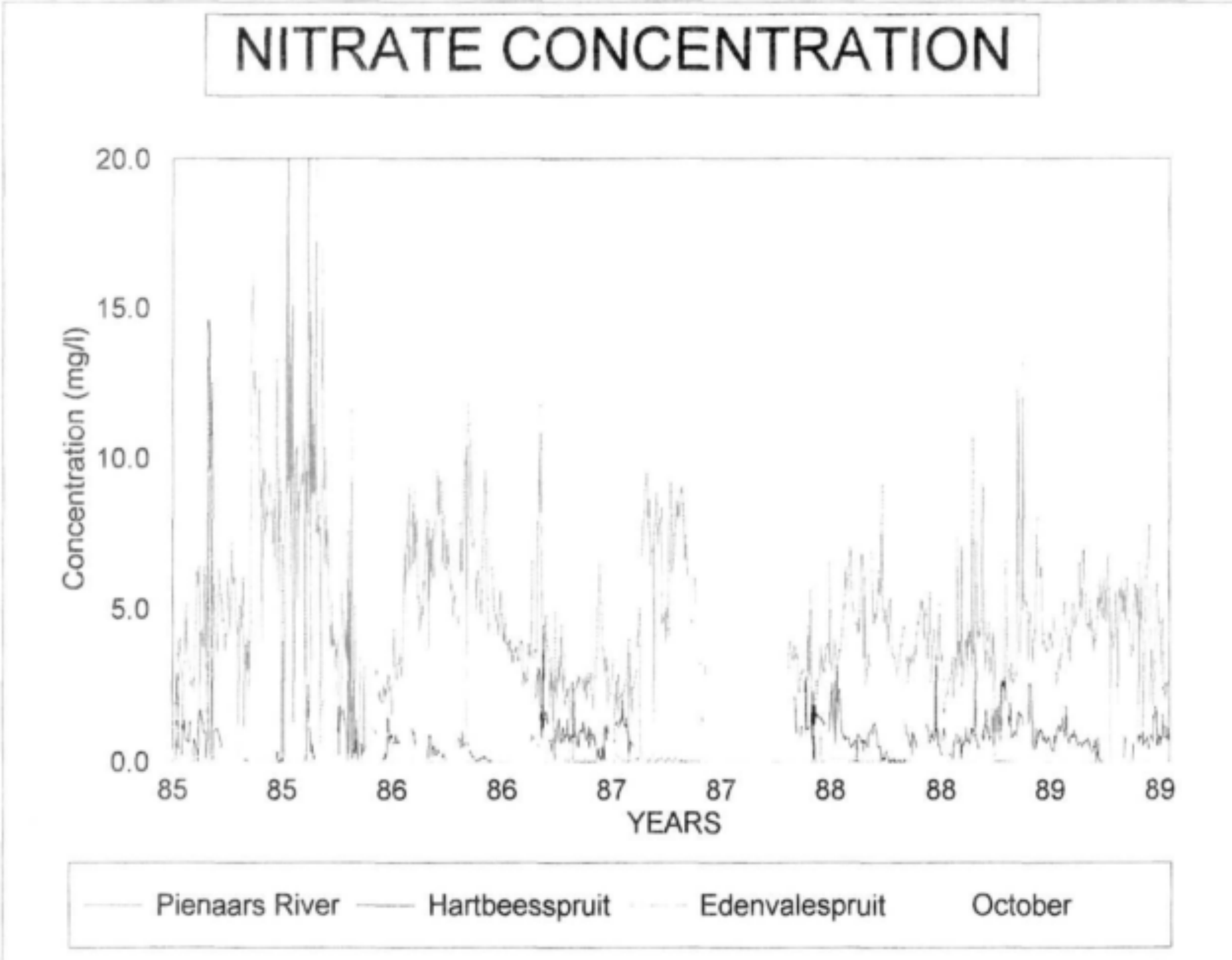

Figure 2.6 Time-series graph of nitrate concentrations as measured in Pienaars River, Hartbeesspruit and Edendalespruit

The least complete record seems to be that for the Hartbeesspruit. Apart from the incomplete periods in 1987 and 1990-1992, the data frequency in the latter half of 1985 is also rather low. The record for the Edendalespruit appears to be more complete, but this is a function of the zero flow that occurred in the river for extended periods. However, as far as the MINLAKE model is concerned, no water quality data are required if there is no flow in a river, therefore the record for the Edendalespruit can be regarded as almost complete, apart from the extended missing periods in 1987, and 1990-1992.

2.4 *Selection of validation period*

The most complete record for both meteorological and water quality data is from September 1988 to 3 January 1990. This period is subsequent to implementation of the 1 mg P standard for Roodeplaat Dam, and therefore it would be a suitable period for validation of the model. Validation of the model during the period prior to implementation of the 1 mg phosphate standard could be problematical in view of the absence of data for the majority of meteorological variables for this period. Also, there are several periods of missing data in the water quality record for the Hartbeesspruit prior to September 1988.

Based on the availability of meteorological and water quality data for Roodeplaat Dam, it was decided to validate the MINLAKE model for the period October 1988 to January 1990. This would coincide with the period subsequent to implementation of the 1 mg P standard for Roodeplaat Dam and thus would be ideal to test the ability of the model to predict the behaviour of an impoundment after a substantial change in inflow nutrient load. The chosen period covers a period of 15 months, which should be adequate for validation of the model.

3. CONSTRUCTION OF DATA BASES

3.1 Introduction

A preliminary investigation of the available data had indicated that a full set of meteorological data monitored at Roodeplaat Dam was available for the period October 1988 to January 1990. However, during construction of the meteorological data base it was discovered that the quality of the meteorological data for some of the variables measured at Roodeplaat Dam was such that the data could not be used, and thus some infilling of meteorological data had to be done.

Regarding the meteorological data, during calibration of the model, wind speed was identified as the driving force in the model, and consequently much time and effort was spent in infilling missing wind speed data. It was therefore very encouraging to find a virtually complete record of wind speed (and wind direction) as measured at Roodeplaat Dam for the period January 1985 to January 1990. The record for sunshine hours in also complete. Regarding the rest of the meteorological variables (air temperature, humidity, precipitation and radiation), no record of the data prior to January 1988 could be found. The data for the period March to August 1988 are also missing. However, the record for the period September 1988 to May 1990 is virtually complete, although there is a slight problem with air temperature and humidity data. The MINLAKE model requires daily average values, whereas the records obtained from Roodeplaat Dam only contain single daily values monitored early in the morning, as well as minimum and maximum air temperatures. However, during calibration of the model it was found that the model it was found that the model is not very sensitive to short term fluctuations in air temperature data, and moderately sensitive to humidity data. Hourly data, as well as the averages for both humidity and temperature are available for the Forum Building in Pretoria, making it possible to construct a suitable data base for Roodeplaat Dam from the data as measured at Roodeplaat Dam, and those measured at Forum Building.

3.2 Infilling of data

Apart from Inorganic Total Suspended Solids (TSS) and BOD concentrations, a complete record of inflow water quality was available for the Pienaars River (the main river flowing into the impoundment) for the selected period. The inflow water quality record for the Hartbeesspruit was virtually complete (*Table 3.1*), and it was possible to fill in missing data by interpolation (with the exception of TSS). The data record for the Edendalespruit was less complete. However, apart from one major storm event, there was either no flow in this river during the study period, or else the flow was very low (Figure 3.1). Hence only limited infilling of inflow water quality data had to be done for the Edendalespruit.

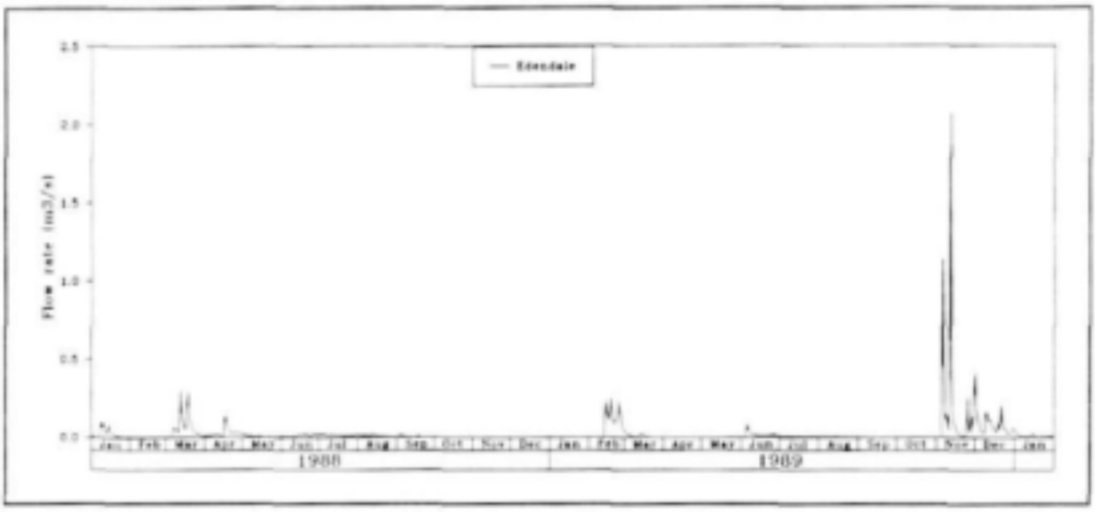

Figure 3.1
Flow in Edendalespruit

Table 3.1
The availability of inflow water quality data

MONTH	FLOW			Temperature, PO_4, NH_4, NO_3, TDS			Chloropyll-a, TSS, BOD		
	M27	M28	M29	M27	M28	M29	M27	M28	M29
10	**	(11)	(31)	**	**	**			
11	**	(8)	(30)	**	3	**			
12	**	**	(31)	**	**	**			
1989									
1	**	(6)	(31)	**	**	**			
2	**	**	(13)	**	**	**			
3	**	**	(10)	**	3	7			
4	**	(7)	(30)	**	8	**			
5	**	**	(31)	**	**	**			
6	**	**	(4)	**	**				
7	**	**	**	**	**				
8	**	**	**	**	**				
9	**	(27)	(21)	**	3				
10	**	(21)	(31)	**	3				
11	**	(3)	(5)	**	**				
12	**	**	**	**	**				

Notes:

(Number)	: Number of days with zero flow
Number	: Number of days of missing data
**	: Data exists for every day of the month
Blank	: The variable was not monitored
M27	: Pienaars River
M28	: Hartbeesspruit
M29	: Edendalespruit

The quality and infilling of the meteorological data, as well as infilling of inflow water quality data for the Edendalespruit and generation of TSS data for all three rivers, are briefly discussed in the following sections.

3.2.1 Infilling of meteorological data

(a) Air temperature

The MINLAKE model requires daily average air temperature. However, examination of the air temperature data monitored at Roodeplaat Dam revealed that the data consisted of a single daily measurement, usually taken at 07h00. Maximum and minimum temperatures were also recorded.

Hourly air temperature data from Forum Building in Pretoria, as well as average daily temperatures, and minimum and maximum temperatures were also available. However, from discussions with Mr Simon Mason (Wits Climatology), the CCWR in Pietermaritzburg, and Mr Bosman (DWAF), it was concluded that the average air temperature as measured at Forum Building was not representative of the average air temperature at Roodeplaat Dam.

After an intensive investigation and comparison of the available air temperature data at Roodeplaat Dam and Forum Building, it was decided that the following method would generate the most representative air temperature data for Roodeplaat Dam:

- Calculate Forum (minimum temperature + maximum temperature)/2
- Calculate the linear regression between the above and the average air temperature at Forum Building ($R^2 = 0.9786$)
- Utilise the same regression equation to calculate the average air temperature at Roodeplaat Dam from the minimum and maximum air temperatures measured at Roodeplaat Dam.

During calibration of the model it was found that the model is not sensitive to air temperature data, and therefore data generated with the above method are considered adequate for validation of the model.

(b) Dew point temperature

The MINLAKE model requires average daily dew point temperature. Data on dew point temperature were not available for Roodeplaat Dam, but daily measurements of relative humidity were available for the study period. (Dew point temperature can be calculated from relative humidity using the Clausius-Clapeyron Equation). However, as with air temperature data, the humidity data consisted of a single daily measurement, usually taken at 07h00.

Hourly data on relative humidity were available at Forum Building in Pretoria. It was decided that the average relative humidity as measured at Forum Building would be more representative of average daily humidity at Roodeplaat Dam than the data measured early in the morning at Roodeplaat Dam. During calibration of the model it was found that the model is moderately sensitive to dew point temperature/humidity data, but in the absence of appropriate data measured at Roodeplaat Dam, the Forum data have to be considered satisfactory.

(c) Precipitation

A full record of precipitation (recorded at Roodeplaat Dam) was available, and thus no infilling was required.

(d) Wind direction

The MINLAKE model requires daily data on wind direction. The model does not utilise wind direction data as such, but it affords the user the opportunity of linking wind fetch to wind direction.

Wind direction data for Roodeplaat Dam were available on an hourly basis for the required period. During calibration of the model the dominant wind direction was determined for each day. The dominant wind direction was then used to determine wind fetch. Due to the shape of Roodeplaat Dam (see Figure 1.1), if the wind is blowing from a north-westerly direction (or south-easterly direction) the wind fetch is 3 400 metre, but if the wind is blowing from a westerly (or easterly direction) the wind fetch is only 1 600 metre.

During model calibration it was found that simulated and observed hypolimnetic water temperature started diverging slightly towards the end of the simulation period, thus a different approach of calculating wind fetch was followed during model validation. Instead of determining the dominant wind direction for each day, the corresponding wind fetch was linked to each of the 24 wind directions that were measured daily during the validation period. Thereafter the average wind fetch for the day was calculated. The model was adapted to read average daily fetch instead of wind direction data. This modification did not result in any significant improvement in simulated hypolymnetic water temperature, which is in accordance with the finding during calibration of the model, i.e. that the model is not very sensitive to wind fetch.

(e) Wind speed

During calibration of the model, wind was identified as the main hydrodynamic driving force, and thus the model is extremely sensitive to wind speed. Fortunately the wind speed record was virtually complete, with only 7 days missing from the record during the study period. The missing data were infilled with average daily values for that particular month.

(f) Sun hours

Sun hours were recorded on an hourly basis at Roodeplaat Dam, but the record was characterised by blanks, with no indication as to whether the blanks represent missing data, or hours with no sunshine. Fortunately it was possible to obtain a complete set of sun hour data from the agricultural station at Roodeplaat Dam, and thus no infilling was required.

(g) Short wave radiation

During calibration, it was found that the model is moderately sensitive to radiation data. Although short wave radiation was measured on a daily basis at Roodeplaat Dam, as required by the model, the quality of the data was suspect. Radiation was measured in DWatt-hr/m^2. However, in February 1989 the level of radiation inexplicably increased to almost double the previous level, staying at these elevated levels until July 1989, whereafter it suddenly dropped to the previous level (Figure 3.2).

Apparently these elevated levels can be related to the way the recorder was set up, but even an intensive investigation of the original recorder charts could not resolve the matter. The following approach was therefore followed to ensure a full set of short wave radiation data:

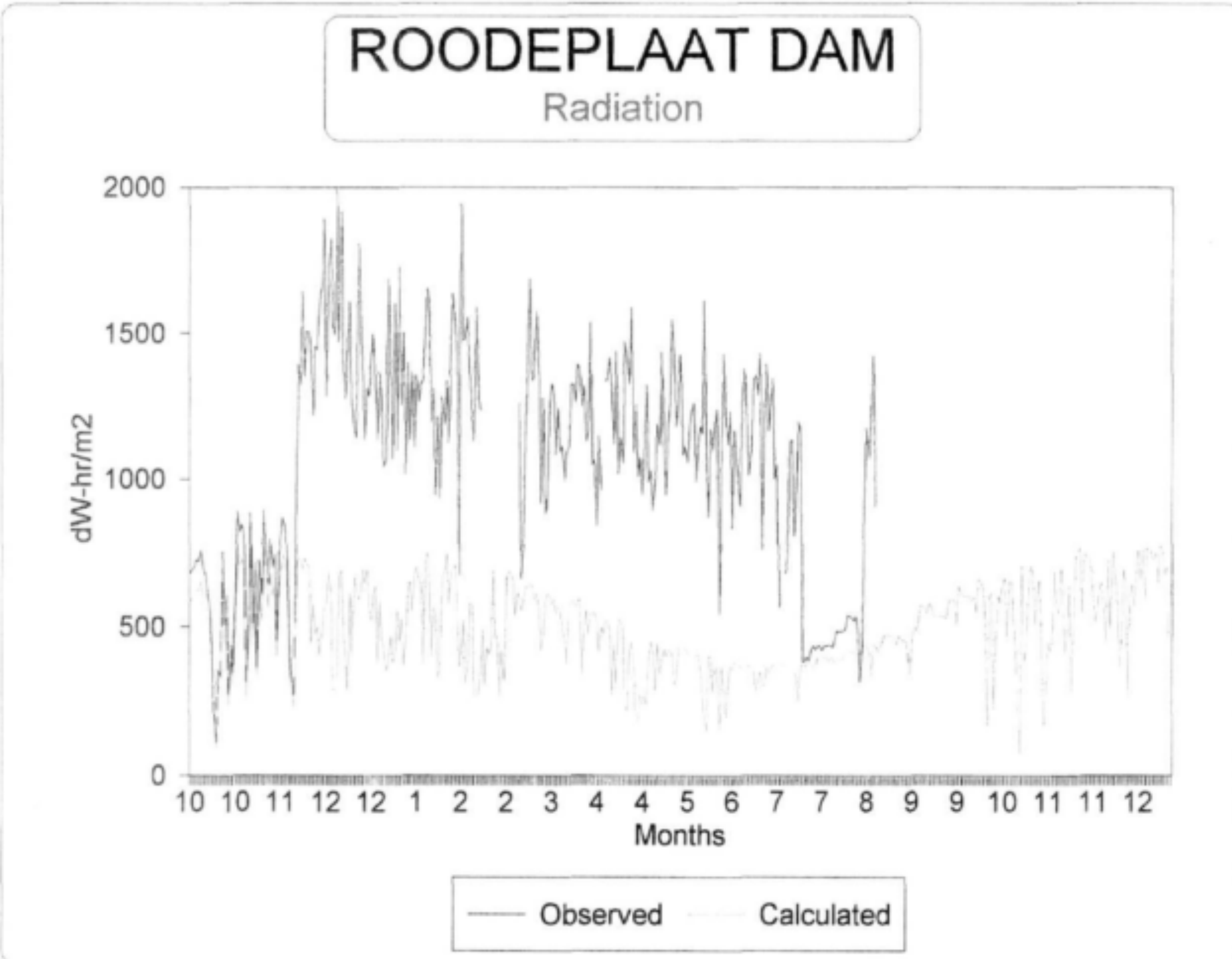

Figure 3.2 Observed radiation data for Roodeplaat Dam

- For the period October 1988 to mid-February 1989, and August 1989 to December 1989, the data as measured at Roodeplaat Dam were utilised.

- For the period mid-February to July 1989, radiation data was generated from sun hour data, using the same regression (R^2 = 0.8441) that was established during calibration of the model.

Correlation between calculated and observed radiation data for the periods with available data is good (Figure 3.2), thus the infilled data are regarded as reliable for the validation of the model.

3.2.2 Infilling of inflow water quality data

Apart from TSS data, infilling of inflow water quality data only had to be done for the Edendalespruit. TSS data had to be generated for all three rivers.

(a) Infilling of water quality data for the Edendalespruit

Apart from one week in March 1989, infilling also had to be done for the months of June, July, August, part of September, November and December 1989 (see Table 3.1). Fortunately the daily flow record for these periods was complete, and thus missing ortho-phosphate, ammonium, nitrate and TDS data could be infilled from daily flow, using the regression equations that were established during calibration of the model (Table 3.2).

Table 3.2: Infilling of water quality variables for Edendalespruit

Parameter with missing data	Parameter used for infilling	R^2	Slope
ln PO_4	ln flow	0.31	0.39
ln NH_4	ln flow	0.05	0.08
ln NO_3	ln flow	0.15	-0.33
ln TDS	ln flow	0.72	-0.13

Missing water temperature data were infilled from average air temperature data, using the same method that was used during model calibration (Venter,1996).

In spite of the low correlation coefficients for ortho-phosphate, nitrate and ammonia, it was decided not to spend unnecessary time on refining the infilled data for the Edendalespruit, as the load from this stream is much smaller than that of the Pienaars River (*cf* Chapter 2). Also, during calibration of the model it was found that the internal ammonia and nitrate loads in Roodeplaat Dam are more significant than the loads entering from the three rivers.

(b) Generation of TSS data

Since no TSS data were measured in any of the three rivers, TSS data had to be generated from flow data. The same rationale was followed as during calibration of the model where TSS data was generated from the daily river flow by using the unit streampower equation as developed by Rooseboom. For the three rivers flowing into Roodeplaat Dam the following function described the relationship between river flow and concentration of total inorganic suspended sediment (TSS):

$$S = A.Q^{0.8718}$$

where

S	=	TSS concentration (mg/l)
A	=	860 (for Roodeplaat Dam)
Q	=	river flow (m^3/s)

3.3 Data base construction

The data required by the MINLAKE model are divided into three data bases, i.e. meteorological, inflow, and input data base.

3.3.1 Meteorological data base

After infilling of the missing meteorological variables was completed, no problems were encountered in construction of the meteorological data base.

3.3.2 Inflow data base

The inflow data base contains data on flow and water quality for each of the rivers flowing into Roodeplaat Dam. Apart from finalising the generation of TSS data, the inflow data base is complete.

3.3.3 Input data base

This data base contains the calibration coefficients, as well as sets of observed profile data (field data) for comparison of simulated and observed results. The values of the calibration coefficients were unchanged from the calibration period, as the purpose of a validation study is to determine whether the values of the coefficients as established during the calibration period are valid for the validation period as well.

The quality of the profile data during the validation period is good, compared to the quality of profile data during the calibration period. Water temperature and dissolved oxygen were monitored every two weeks. Measurements were often done to a depth of 30 metres. Integrated (0-5 metre) samples of TDS, orthophosphate, ammonia and nitrate were taken every two weeks. Samples at greater depth (20, 22, or 30 metres) were also taken regularly, which greatly facilitates comparison of observed and simulated water quality variables.

As the MINLAKE model is a lake-averaged model (Henderson-Sellers 1984, Venter 1996), the data monitored at the various points/similar depths in the dam (*cf* Figure 1.1) were also averaged to obtain a set of observed data against which the simulated data could be compared.

4. VALIDATION RESULTS

4.1 Introduction

In validating a model, the reliability with which the model can predict the effect of changes in the forcing functions is tested. With regard to limnological modelling of non-conservative water quality variables such as chlorophyll-a that are difficult even to measure consistently, it is impractical to expect a model to produce time series that closely matches the observed data in detail. What can more realistically be expected of the model is the ability to follow the general trend and the direction in which the water quality will shift in response to the implementation of a management change. In testing the effect of various treatment options, a water manager would typically like to know the percentage time that he can expect algae at nuisance concentrations. Thus the water quality validation results are presented in the form of time-series graphs as well as duration curves. The duration curves are based on the following data:

Observed concentrations: These values represent the concentrations obtained when an *integrated* sample (taken over 0-5 metres) was analyzed.

Simulated concentrations: As the observed data are based on samples that were integrated over 0-5 metres, simulated data was also averaged over 0-5 metres[1].

4.2 Hydrodynamic validation results

Time-series graphs of simulated and observed water temperature data are shown in Figures 4.1 and 4.2, and depth profiles of simulated and observed temperatures in Figure 4.3.

[1] It should be noted that the simulated water quality concentrations in the time-series graphs represent the concentrations over a depth interval of 1 m. Thus a point-to-point fit of simulated and observed data cannot be expected.

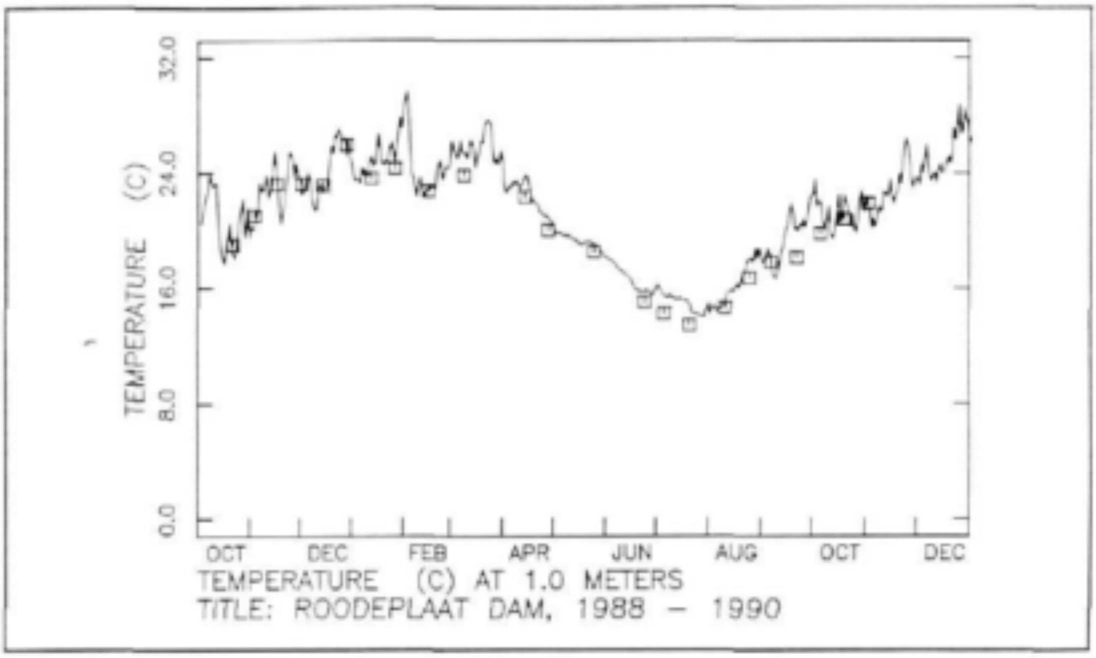

Figure 4.1
Time-series graph of simulated and observed water temperature at a depth of 1 metre in Roodeplaat Dam

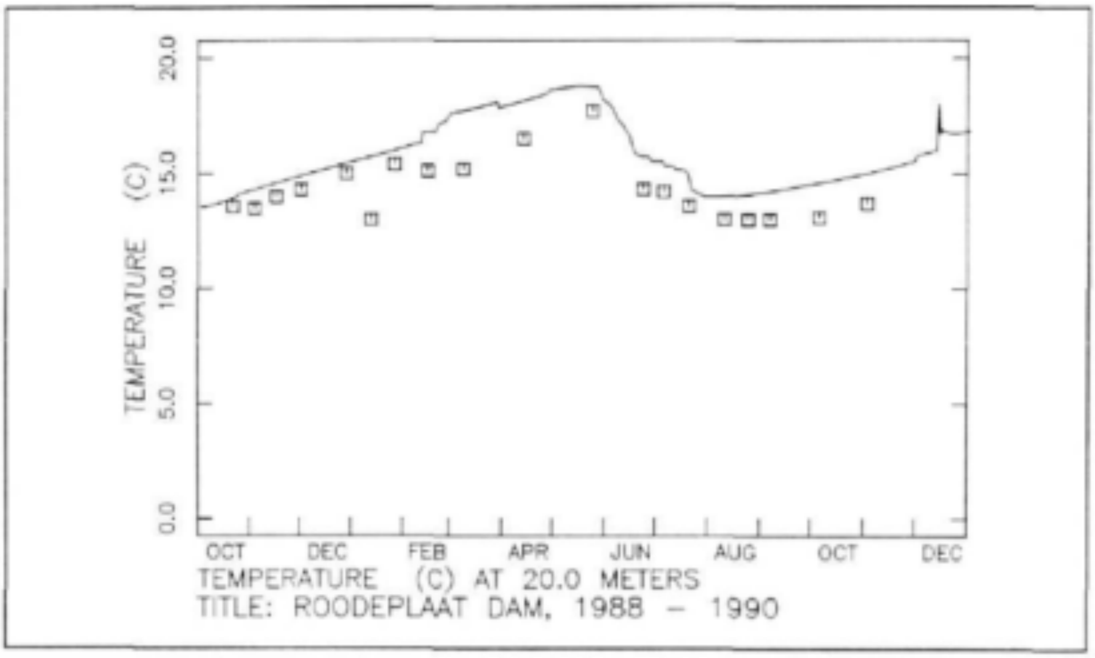

Figure 4.2
Time-series graph of simulated and observed water temperature at a depth of 20 metre in Roodeplaat Dam

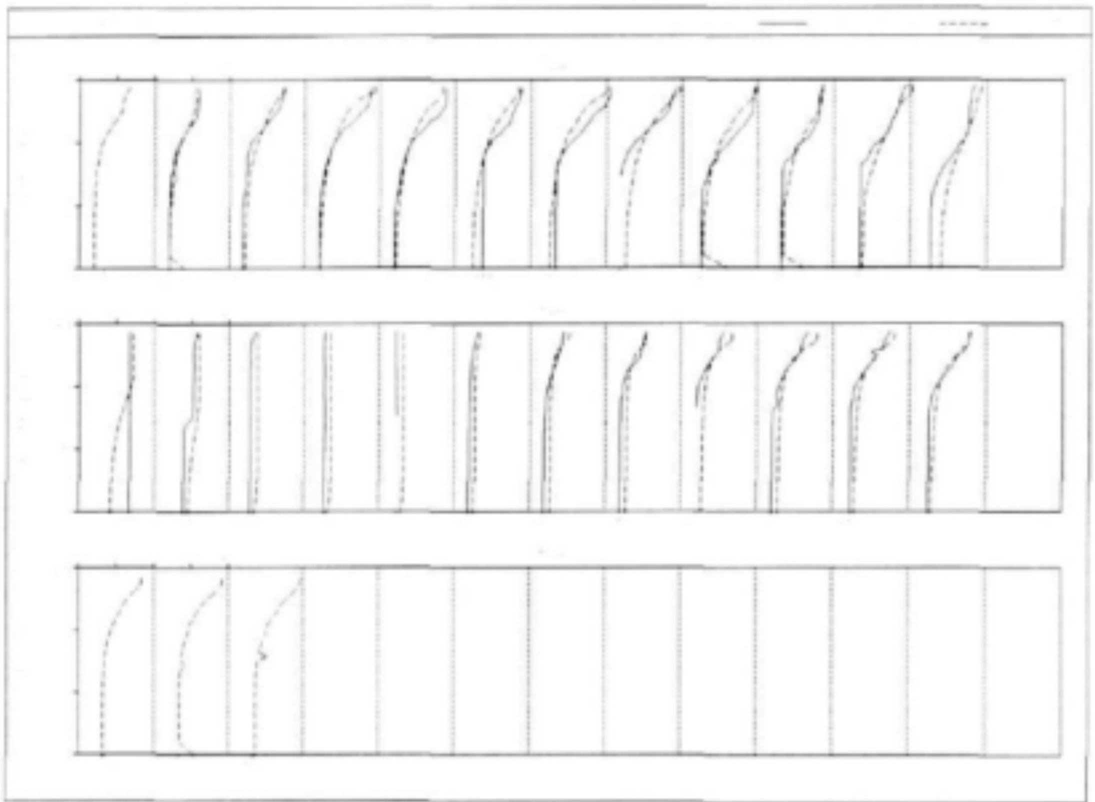

Figure 4.3
Depth profiles of simulated and observed water temperature in Roodeplaat Dam for the period October 1988 to December 1989

Correlation between simulated and observed temperatures is good at all depths. Simulation of mixing depth (Figure 4.4) is satisfactory, thus it would seem that the model is well able to simulate the hydrodynamic behaviour of Roodeplaat Dam during the validation period.

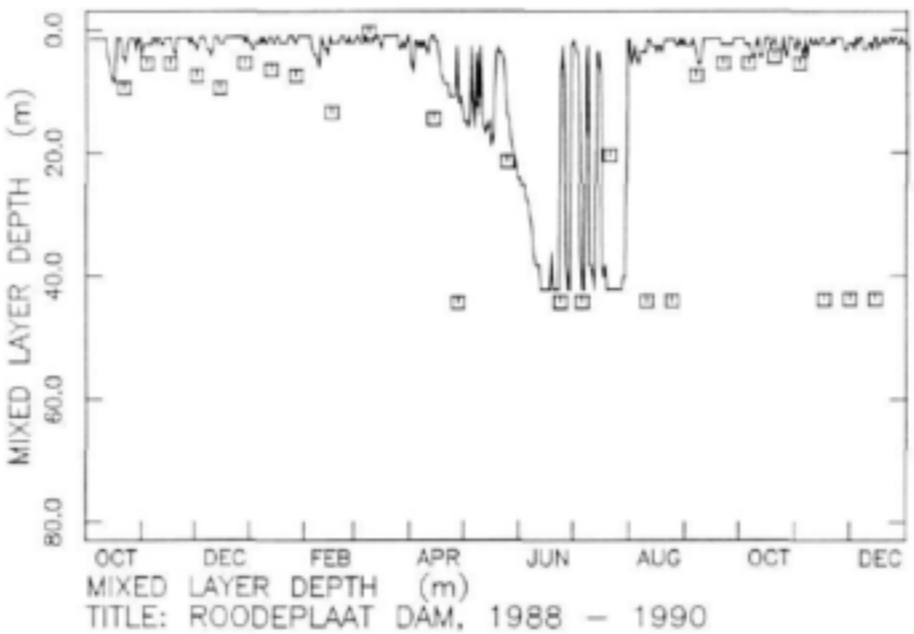

Figure 4.4
Time-series graph of mixing depth in Roodeplaat Dam for the period October 1988 to January 1990

4.3 Water Quality Validation Results

4.3.1 Chlorophyll-a

Time-series graphs of observed and validated chlorophyll-a concentrations are shown in Figure 4.5. Duration curves of simulated and observed concentrations during both the validation and calibration period are shown in Figures 4.6 and 4.7, and summarised in Table 4.1.

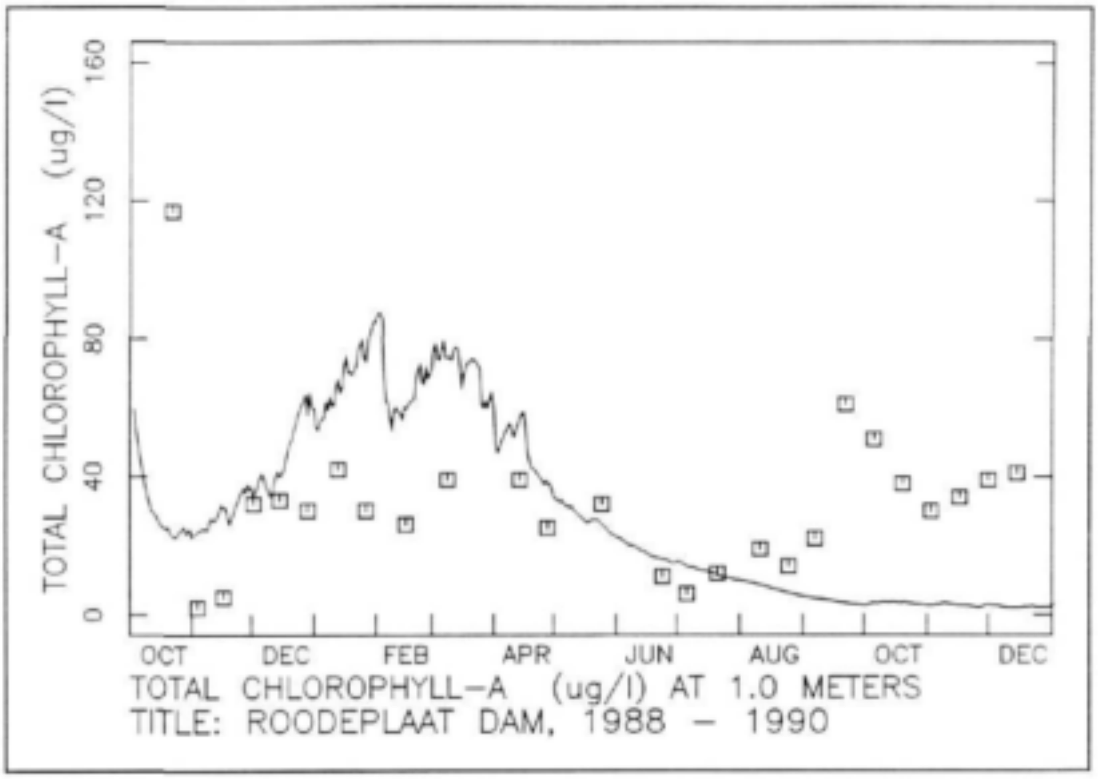

Figure 4.5
Time-series graph of simulated and observed chlorophyll-a concentrations at 1 m depth in Roodeplaat Dam during the validation period.

Figure 4.5 shows a poor correspondence between observed and simulated chlorophyll-a concentrations. Figures 4.6 and 4.7, and Table 4.1 show that the model failed to predict the observed degree of reduction in peak chlorophyll-a concentrations, although it did correctly indicate little change in the average concentration.

Simulated values of blue-green algae during the period December 1988 to March 1989 are too high, and observed growth of green algae during August and September 1989 was not replicated (Figure 4.5). From Figure 4.6 and Table 4.1 it can be seen that the model tends to over-predict total algal growth. For instance, the model predicted an average chlorophyll-a concentration of 40 μg/l, whereas the observed was 24 μg/l. The model also predicted that algae will be at nuisance levels (> 30 μg/l) for about 50 % of the time, whereas the observed value was only 20% of the time.

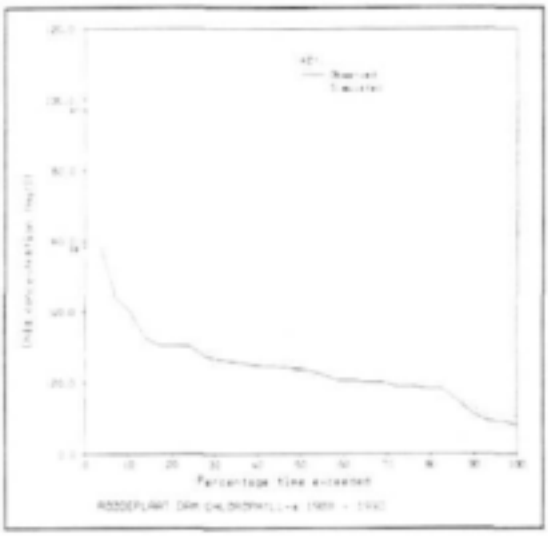

Figure 4.6
Duration curves of simulated and observed chlorophyll-a concentrations during the validation period.

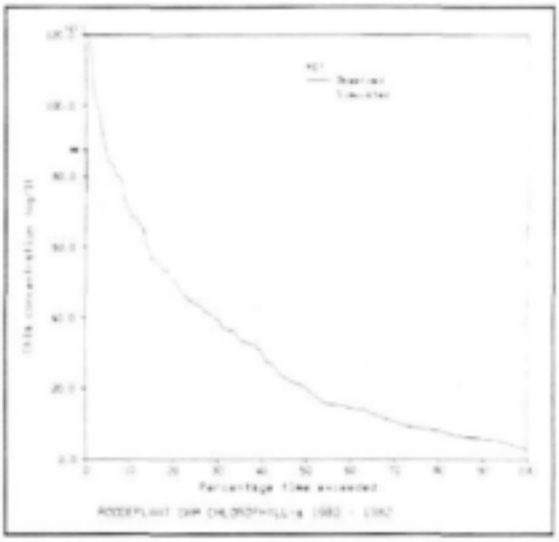

Figure 4.7
Duration curves of simulated and observed chlorophyll-a concentrations during the calibration period

Table 4.1

Simulated and observed chlorophyll-a concentration percentile values during the validation and calibration periods

Percentile	Chlorophyll-a concentration (µg/l)			
	Validation period		Calibration period	
	Observed	Simulated	Observed	Simulated
10	40.5	76.0	70.3	67.4
20	30.4	65.9	50.4	58.2
50	23.8	33.0	20.1	38.2
80	18.3	17.0	8.0	22.4
90	11.3	12.8	5.7	20.1
Average	24.1	40.1	29.8	40.1

4.3.2 Ortho-phosphate

Time-series graphs of observed and simulated ortho-phosphate concentrations at the surface and at 20 metre depth are shown in Figures 4.8 and 4.9. Duration curves of simulated and observed monthly surface ortho-phosphate concentrations for the validation and calibration periods are shown in Figures 4.11 and 4.12, and summarised in Table 4.2.

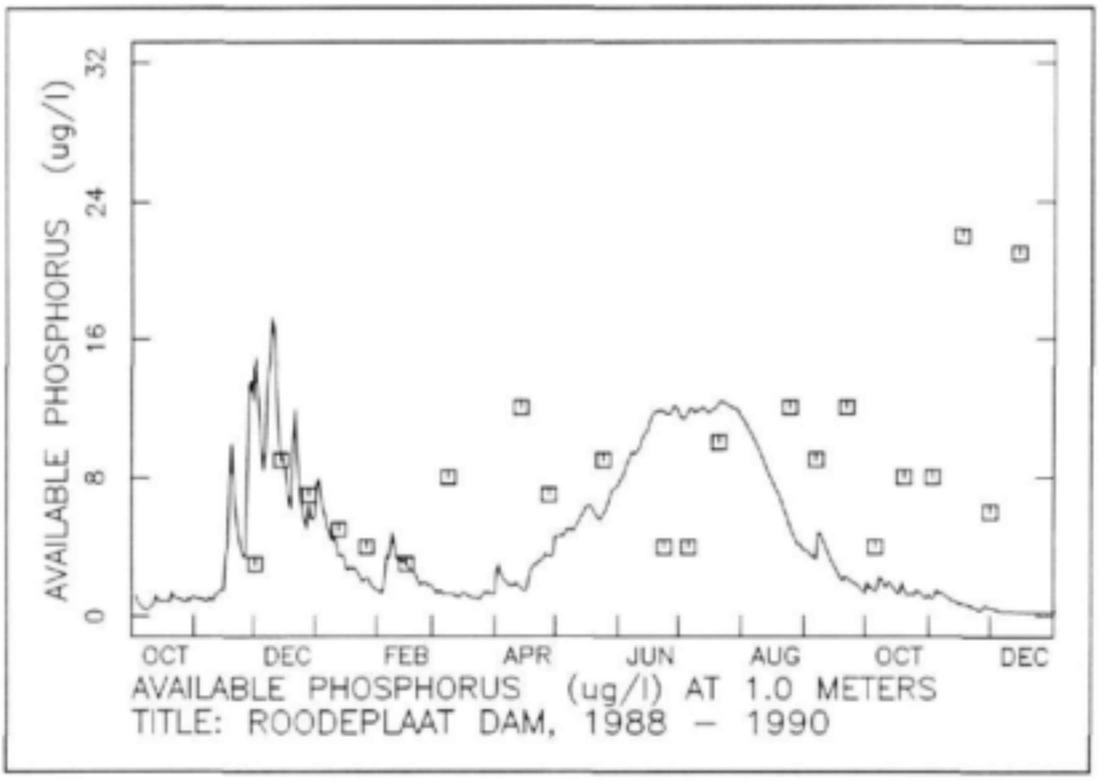

Figure 4.8
Time-series graph of simulated and observed ortho-phosphate concentrations at 1 m depth during the validation period.

Figure 4.8 shows a good match between the modelled and observed surface phosphate concentrations during the period November 1988 to February 1989. Thereafter the fit between modelled and observed values deteriorates, with the model incorrectly predicting troughs in the periods March to April, and September to December 1989. Simulated values at 20 metre depth (Figure 4.9) tend to be too high.

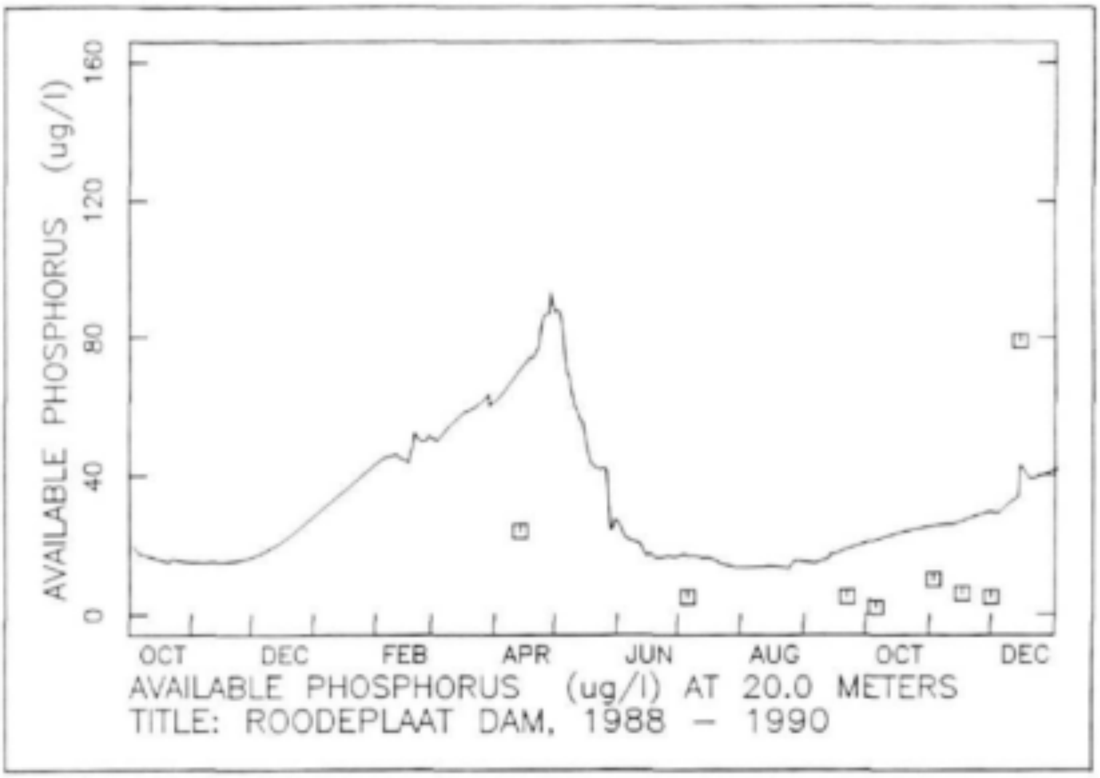

Figure 4.9
Time-series graph of simulated and observed ortho-phosphate concentrations at 20 meter depth during the validation period.

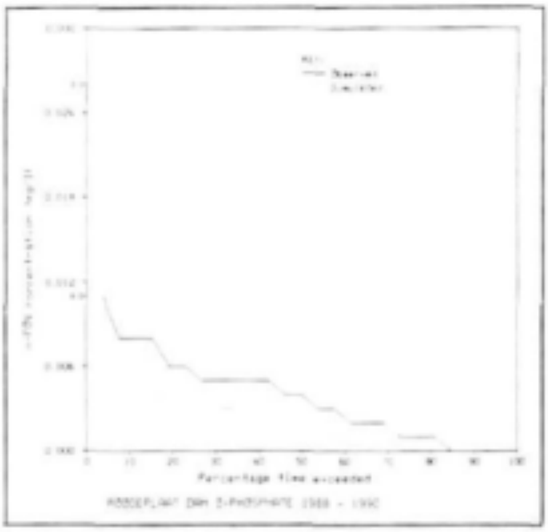

Figure 4.10
Duration curves of simulated and observed monthly surface ortho-phosphate concentrations during the validation period

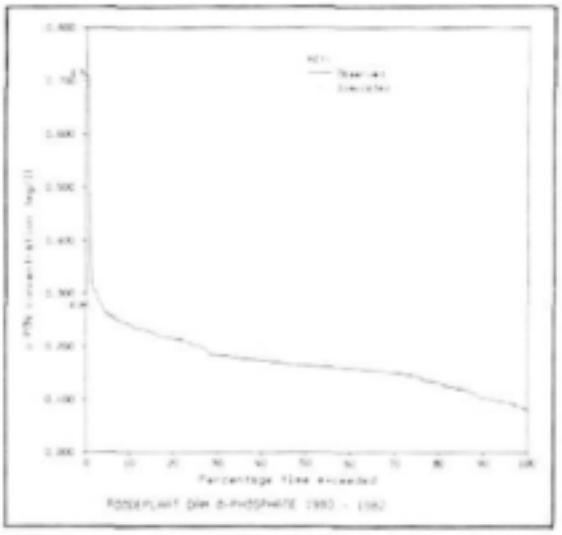

Figure 4.11
Duration curves of simulated and observed monthly surface ortho-phosphate concentrations during the calibration period

Table 4.2

Simulated and observed monthly surface ortho-phosphate concentration percentile values during the validation and calibration periods

Percentile	**Ortho-phosphate concentration** (mg/l)			
	Validation period		Calibration period	
	Observed	Simulated	Observed	Simulated
10	0.008	0.015	0.243	0.249
20	0.006	0.003	0.215	0.227
50	0.004	0.002	0.165	0.181
80	0.001	0.000	0.132	0.132
90	0.000	0.000	0.103	0.115
Average	0.004	0.004	0.173	0.180

The duration curves in Figure 4.10 show that for the validation period the model over-predicted peak phosphate concentrations, and under-predict at lower concentrations. This compares with the calibration period (Figure 4.12), when the model simulated a lower extreme short duration peak with a good fit for the remaining 95% of the time. However, during the validation period phosphate concentrations were extremely low, with the observed peak phosphate concentration less than one sixtieth of that observed during the calibration period. Thus what may seem to be a large discrepancy between simulated and observed concentrations represents a very small difference in actual concentration. Hence, although the model fit for the validation period is coarse, it was successful at predicting the absolute change in concentration resulting from the reduced input load. Again it must be emphasized that it is impractical to expect a reservoir model to produce time series that closely match the observed data in detail. What is of greater importance is the ability of the model to follow the general trend and the direction in which the water quality will shift in response to the implementation of a management change. Thus, if the magnitude of the change in simulated ortho-phosphate concentration from the calibration to the validation period is compared with the magnitude of change in the observed phosphate concentrations, it can be seen that the model was well able to predict the change that occurred. Concentrations observed during the validation period had decreased by 97% from those observed during the calibration period, whereas the model predicted a 98% change.

4.3.3 Ammonia

Time-series graphs of simulated and observed ammonia concentrations at the surface and 20 m depth are shown in Figures 4.12 and 4.13. Duration curves of simulated and observed values are shown in Figures 4.14 and 4.15, and summarised in Table 4.3.

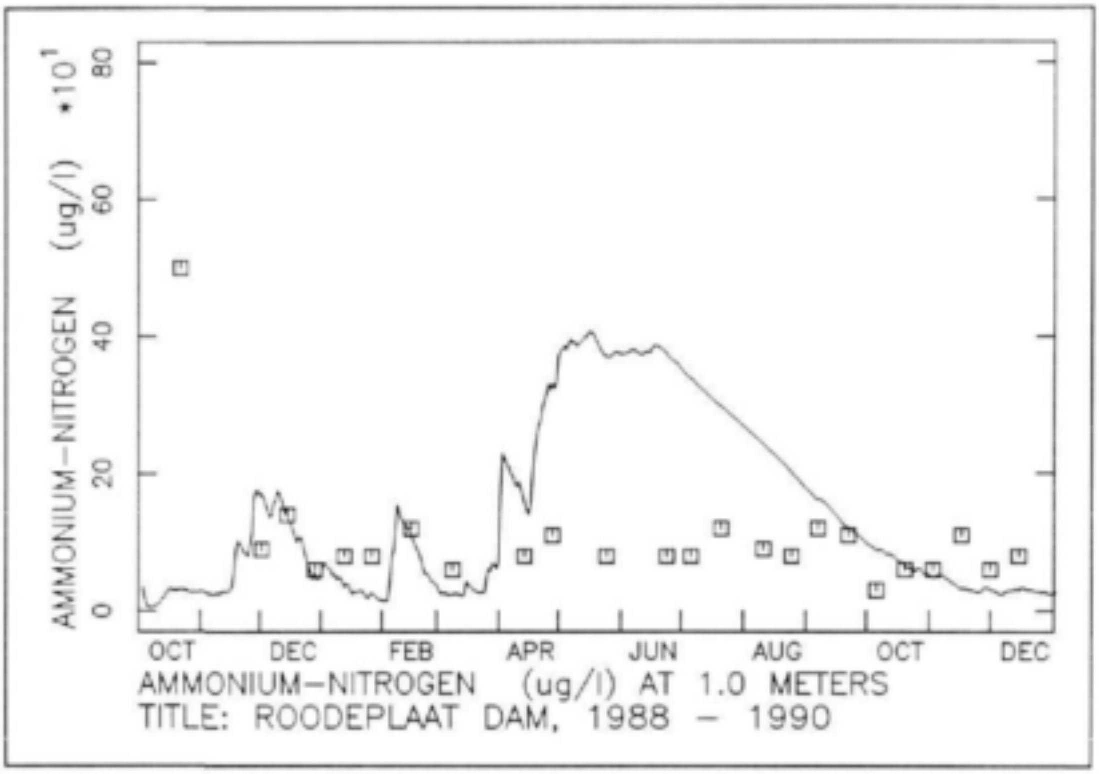

Figure 4.12
Time-series graph of simulated and observed ammonia concentrations at 1 m depth during the validation period

Simulated and observed surface concentrations of ammonia correspond reasonably during the first part of the validation period, but deviate significantly during the 1989 winter period. The reason for this deviation is not clear. The high simulated concentration during the winter period can be attributed to the simulated algal concentration being too low during this period.

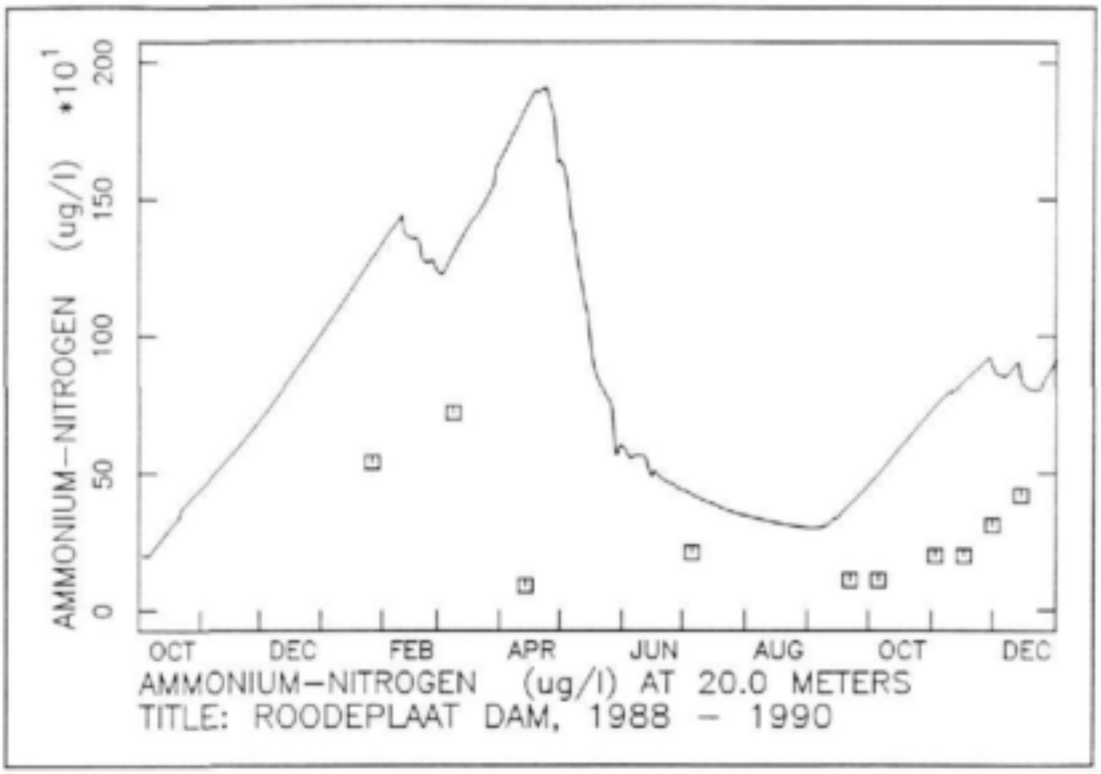

Figure 4.13
Time-series graph of simulated and observed ammonia concentrations at 20 m depth during the validation period

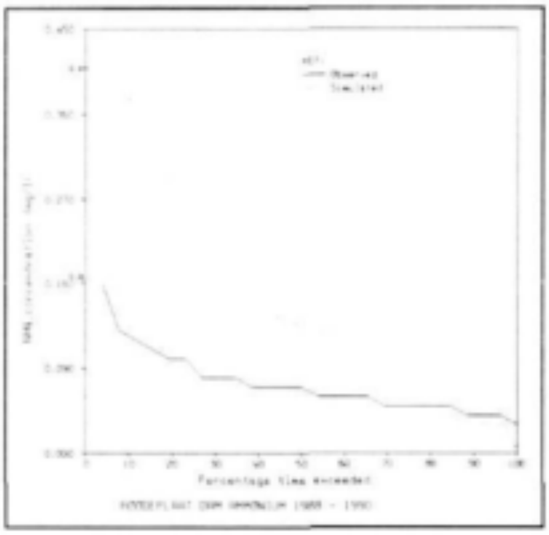

Figure 4.14
Duration curves of simulated and observed monthly surface ammonia concentrations during the validation period

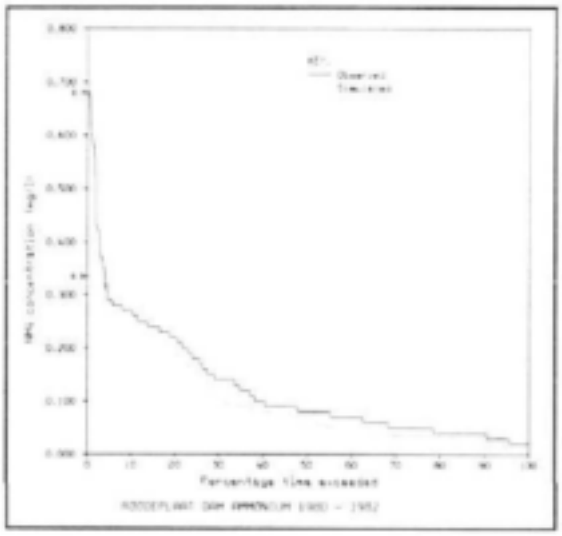

Figure 4.15
Duration curves of simulated and observed monthly surface ammonia concentrations during the calibration period

Table 4.3

Simulated and observed monthly surface ammonia concentration percentile values during the validation and calibration periods

Percentile	**Ammonia concentration** (mg/l)			
	Validation period		Calibration period	
	Observed	Simulated	Observed	Simulated
10	0.124	0.376	0.270	0.286
20	0.100	0.293	0.220	0.183
50	0.070	0.134	0.080	0.065
80	0.050	0.041	0.040	0.033
90	0.040	0.030	0.040	0.030
Average	0.073	0.165	0.124	0.104

Simulated ammonia concentrations at 20 metre depth (Figure 4.14) are consistently too high, but do follow the general pattern of the observations. The main source of ammonia in the hypolimnion is sediment ammonia release, thus the results in Figure 4.13 could indicate that the simulated ammonia sediment release rate is too high, i.e. the ammonia sediment kinetics have changed from the calibration period 8 years earlier. The duration curves in Figure 4.14 also show that for the validation period the simulated ammonia concentration is too high for 80% of the time.

Table 4.3 shows that the model predicted an average increase of 33%, and that ammonia concentrations at all levels would increase from the calibration period. However, there was actually a 41% decrease in the average observed concentrations from the calibration to the validation period, though it is interesting to note that the decrease occurred mainly at higher ammonia concentrations, with hardly any change in the lower concentrations.

4.3.4 Nitrate

Time-series graphs of simulated and observed nitrate concentration at the surface and 20 m depth are shown in Figures 4.16 and 4.17. Duration curves of simulated and observed values are shown in Figures 4.18 and 4.19, and summarised in Table 4.4.

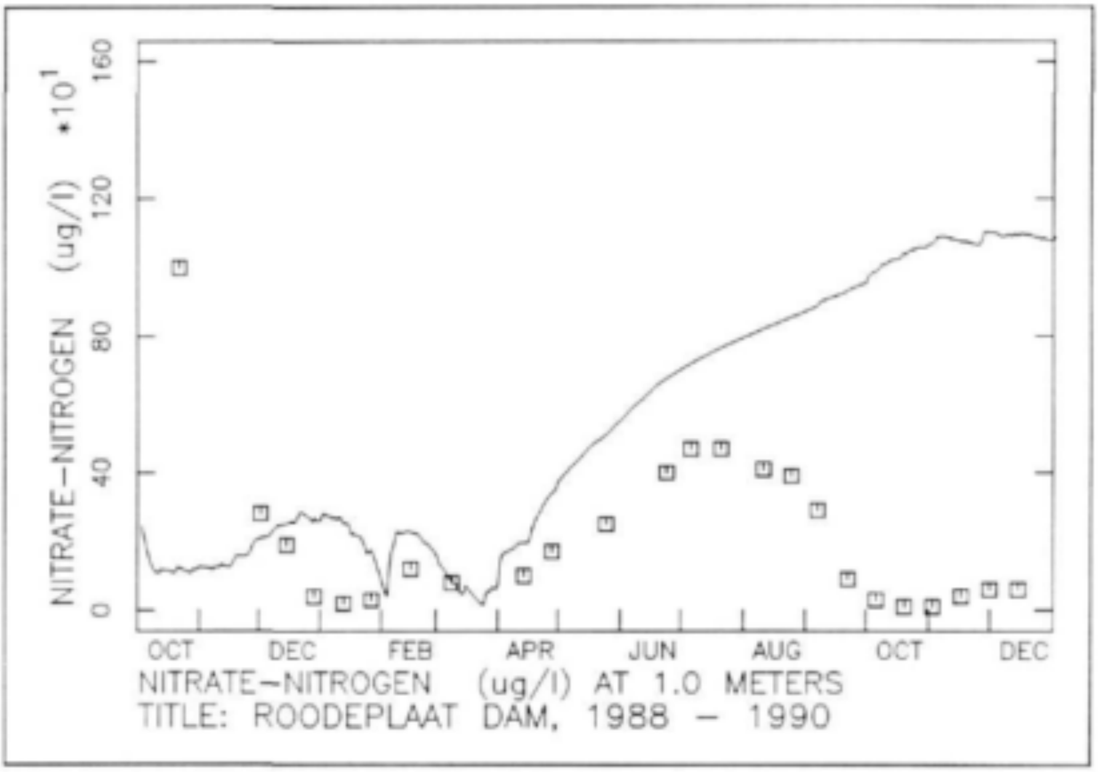

Figure 4.16
Time-series graph of simulated and observed nitrate concentrations at a depth of metre in Roodeplaat Dam during the calibration period

Figure 4.16 shows reasonable correspondence between simulated and observed nitrate concentrations for the first part of the validation period, but after mid-1989 the simulated concentration deviates significantly from the observed. Although the observed average nitrate concentration reduced by 30% from the calibration to the validation period, the model predicted an increase of 63%.

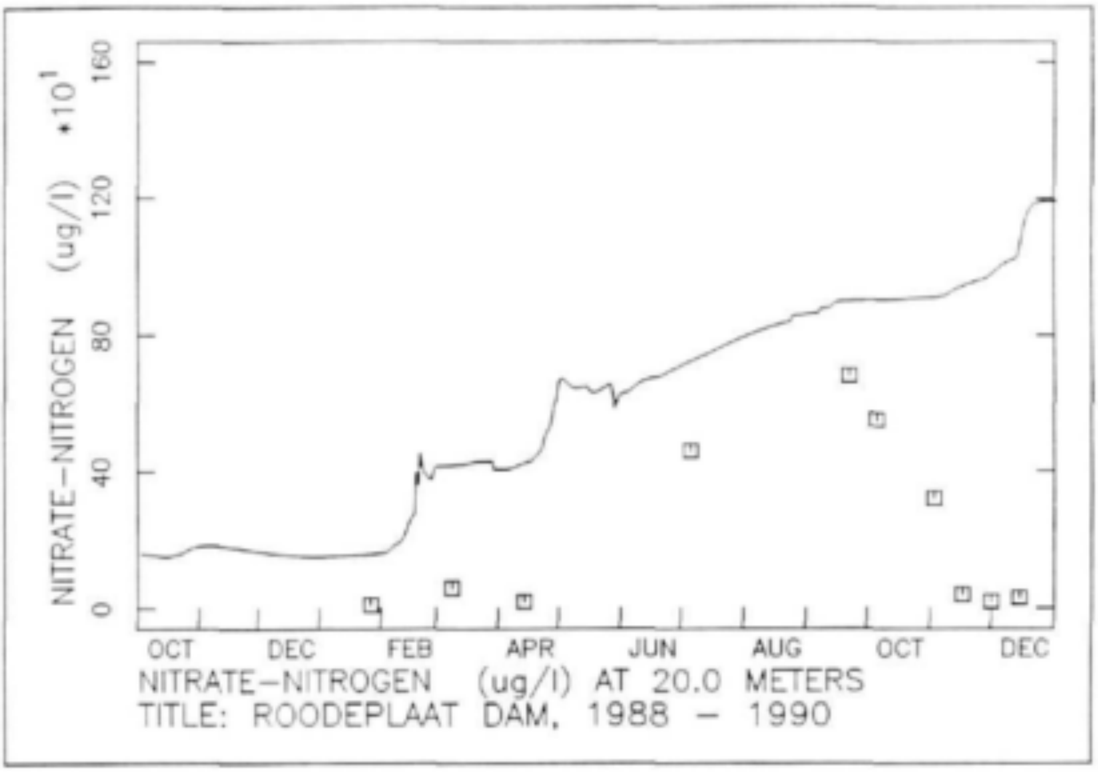

Figure 4.17
Time-series graph of simulated and observed nitrate concentrations at a depth of 20 metre in Roodeplaat Dam during the validation period

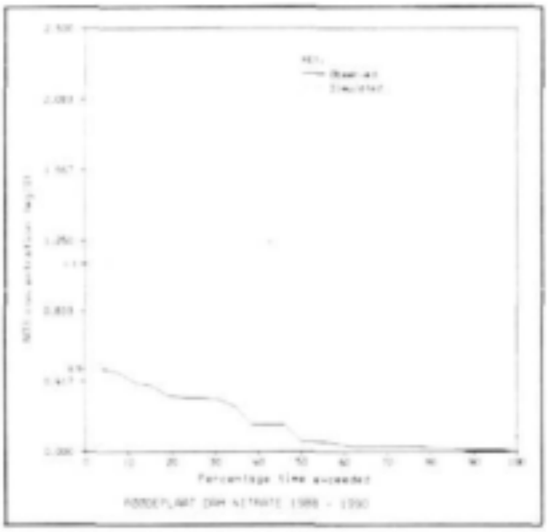

Figure 4.18
Duration curves of simulated and observed monthly surface nitrate concentrations during the validation period.

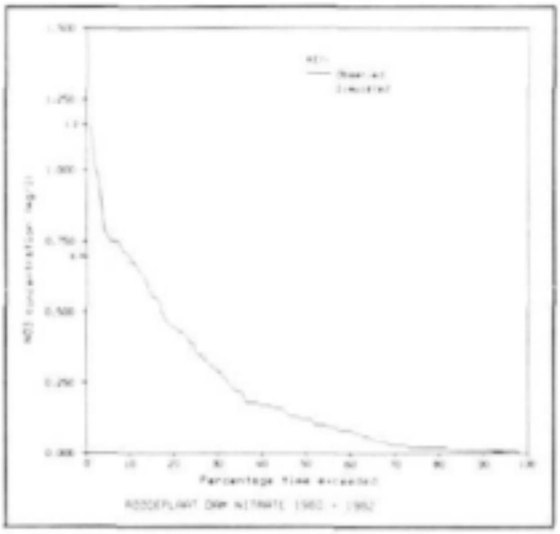

Figure 4.19
Duration curves of simulated and observed monthly surface nitrate concentrations during the calibration period.

Table 4.4

Simulated and observed monthly surface nitrate concentration percentile values during the validation and calibration periods

Percentile	**Nitrate concentration** (mg/l)			
	Validation period		Calibration period	
	Observed	Simulated	Observed	Simulated
10	0.434	1.09	0.692	0.674
20	0.328	0.994	0.450	0.621
50	0.060	0.495	0.120	0.360
80	0.022	0.191	0.020	0.124
90	0.010	0.131	0.010	0.030
Average	0.161	0.559	0.231	0.342

A likely explanation for the high simulated nitrate concentrations is that the sediment nitrate kinetics have changed since the calibration period 8 years previously. As nitrate is only released from the sediments under aerobic conditions, this effect would be greater in the epilimnion than in the hypolimnion, and greater during winter than during summer.

It is also possible that the calibration parameters contained compensating errors that where not apparent during the initial calibration period. With the benefit of hindsight it might be possible to choose a more appropriate set of calibration parameter values. But such re-calibration would have defeated the main purpose of the investigation, which was to verify the ability of the model to predict the impact of as yet unseen future conditions or management interventions.

4.3.5 TSS

Simulated TSS concentrations at 1 metre depth are shown in Figure 4.20. Unfortunately no observed TSS data are available with which the simulated TSS concentrations can be compared. However, simulated TSS concentrations follow the same trend as total flow rate into the river and thus it is accepted that the simulation of TSS concentration is plausible.

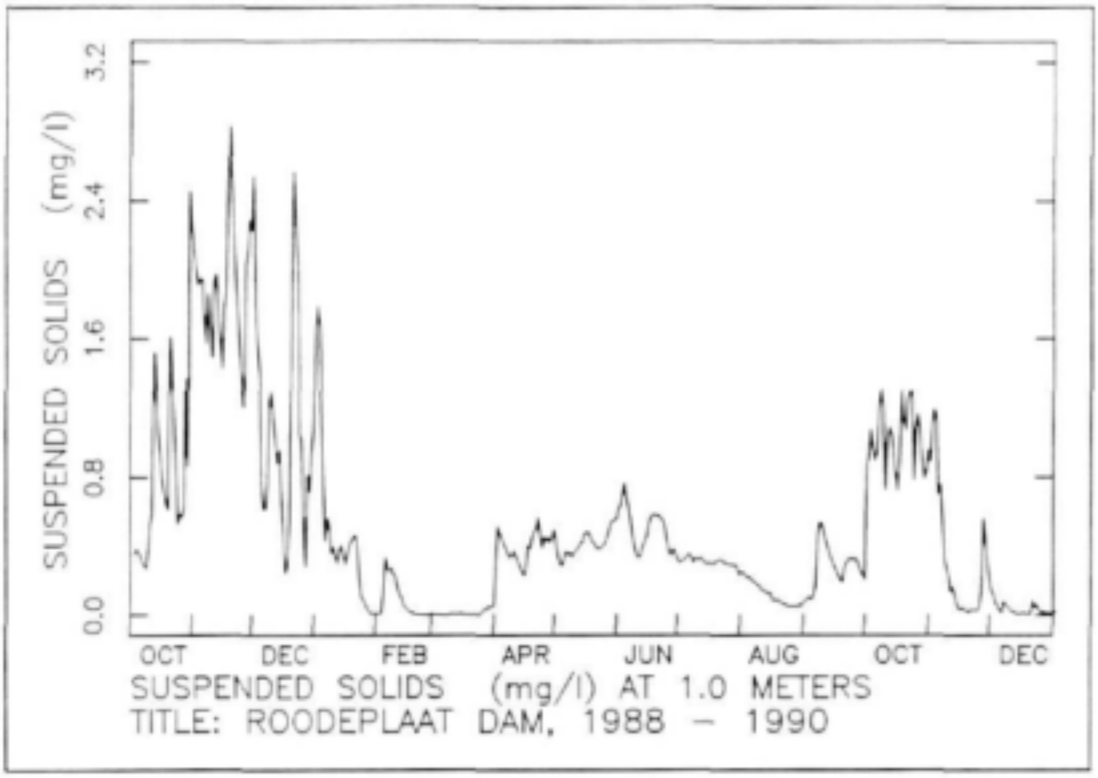

Figure 4.20
Time-series graph of simulated TSS concentrations in Roodeplaat Dam during the validation period.

4.3.6 Dissolved oxygen

Time-series graphs of dissolved oxygen concentration at 1 and 20 m depth are shown in Figures 4.21 and 4.22. As the concentration of dissolved oxygen is affected by so many processes, particularly the epilimnion, it will never be possible to get a very good fit between simulated and observed values. Despite this, the simulated values at 1 m depth (Figure 4.21) are regarded as satisfactory. The correlation between simulated and observed values in the hypolimnion (Figure 4.22) is good.

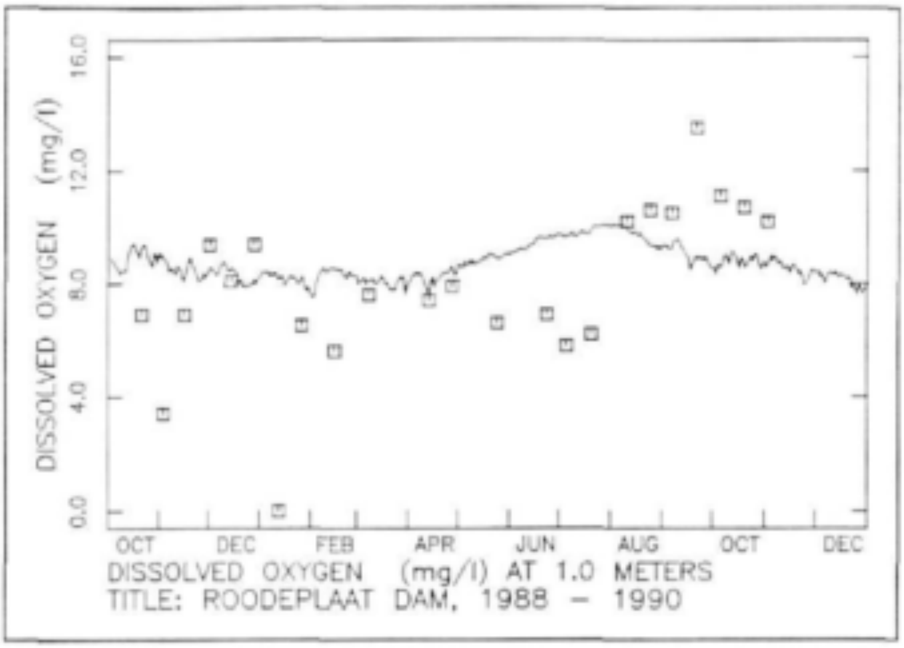

Figure 4.21
Time-series graphs of simulated and observed dissolved oxygen concentration in Roodeplaat Dam at 1 m depth during the validation period

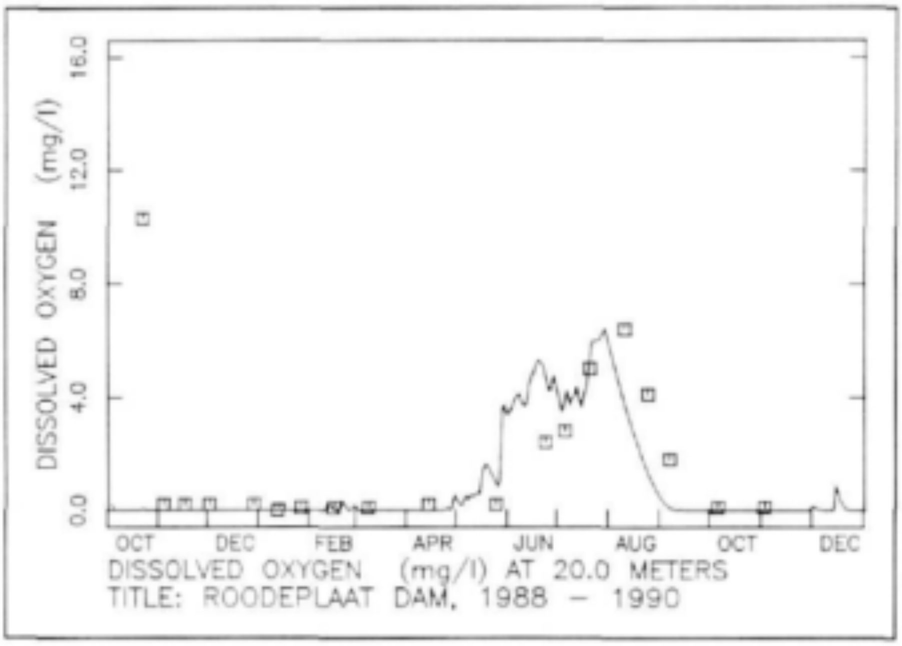

Figure 4.22
Time-series graph of simulated and observed dissolved oxygen concentrations in Roodeplaat Dam at 20 m depth during the validation period.

4.4 General Discussion of Water Quality Simulation Results and Possible Uses of the Modified Minlake Model

The modified MINLAKE model was able to adequately predict the degree of change in the ortho-phosphate concentration from the calibration to the validation period after implementation of the 1 mg phosphate standard.

Though the model accurately predicted the degree of change in average chlorophyll-a concentration from the calibration to the validation period, it over-predicted peak chlorophyll-a concentrations during the validation period. This over-prediction can probably be attributed to the over simulation of nitrogen concentration, especially NO_3-N. During calibration of the model it was found that algal growth in Roodeplaat Dam is either nitrogen or light limited, and that the phosphate concentrations during the calibration period were too high to limit algal growth. As algal growth was nitrogen limited during the calibration period, any increase in nitrogen concentration will cause an increase in chlorophyll-a concentration as well, provided that phosphate concentrations are not low enough to be limiting.

Although the model was not successful in predicting the change in ammonia and nitrate concentrations, it can be used to predict a change in phosphate concentrations, as well as chlorophyll-a concentrations, although with a lesser degree of reliability.

Apart from using the model to predict future conditions due to a change in forcing functions, the model has many other uses as well:

Improving water quality in a reservoir:

The complex nature of reservoir processes makes selection of the most suitable water quality treatment option, and prediction of its effectiveness very difficult. Any treatment strategy may also have secondary, undesirable effects on other reservoir processes. Although it is difficult to foresee these effects, the problem can be better understood by modelling the reservoir. One of the greatest strengths of the modified MINLAKE model is its use to determine the relative importance of the various factor(s) that may limit algal growth in a particular reservoir, thereby assisting the water manager to implement an optimum water treatment strategy. By using the model to introduce the most appropriate treatment strategy at the most appropriate time, the cost effectiveness of the operation can be enhanced.

The possibility and effectiveness of improving water quality by switching between water sources, altering release patterns, or importing better quality raw water, as well as the best time to import raw water, can also be evaluated on a first order basis with the aid of the modified MINLAKE model. The structure of the model is such that, where several reservoirs are situated on the same river, the simulated output data from an upstream reservoir can serve as water quality input data for a downstream reservoir.

The model can also be used as an aid in determining the relative importance of point and diffuse pollutant loads, and to show to what extent the water quality in the reservoir could be altered by changing loads from these sources. For instance, diffuse sources such as informal settlements in the catchment area often contribute significantly to the phosphorus load in the reservoir. Not only can the model be used to illustrate the detrimental effect an increase in phosphorus from these sources would have on the water quality in the reservoir, it can also be used to make a first order assessment of whether provision of improved sanitation facilities to these settlements would be the best way of treating the problem, or whether another treatment option would be more effective.

Managing water quality for water treatment:

Where a reservoir serves as a source of raw water to a water treatment works, deteriorating water quality in the reservoir will have an impact on water treatment. In such instances, a water manager may have to decide whether treating the raw water in the reservoir, treating the water before it flows into the reservoir, or improved water treatment at the treatment works would be the better option, ecologically and economically. The modified MINLAKE model can be used to provide a first order estimate of the change in eutrophic status likely to arise from such options.

Setting of water quality standards:

Each reservoir will respond in a unique way to the load from inflowing rivers, as the trophic state of a reservoir is determined by a multitude of factors such as climate, meteorology, shape and depth of the reservoir, internal nutrient load, and the nutrient load from inflowing rivers. Therefore, some reservoirs may be able to tolerate a higher pollutant load than others (and *vice versa*). Thus, where a reservoir serves as a receiving water body, the trophic response of the reservoir to incoming loads should serve as a measure for setting water quality guidelines for the inflowing rivers. The trophic response of a reservoir is best determined by using a model such as the modified MINLAKE model, which takes account of all the main factors that affect the trophic response of the reservoir.

Design and optimization of monitoring programmes:

Monitoring of water quality and meteorological data is very expensive and hence the frequency of measurement should be kept to the minimum necessary for the efficient operation of a reservoir. Some parameters are more important than others, but, because of the complexity of reservoir processes, it is difficult to determine their relative importance. Often it is only with hindsight that costly deficiencies (or unnecessary monitoring) becomes obvious. One of the great advantages of using the modified MINLAKE model to simulate the complexity of processes in a reservoir, is that it shows the relative importance of the different water quality and meteorological variables. The cost effectiveness of the monitoring programme can be further increased by using the model to determine the optimum monitoring frequency, and in the case of reservoir profile data, optimum depth of measurement. It should therefore be possible to reduce the intensity of monitoring of certain parameters at certain times, without comprising data and information.

Planning of proposed reservoirs:

The model can play a role in planning the sizing and siting of new reservoirs, by giving an indication of the likely trophic state of the reservoir under various conditions.

5. CONCLUSIONS

5.1 Data Bases

The frequency of measurement as well as the quality of the inflow water quality data generally was very good for the early part of the record. Apart from TSS data, the required data were available on a daily basis for almost the entire validation period (October 1988 to January 1990) for the Pienaars River, the major river flowing into the impoundment. With the exception of TSS, virtually no infilling of data was necessary for this river. The frequency of measurement was less good for the Hartbeesspruit and the Edendalespruit and thus limited infilling of data had to be performed. As there often was no flow in the Edendalespruit during the validation period, very little infilling of data was required for this stream. No TSS data were monitored in either the Hartbeesspruit or the Edendalespruit, and thus TSS data had to be synthesized for all three rivers from river flow rate. Validation of the model was hampered to a certain extent by the lack of TSS data.

Although the frequency of measurement as well as the quality of the inflow water quality data during the calibration period generally was very good, the frequency of measurement prior, as well as subsequent to the validation period is poor. Of particular concern is the fact that no river water quality data was monitored from the period January 1990 to July 1993.

The frequency of measurement of some of the required meteorological data was good, but unfortunately the quality of the meteorological data for variables such as sun hours, radiation, air temperature and humidity was poor. Extensive manipulating and infilling of data had to be performed to construct the meteorological data base required by the model. Although the model is moderately sensitive to humidity, it is not very sensitive to the other variables that required extensive infilling, and thus model performance should not have been affected by the relatively poor quality of the meteorological data. The model is extremely sensitive to wind speed, but fortunately the data bases for both wind speed and wind direction were very good for the selected validation period and no infilling was required.

Of particular concern is the fact that meteorological monitoring appears to have been discontinued since July 1990 and that no meteorological monitoring is currently performed at Roodeplaat Dam.

The frequency of measurement and the quality of in-dam data were adequate, with regular water quality measurements carried out in the hypolimnion. The data from these greatly facilitated model validation.

5.2 Validation of the Hydrodynamic Behaviour of Roodeplaat Dam

The modified MINLAKE model was well able to simulate the hydrodynamic behaviour of Roodeplaat Dam during the validation period. This implies that the model can be used to simulate the effect of, for instance, artificial de-stratification on the hydrodynamic behaviour of the impoundment.

5.3 Validation of the Water Quality Behaviour of Roodeplaat Dam

The modified MINLAKE model was well able to predict the magnitude of the change in ortho-phosphate concentration that occurred in the impoundment as a result of the implementation of the phosphate standard.

The model was unsuccessful in predicting the change in ammonium concentration from the calibration to the validation period. Correlation between simulated and observed nitrate concentrations during the validation period were also poor. The exact cause for the inability of the model to simulate nitrogen concentrations correctly could not be established, but the most likely possibility is that the sediment nitrogen release rates have changed from the calibration to the validation period (a period of 8 years).

The model was only moderately successful in predicting the change in chlorophyll-a concentrations from the calibration to the validation period. There was very little change the observed average chlorophyll-a concentration from the calibration to the validation period, and though the model was successful in predicting this, it over-predicted peak concentrations and the percentage time that algae would reach nuisance concentrations. The poor performance in predicting the change in chlorophyll-a concentrations probably can be linked to the failure of the model to simulate nitrogen concentrations correctly, as algal growth in Roodeplaat Dam during the calibration period was nitrogen (and light) limited.

5.4 Possible Uses of the Modified Minlake Model

The model can be used to predict the change in reservoir phosphate concentration as a result of the implementation of the phosphate standard. However, it should be used with caution to predict the change in algal concentrations, and in its present form should not be used to predict the change in nitrogen concentrations.

One of the greatest strengths of the modified MINLAKE model is its use to determine the relative importance of the various factors that may limit algal growth in a particular reservoir. Thus it can be of great assistance to the water quality manager in gaining an understanding of the processes in a particular reservoir and assist in identifying an optimum water treatment strategy.

The model is also well suited to assisting in the design/optimisation of water quality and meteorological monitoring programmes by using the model to determine the relative importance of the variables to be monitored and determine the optimum monitoring frequency and, in the case of reservoir data, the optimum depth of measurement.

The modified model can also be used to provide first order estimates of:

- the effectiveness of improving water quality by importing water from another source;

- the impact of growing pollution inputs;

- the assimilative capacity of a reservoir and

- the trophic status of proposed new reservoirs.

6. RECOMMENDATIONS

The following recommendations arise from the study:

- Monitoring of meteorological data should be reinstated at Roodeplaat Dam;

- TSS monitoring should carried out regularly in both the rivers and the impoundment;

- The sediment uptake/release algorithms should be improved;

- The possible use of the model as a tool in de-stratification experiments should be investigated;

- The model should be tested on another reservoir;

- Further work is required to better determine the most appropriate ranges and combinations of values for the host of model calibrations values.

7. REFERENCES

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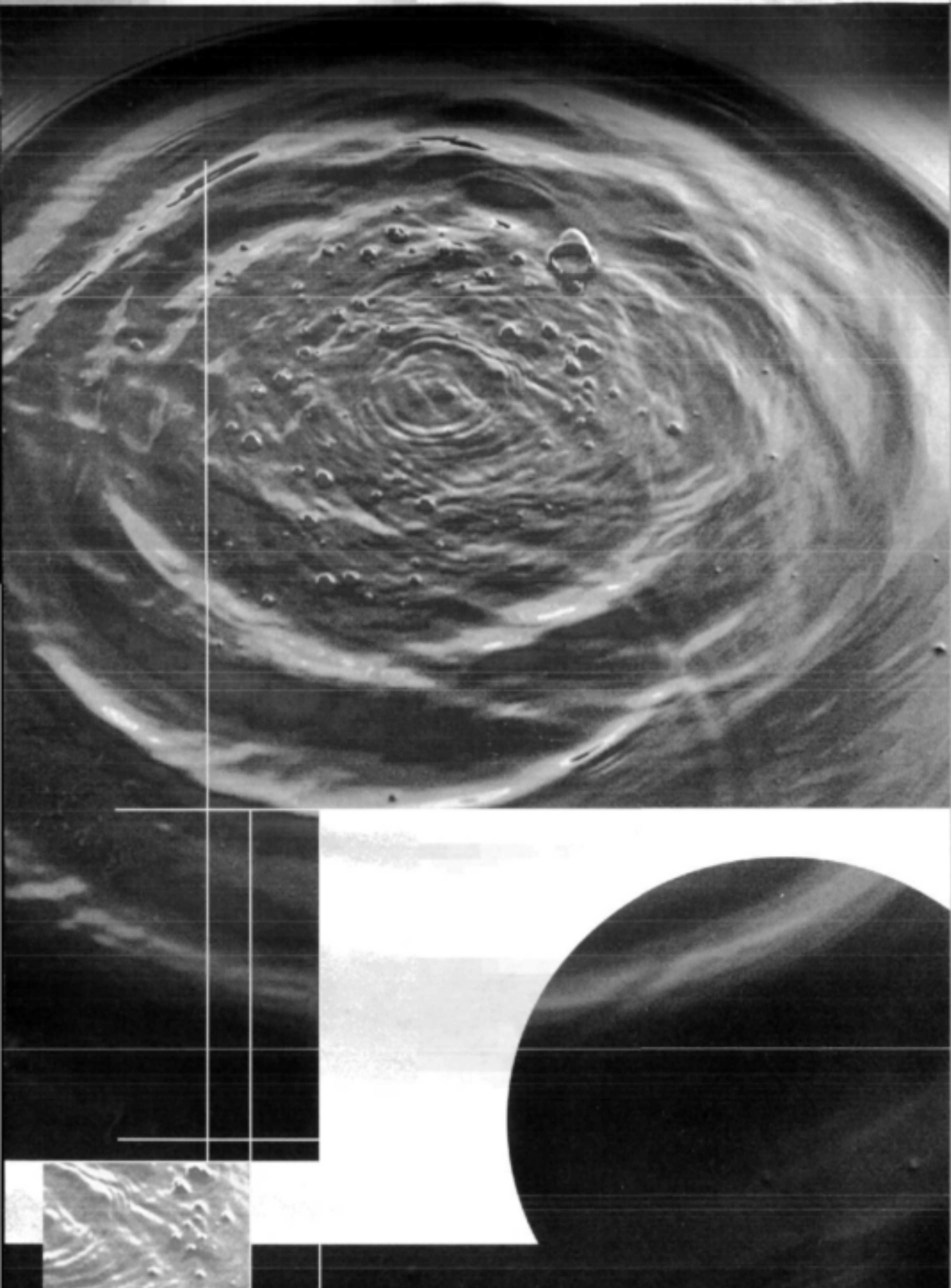

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