# THE DEVELOPMENT OF MANAGEMENT ORIENTATED MODELS FOR EUTROPHICATION CONTROL

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# EXECUTIVE SUMMARY

## 1. Introduction

Like many other countries in the world (Vollenweider, 1981), South Africa experiences serious water quality problems as a result of eutrophication. In South Africa management-oriented prediction of the consequences of eutrophication has gone through several phases. The first was a report reviewing eutrophication and providing tentative guidelines for its control in South Africa (Toerien, 1977). A second report provided guidelines for the control of eutrophication in South Africa (Walmsley and Butty, 1980). On the basis of these reports, the Department of Water Affairs decided to implement a special phosphorus (P) standard on effluents discharged in sensitive catchments. The special P standard was severely criticized and led to a third study in which available data and models were used to assess the impact of eutrophication control strategies on the trophic response of reservoirs in sensitive catchments (Grobler and Silberbauer, 1984). One of the conclusions of the study was that the highly variable hydrological conditions in South Africa required dynamic eutrophication models to be developed. During the fourth phase a dynamic Reservoir Eutrophication Model (REM) was developed for South African reservoirs (Grobler, 1985).

The development of a decision support system (DSS) for using the REM submodels as an aid to decision-making in implementing eutrophication control measures, represents the fifth phase in this research and is described in this report.

## 2. Objectives of the project

A joint project was initiated between the Division of Water Technology, Department of Water Affairs and the Water Research Commission. The primary goals of the project were (1) to develop the Reservoir Eutrophication Model (REM) further and (2) to implement this model by means of user-friendly software on a microcomputer to serve as a decision support system.

The objectives of each of these goals were:

1. **Goal 1 - Further development of the REM submodels**

   (a) Develop models for calculating P loads from flow and concentration records.
   (b) Refine the prediction of nonpoint source P loads.
   (c) Estimate the loss of point source P in rivers.
   (d) Refine the dynamic phosphate model by incorporating a reservoir water balance.
   (e) Refine the models for simulating the trophic response of reservoirs.
   (f) Develop an uncertainty analysis procedure.

2. **Goal 2 - Development of a decision support system for eutrophication control.**

   (a) Implement the REM submodels on a microcomputer.
   (b) Incorporate the REM submodels into a user friendly Decision Support System.
   (c) Write a comprehensive user's manual for the software which was to be developed.
   (d) Investigate ecological - economic - management decision models which could be used to include the quantifiable and unquantifiable consequences of eutrophication into the decision-making process.

## 3. Major results and conclusions of the project

### 3.1 Modelling the eutrophication process

In order to assess the impacts of different P control measures on water quality in receiving water bodies, the simulation of the three main components of the eutrophication process was required.

**Subsystem 1** describes the relationship between P control measures in a catchment and the external P loads received by reservoirs. A statistical approach, i.e. a regression model, was developed to simulate nonpoint source P export as a function of runoff and catchment properties. Point source loads, where the discharge and concentration can be measured, were estimated as the product of the mean effluent discharge and the mean P concentration.

**Subsystem 2** describes the relationship between external P load and P concentrations in a reservoir. The principle of conservation of mass was used to simulate the change in the mass of P in the reservoir with time. A water balance was carried out simultaneously with the phosphorus mass balance in order to calculate the ambient P concentration in the reservoir.

**Subsystem 3** describes the relationship between in-lake P concentration and indicators of algal production, e.g. standing biomass (chlorophyll a concentration). A statistical approach, i.e. a regression model, was used to simulate temporal changes in algal biomass (as chlorophyll) as a function of the ambient P concentration (in clear water reservoirs) as well as a function of inorganic suspended sediments (in turbid reservoirs).

## 3.2 A decision support system for the REM models

The models which describe the eutrophication process were incorporated into a user friendly Decision Support System (DSS). The DSS consist of three components i.e. a model base, a data base and a computer program. The computer program links the model base and the data base and provides the interface with the user.

The model base contains the different REM submodels which describe the different subsystems of the eutrophication process. The data base contains the hydrological, point source, catchment and reservoir characteristic data of a specific reservoir. The DSS which was developed for REM, is a program which helps the user prepare the input data to the models, then runs the models and displays the simulation results in different formats. It is responsible for storing and retrieving data, organizing interim results and displaying results in a graphical from. The interface with the user is a dialogue system which uses menus which have to be completed by the user. The DSS furthermore checks for errors, corrects these if necessary and provides help facilities to new users.

The Dialogue system is the most important feature of the DSS because it characterizes the power, flexibility and usability of the DSS. In the past modellers were preoccupied with the structure of their models. Separate models were developed for each distinct part of the problem but were not integrated with each other. It was left to the manager as a manual and frustrating process to establish the necessary communication between the relevant models. With the DSS this problem is solved by incorporating the models into a framework which performs the integration between the different models and the data as well as provide an interface with the user. The interface which was developed is largely menu driven and makes ample use of graphics to display numerical data.

An important feature in the development of the DSS was the iterative development process in collaboration with the users. The users were presented at the earliest opportunity with a prototype of the DSS. Through using the system, the user fed back information on shortcomings experienced and enhancements required. These were taken care of in subsequent versions of the DSS which, upon completion were passed back to the user for re-evaluation. The value of the user in this phase of the development cannot be overemphasized.

The program software (REMDSS) which was developed runs on a IBM compatible personal computer under the MS-DOS operating system. All the simulation results are displayed on screen and the user has the option of displaying results also on a printer or plotter. The program was developed with TURBO PASCAL (Borland International) and various third party supporting software. A comprehensive user's manual (Rossouw and Kelly, 1989) for the DSS was developed as part of the project.

### 3.3 Management decision models

The decision support system described so far provides decision makers only with information about the predicted physical, chemical and biological response of the reservoir to different eutrophication control measures. In the selection of appropriate control strategies, decision-makers are often faced with a multiplicity of conflicting objectives. The problem decision makers are faced with is how to integrate quantitative and qualitative information in the same decision framework. In this project the Analytical Hierarchy Process (AHP) developed by Saaty (1982) was used as decision model.

The AHP was applied with water resource managers from the Department of Water Affairs to select an optimum eutrophication control measure for Hartbeespoort Dam. The REMDSS was used to predict the impact of different control measures on water quality. After the actual control measure was selected for Hartbeespoort Dam, the AHP was retrospectively applied to analyze the decision which resulted in the particular control measure being selected.

## 4. Statements about the objectives

All but two of the objectives set for the project was met to the satisfaction of the users of the DSS. In the initial phase of the project, it became clear that it would not be possible to meet the objective of refining various aspects of the nonpoint source export model in this project because of the amount of research required. A separate project with the WRC, entitled "The development of phosphate export models for catchments", was therefore initiated to fully investigate this aspect.

The second objective which was not met was the development of an uncertainty analysis procedure. There were two basic reasons for this. The first was that the project responded to user needs throughout the development phase of the DSS. For various reasons they did not require uncertainty analysis. The second reason was that problems were experienced with obtaining the services of an overseas expert to help with this phase. At the penultimate steering committee meeting is was decided that uncertainty analysis should only be done if the time allowed it.

## 5. Technology Transfer

The success of the project can also be measured in the acceptance of the decision support system by water resource managers. The decision support system for eutrophication control was used to assess the impact of the 1 mg P/ℓ effluent standard on reservoirs in sensitive catchments. The project team were directly involved in applications which resulted in eight reports to the Department of Water Affairs. The following systems were investigated by the project team:

1. Crocodile River catchment - Hartbeespoort Dam and Rietvlei Dam.
2. Umgeni River system catchment - Midmar, Albert Falls, Nagle and Inanda dams.
3. Vaal River catchment - Vaal Dam and Bloemhof Dam and the middle Vaal River system.

The decision support system for eutrophication control was also used by the Department of Water Affairs for applications to the following reservoirs:

1. Roodeplaat Dam in the Pienaars River catchment.
2. Loskop Dam and Bronkhorstspruit Dam in the Olifants River catchment.
3. Shongweni Dam in the Umlaas River catchment.
4. Laing Dam and Bridle Drift Dam in the Buffalo River catchment.
5. Grootdraai Dam in the Vaal River catchment.

The decision support system was also used in the following studies:

1. An assessment of the impact of point and nonpoint source P pollution from Botshabelo, a high density low cost housing project in the eastern Free State, on reservoirs in the Modder River.
2. A M.Sc study to assess the economic impacts of eutrophication (Botha, 1989).

Two international publications (Grobler *et al.*, 1987; Grobler and Rossouw, 1989) were also produced during the course of the project and various concepts of the decision support system were introduced with six papers presented at national and international conferences.

## 6. Recommendations

At present, the DSS only simulates the transport and fate of P in catchment-river-reservoir systems. In the course of applications, four limitations in the DSS were identified. In order to develop realistic eutrophication control strategies, these shortcomings should be addressed in future development work on management orientated models.

6.1 **Nitrogen limited systems** - It was found that in some cases eutrophication related water quality in reservoirs were primarily regulated by the availability of nitrogen (e.g. Rietvlei Dam). Under these circumstances the export of N from a catchment, its fate in water bodies and the biological response to the ambient N and P concentrations should be simulated.

6.2 **Light limited systems** - In reservoirs where the growth of algae is limited by the availability of light as a result of high suspended sediment turbidity, much higher nutrient concentrations can be tolerated than in clear water systems. To simulate algal growth in these systems turbidity should be incorporated into the models. This may also require that attention be given to characterizing the effects of salinity on turbidity.

6.3 **Spatial variability** - REMDSS assumes a completely mixed system. In some cases the water quality at specific abstraction points are of importance rather than the average water quality of the system. To meet these needs, methods to simulate spatial variability in management orientated models should be investigated.

6.4 **Sediment release processes** - Methods should be investigated to modify the sedimentation parameter to describe the increase in P losses which were observed after the sediment was exposed during a drought.

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## LIST OF FIGURES

## GLOSSARY OF ACRONYMS

| | |
|---|---|
| AB | Algal Biomass. |
| AHP | Analytical Hierarchy Process. An operations research tool that is a multi-objective, multi-criterion decision-making system which employs a pairwise comparison procedure to arrive at a scale of preferences amongst sets of alternatives. |
| Chl | Chlorophyll a. Indicator of algal biomass in water. |
| DBMS | Data Base Management System |
| DSSB | Decision Support System. |
| ISSB | Inorganic Suspended Solids. Measure of suspended sediment in the water. |
| ODEB | Ordinary Differential Equation. |
| OECD | Organization for Economic Community Development. |
| P | Phosphorous. |
| REM | Reservoir Eutrophication Model. |
| REMDSS | Reservoir Eutrophication Model Decision Support System. The software package developed during the course of the contract. |
| RMSE | Root Mean Square Error. Used to quantify goodness-of-fit. |
| SD | Secchi Disk depth. Used as a measure of water clarity. |
| WRC | Water Research Commission |

# 1. INTRODUCTION

## 1.1 Introduction to eutrophication and management orientated models

Like many other countries in the world (Vollenweider, 1981), South Africa experiencing serious water quality problems as a result of eutrophication. Phosphorus has been identified as the plant nutrient which limits plant growth most often in freshwater systems and is considered to be the easiest to control (Toerien, 1977).

South African authorities responsible for water resource management adopted a policy whereby preference is given to controlling the causes rather than the consequences of eutrophication. The assumption was that point sources are responsible for between 80% and 90% of phosphorus loads to receiving water bodies in the so called 'sensitive' catchments (Taylor *et al.*, 1984). As a result, all wastewater effluents which are returned to water bodies in sensitive catchments are legally required to comply to a 1 mg P/ℓ phosphorus standard. This standard was derived from an assessment of the technological and economic feasibility of phosphorus removal from the effluent of typical wastewater treatment plants.

The assimilative capacity of individual water bodies to absorb phosphorus loads without experiencing undesirable changes in eutrophication-related water quality was ignored in setting a uniform effluent standard. Therefore, enforcing it could be expected to have either very little impact, e.g. if the receiving water body has a large assimilative capacity, or not enough impact, if the assimilative capacity of the receiving water is grossly exceeded. It was realized that a phosphorus control strategy based on enforcing a uniform standard would be inappropriate. It would lead either to unnecessary expenditure or to inadequate protection of water quality. Fortunately, the 1 mg P/ℓ standard does not have to be applied uniformly. The laws governing water quality protection allow for standards to be relaxed or even to be made stricter if required. This flexibility allows the authorities to take into account the assimilative capacity of receiving waters for phosphorus pollution in designing and implementing phosphorus control strategies for point sources.

If the assimilative capacity of receiving water bodies for phosphorus pollution is to be considered in decisions on the implementation of a phosphorus standard, the impacts of these decisions on water quality must be assessed. One of the best ways to do this is to use water quality models to simulate eutrophication-related water quality in the receiving water bodies in response to different point source control strategies.

A suite of dynamic eutrophication models were developed for South African reservoirs, called the Reservoir Eutrophication Model (REM) (Grobler, 1985). However, an experienced modeller is required to run these models. It was soon realized that to gain acceptance by water resource managers, these models had to be incorporated into an integrated modelling framework which could be used by inexperienced computer users.

### 1.2 Detailed objectives of the project

A joint project was initiated between the Division of Water Technology, Department of Water Affairs and the Water Research Commission. The primary goals of the project were: (1) to development of the Reservoir Eutrophication Model (REM) further, and (2) to implement this model by means of user-friendly software on a microcomputer to serve as a decision support system.

The objectives of each of these goals were:

1. **Goal 1 - Develop the REM submodels further**

(a) To develop models for calculating phosphorus loads from flow and concentration records. Investigate statistical and flow interval methods to determine their applicability to South African rivers.

(b) To refine the prediction of nonpoint source phosphorus loads. A model had already been developed to estimate phosphorus export from a catchment as a function of runoff. However, a quantifiable relationship between catchment characteristics and phosphorus export still had to be established.

(c) To estimate the loss of point source phosphorus in rivers.

(d) To refine the dynamic phosphate model by adapting the reservoir water balance model in "Water Resources of South Africa" for the project's needs. The sedimentation parameter which describe the in-lake phosphorus losses had to be recalibrated with the most recent data available.

(d) To refine the models for simulating the trophic response of reservoirs. Models were available to relate reservoir phosphorus concentrations to chlorophyll concentrations in clear water reservoirs. However, a chlorophyll:phosphorus relationship had yet to be found for reservoirs which receive high suspended sediment loads, as is the case with most South African reservoirs.

(e) To develop an uncertainty analysis procedure for quantifying the usefulness of predictions to management.

2. **Goal 2 - To develop a decision support system for eutrophication control.**

(a) To implement the REM submodels on a microcomputer.

(b) To incorporate the REM submodels into a user friendly Decision Support System. The software had to be able to carry out data management, link the REM submodels and display the simulated output in an acceptable format.

(c) To write a comprehensive user's manual for the software which was developed and prepare the decision support software for distribution to interested parties.

(d) To investigate ecological - economic - management decision models which could be used to include the quantifiable and unquantifiable consequences of eutrophication into the decision-making process.

The details of how the REM models were incorporated into the Decision Support Software (REMDSS) and how to run the software are given in the user's manual (Rossouw and Kelly, 1989).

## 1.3 Overview of research into management-orientated eutrophication control

In South Africa management-oriented prediction of the consequences of eutrophication has gone through several phases. The first was a report reviewing eutrophication and providing tentative guidelines for its control in South Africa (Toerien, 1977). After that the eutrophication problem was studied in several South African reservoirs. This resulted in the publication of a second report providing guidelines for the control of eutrophication in South Africa (Walmsley and Butty, 1980). An important concept dealing with the impact of eutrophication, namely that of nuisance conditions varying in severity and frequency of occurrence, was developed as part of that study (Walmsley, 1984).

On the basis of these reports, the Department of Water Affairs decided to implement measures to control the causes of eutrophication rather than the consequences. It was assumed that between 80% and 90% of the total phosphorus load from 'sensitive' catchments, originated from point sources (Taylor *et al.*, 1984). As a result, all waste water effluents which are returned to water bodies are legally required to comply to a 1 mg/ℓ phosphorus standard (Government Gazette, 1984). The legislation was promulgated in 1980 for full implementation in 1985.

The 1 mg P/ℓ standard was severely criticized by industries and local authorities having to comply with the standard (they felt it is unnecessary or to stringent) and limnologists (who felt that it was not stringent enough to prevent eutrophication in many aquatic systems). This led to a third study in which available data and models were used to assess the impact of certain eutrophication control strategies, i.e. the 1 mg P/ℓ standard and the control of phosphorus in detergents, on the trophic response of reservoirs in sensitive catchments (Grobler and Silberbauer, 1984). In this study the applicability of the OECD type (steady state) eutrophication models to South African reservoirs was investigated. It was concluded that the highly variable hydrological conditions in South Africa requires dynamic eutrophication models to be used.

During the fourth phase a dynamic Reservoir Eutrophication Model (REM) was developed for South African reservoirs (Grobler, 1985). It was soon realized that to ensure that REM is used in the decision-making process it needed to be made user friendly. The development of a decision support system (DSS) for using REM as an aid to decision-making in implementing eutrophication control measures, represents the present and fifth phase in this research.

## 1.4 Format of the report

The report begins by describing how the eutrophication process is conceptualized as three subsystems in the REM model and the different modelling approaches for simulating each subsystem. Each of the three subsystems is then broken down into its components and each component is discussed separately. Refinements which were made to the models are then discussed in greater detail.

In chapter 6 a description is given of how the models were integrated into a Decision Support System for use by water resource managers. The details of how the REM models were incorporated into the Decision Support Software (REMDSS) and how to run the software are given in the user's manual (Rossouw and Kelly, 1989).

In chapter 7 a description is given of how the results of DSS applications are incorporated into the decision making framework to be considered along with other aspects which may influence the final decision to taken.

Chapter 8 is a list of the applications which were done with the DSS to assess different eutrophication control measures. In section 9 the lack of progress with uncertainty analysis is discussed and finally, recommendations are made of research needs identified during the project.

## 2. MODELLING THE COMPONENTS OF THE EUTROPHICATION PROCESS

To assess the impacts of different phosphorus control measures on water quality in receiving water bodies required simulation of the three main components of the eutrophication process. These are: the export of nutrients from the catchment, their fate in river-reservoir systems and the eutrophication related water quality resulting from the ambient nutrient concentrations (Figure 1).

Caswell (1976) distinguished between two types of models which could be developed for simulating the behaviour of ecosystems, i.e. research and management-oriented models. Research models are used mainly as aids to understand the functioning of ecosystems whereas management-oriented models are used to predict the response of systems to alternative management options. The requirements of management-oriented models are that they should be conceptually simple, easy to implement and compatible to the available data (Skopp and Daniel, 1978). Separate models, conforming to the requirements of management-oriented models, were developed for simulating each of the three main components of the eutrophication process in South African reservoirs (Grobler, 1985). These models were later incorporated into a decision support system which was used to predict the impacts of alternative phosphorus control measures on water quality in South African reservoirs.

In the analysis of reservoir rehabilitation by phosphorus reduction, it is recommended that analysis of the recovery behaviour is performed by conceptually dividing the ecosystem into two compartments. These are a subsystem for describing the fate of phosphorus in reservoirs and a subsystem for describing the relationship between biological response variables and in- lake phosphorus concentrations (Sas, 1988). The two subsystems require different modelling approaches. A similar framework was used in the analysis of eutrophication of reservoirs and the effect of control measures, but three instead of two subsystems were used.

**Subsystem 1** describes the relationship between phosphorus control measures in a catchment and the external phosphorus loads received by reservoirs (Figure 2).

In this case, the primary interest is in the amount of phosphorus leaving the catchment. The processes causing changes in the amount of phosphorus leaving the system are the phosphorus entering the system (interbasin water transfers and point sources) and the changes with time in

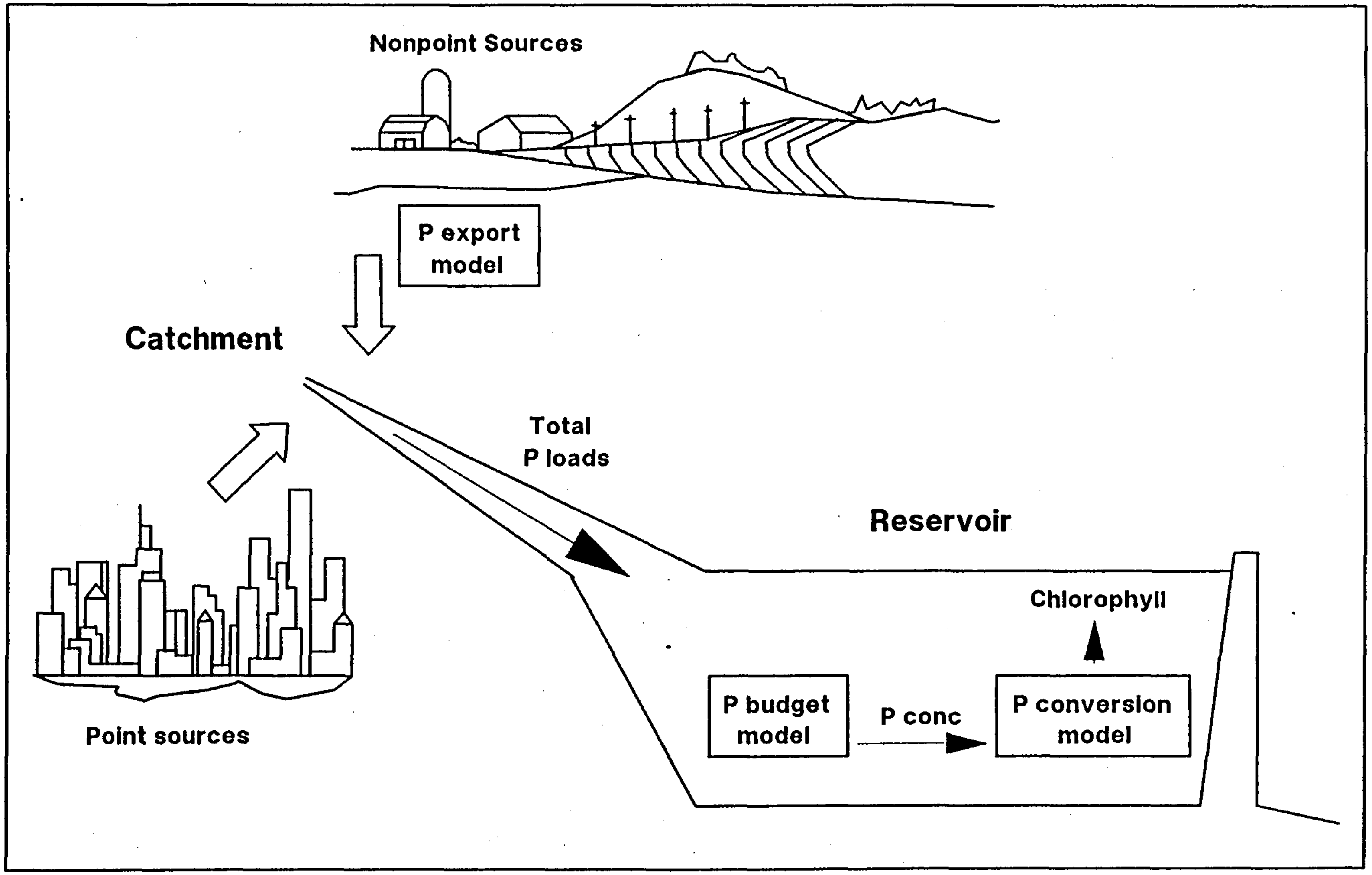


Figure 1 Conceptual diagram of the components of the eutrophication process. The sources of phosphorus are divided into point sources (which can be easily measured) and nonpoint sources (all other sources).

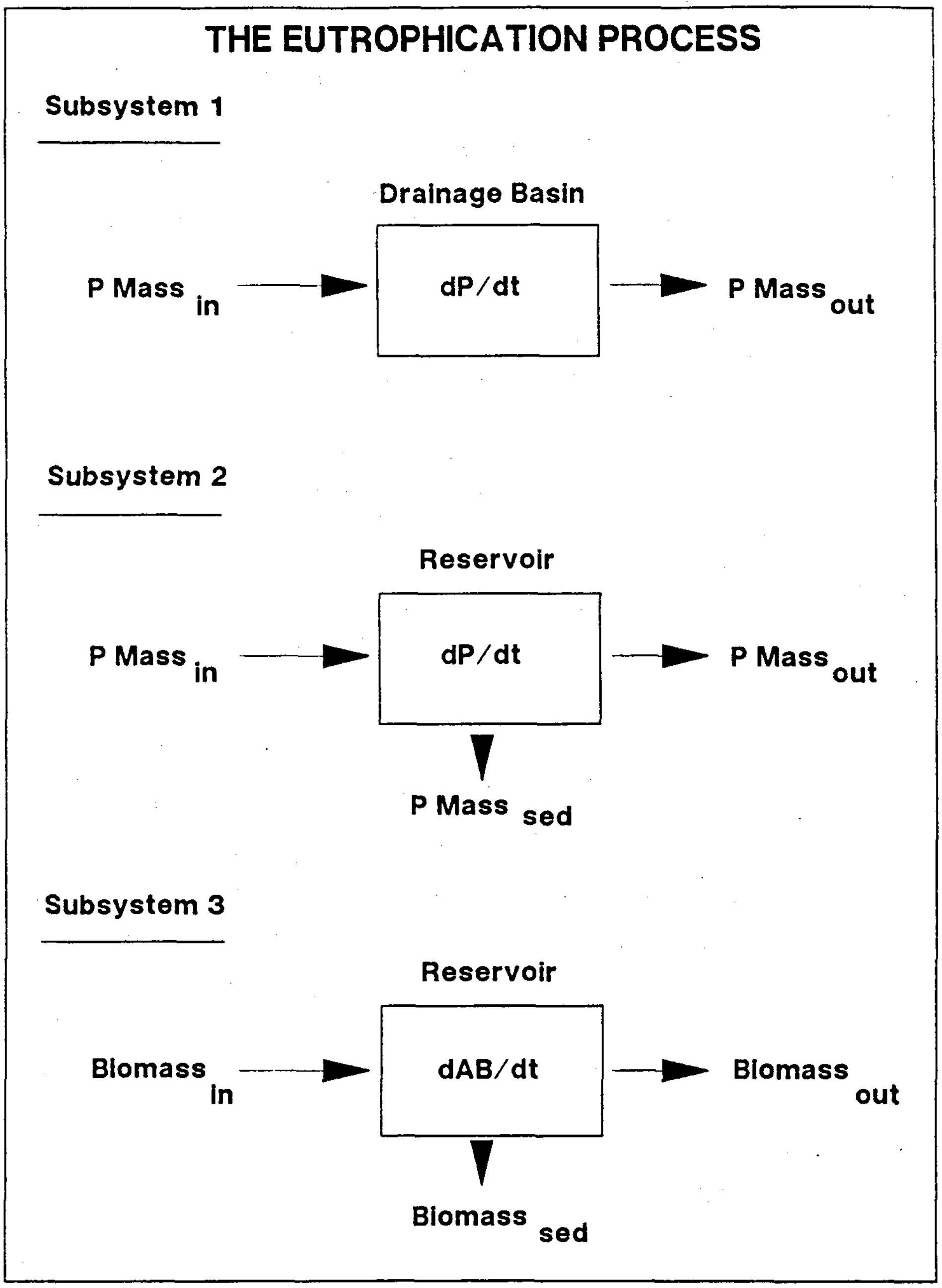


Figure 2 Three different subsystems considered in modelling the eutrophication process.

phosphorus content of the system (dP/dt). The processes affecting dP/dt in a catchment (erosion, storage, remobilization etc.) are highly complex and it is very difficult to quantify dP/dt. If dP/dt cannot be estimated independently, the principle of conservation of mass cannot be used to simulate the mass of phosphorus leaving the system (P export) simply as a function of phosphorus entering the system and changes in the phosphorus content of the system. Consequently a statistical approach, i.e. a regression model, was developed to simulate P export as a function of phosphorus entering the system and catchment properties.

**Subsystem 2** describes the relationship between external P load and P concentrations in a reservoir (Figure 2).

The dominant processes causing changes in phosphorus mass with time (dP/dt) in the reservoir are the mass of phosphorus entering and leaving the system and the mass lost through sedimentation. These (P $Mass_{in}$, P $Mass_{out}$ and P $Mass_{sed}$) can be estimated independently. Therefore, the principle of conservation of mass can be used to simulate dP/dt. Changes in the volume of water stored also need to be simulated because, ultimately, the phosphorus concentration in the water body has to be calculated. Therefore, a water balance must be calculated simultaneously with the phosphorus mass balance.

**Subsystem 3** describes the relationship between in-lake P concentration and indicators of algal production, e.g. standing biomass (chlorophyll a concentration) (Figure 2).

The processes causing changes in standing Algal Biomass (AB) with time (dAB/dt) in the reservoir are the biomass entering and leaving the system, i.e $biomass_{in}$, $biomass_{out}$ and $biomass_{sed}$, as well as the growth (as a function of P concentration and other factors) and decay (respiration, grazing etc.) of biomass in the system. $Biomass_{in}$, $Biomass_{out}$ and $Biomass_{sed}$ can be estimated independently. However, these are generally not the dominant processes determining dAB/dt. Growth and decay dominate the changes with time in standing algal biomass in most reservoirs and are generally very difficult to quantify. Therefore, the principle of conservation of mass cannot be used to simulate the change in biomass with time in the system (dAB/dt) simply as a function of biomass entering and leaving the system as was the case with phosphorus. Consequently a statistical approach, i.e. a regression model, is generally used to simulate temporal changes in algal biomass (as chlorophyll) as a function of the ambient phosphorus concentration.

The combination of models developed for the different subsystems required for simulating the eutrophication process are referred to as the Reservoir Eutrophication Model (REM). These models are described in greater detail below.

Although REM is conceptually similar to the OECD eutrophication modelling approach (Vollenweider and Kerekes, 1981; OECD, 1980) it represents some major departures from the OECD approach (Grobler, 1985).

(i) REM is a dynamic model whereas the OECD eutrophication modelling approach assumes water bodies to be in steady state. REM accepts time varying inputs of hydraulic and phosphorus loads to simulate time varying output of state variables such as the volume of water stored and the phosphorus concentration in a water body. This departure from the OECD modelling approach was required because the very large hydrological variability characteristic of semi-arid regions, such as South Africa, makes the assumption of steady state untenable. To be able to simulate accurately the eutrophication process for a representative range of hydrological conditions in regions experiencing highly variable hydrology, requires that long time series of hydrological data be used. These data series are generally not available and hydrological models are used to extend existing hydrological records. In South Africa, 60 years and longer time series of hydrological data, e.g. monthly runoff, are typically used in investigations for water quality modelling.

(ii) Parameter estimation and verification for the OECD modelling approach was done with data from a cross section of lakes (Reckhow and Chapra, 1983). In the case of REM it is done with time series data from a specific water body (Grobler, 1985). The departure from the cross sectional to a time series approach is required because temporal variation usually exceeds spatial variation in semi-arid regions that REM was developed for.

All applications of REM are made to assess the probable impacts of alternative phosphorus, or other water resources management options, on future water quality in reservoirs. Thus, all the input data are also derived from predictions of what is expected to happen under each of the management options being investigated.

# 3. MODELLING SUBSYSTEM 1

The sources of phosphorus from a catchment are divided into point sources i.e. sources which can be easily identified, quantified and controlled; and nonpoint sources, i.e. all the remaining ones. The contributions from point and nonpoint sources to the total phosphorus load are estimated separately. The REM model requires as input, monthly phosphorus loads entering the reservoir.

The term load is used to describe the phosphorus flux (mass time$^{-1}$), entering a water body in the form of an effluent or passing a sampling point in a river. The term export, which has units of mass area$^{-1}$ time$^{-1}$, is used to describe the total phosphorus load from a catchment which was normalized through dividing it by the catchment area. Similarly, the term discharge is used, with units of volume time$^{-1}$, to describe the flow of water past a point and the term runoff, with units of volume area$^{-1}$ time$^{-1}$ (depth time$^{-1}$), for discharge normalized per unit area of a catchment.

## 3.1 Point sources

The most important point sources of plant nutrients in South African catchments are effluents from domestic and industrial wastewater treatment plants. The discharge of these effluents can be measured and future discharges can be estimated, in the case of domestic wastewater, as a function of population growth rates or, in the case of industrial or mining effluents, according to planned future activities.

Monthly phosphorus loads from point sources are estimated as the product of the mean monthly effluent discharge and phosphorus concentrations in the effluent:

$$PL_{ij}=PQ_{ij}\times C_{ij} \tag{1}$$

where $PL_{ij}$ is the P load, $PQ_{ij}$ is the average effluent volume, and $C_{ij}$ is the average P concentration during month i in the effluent from point source j. The total point source phosphorus load contributed by the different point sources in a catchment is calculated as the sum of the individual point loads, modified by a loss rate (LR) which takes into account losses of phosphorus between a specific point source and the receiving water body:

$$PL_i = \sum_{j=1}^{n} (PL_{ij} \times LR) \tag{2}$$

### River P losses

Not all the P released from point sources into rivers actually reaches downstream reservoirs. In some cases losses of as much as 50% of the original amount of P entering the river have been measured. This is often the case in turbid rivers where most of the P is adsorbed onto suspended sediment particles which settle out before reaching the downstream reservoir. There is uncertainty whether the observed loss is permanent or whether the sediment will merely be resuspended during flood events and be deposited in the downstream reservoir. Although it was one of the original tasks of the project to model phosphorus losses in the rivers, it was soon realized that the models were not readily available but, more importantly, the data required to calibrate and verify these models for South African rivers, did not exist.

At present, LR is estimated on the basis of historical data and an understanding of the behaviour of the stretch of river between a given point source and what is considered to be the receiving water body. LR can be varied to establish how sensitive the model output is to different assumed values for LR. The worst possible case can be simulated by assuming no P losses in the river.

### Projected effluent P loads

Projections of future phosphorus loads from point sources in a catchment are calculated as the product of mean projected effluent discharge and assumed mean P concentrations in the effluent, which reflect the particular phosphorus control option being evaluated. Mean projected effluent discharges are estimated as a function of assumed effluent growth rates which are based on projected growth rates for the population and industrial and mining activities in the catchment under consideration.

The mean values of projected effluent volumes and phosphorus concentrations in effluents were used to estimate mean point source derived phosphorus loads instead of time series data. There usually is so little temporal variation in point source phosphorus loads that it did not justify the extra effort to develop time series of projected effluent volumes and phosphorus concentrations in effluents.

## 3.2 Nonpoint sources

In contrast to point sources, it is much more difficult to estimate P loads derived from nonpoint sources. Nonpoint source derived phosphorus loads are characterized by large temporal and spatial variability. Consequently, they are difficult to estimate and predict, and require the use of mathematical models that relate phosphorus export to hydrological factors and catchment characteristics (Grobler, 1985). Runoff, land form and land use are considered to be the most important factors affecting the quantity of nonpoint source derived phosphorus exported from drainage basins (Sonzogni *et al.*, 1980; Jolankai, 1983).

It was found that runoff was the most important of the factors effecting nonpoint source phosphorus export, explaining more than 80% of the variance in phosphorus export from catchments in South Africa and the United States (Grobler and Silberbauer, 1984; Grobler, 1985). It was only after the variance explained by runoff had been removed that the effects of land form and land use on phosphorus became apparent. Contrary to what is often believed, land form is the dominant factor of these two (Sonzogni *et al.*, 1980; Grobler, 1985). Possible reasons for the confusion about the effects of land use and land form on nonpoint source phosphorus export are the multicollinearity between land use and physiography of catchments (Hill, 1978), or, as Walker (1978) has shown, regional effects (differences in climate, general agricultural practices and soils) may be greater than land use effects.

Because runoff has such a dominating effect on nonpoint source derived phosphorus export from catchments, a nonlinear regression model was used to simulate monthly phosphorus export as a function of monthly runoff, i.e.:

$$Pexport_i = a \times Runoff_i^b \tag{3}$$

where P export is the mass of nonpoint source P exported from a catchment (mass area$^{-1}$ time$^{-1}$), Runoff (area time$^{-1}$) at time i and $a$ and $b$ are P export parameters calibrated for each catchment.

### Hydrology

The quantity and timing of runoff from a catchment has a large effect on the phosphorus exported from the catchment and on the fate of phosphorus in the reservoirs. It is difficult to predict future runoff patterns and our approach was to assume that the historical runoff record of a reservoir was a representative time series of runoff i.e. it contained periods of high runoff, low runoff, wet and dry cycles etc. Hydrological simulation models are available to modify the historical runoff records to reflect changes in landuse such as increased urbanization (increased runoff) or increased afforestation (reduced runoff). A representative time series of runoff can then be used to predict a range of nonpoint source P exports and a range of trophic responses of the reservoir to different phosphorus loads.

### Estimating the P export parameters

Land form and land use effects are taken into account by estimating the regression model parameters *a* and *b* for specific catchments. Before this model can be used to simulate the nonpoint source phosphorus export that would result from predicted runoff, the parameters of the model need to be estimated from historical runoff and P export data. The following procedure (Grobler and Rossouw, 1988a) is used to calibrate the model parameters:

1. Select a catchment, or some part of it, which contains no significant point sources for calibrating the parameters of the model. No point sources must be present because it is impossible to separate the contributions from point and nonpoint sources in the total amount of phosphorus exported from a catchment. The catchment must be adequately gauged over a long enough period for the discharge and phosphorus concentration records to be accurate and representative.

2. Estimate the daily phosphorus flux from continuously recorded daily discharge and phosphorus concentration records obtained from grab samples. The methods described in Walker (1987) were used to estimate daily phosphorus flux.

3. Calculate monthly flows and phosphorus loads from daily discharge and phosphorus flux data and convert these to monthly runoff and phosphorus export through dividing flows and loads by the area of the catchment.

4. Use a nonlinear regression procedure to estimate the parameters for the nonlinear regression model of phosphorus export as a function of runoff.

The procedure described above was used to calibrate the nonpoint source export parameters for a number of catchments (Table 1):

Table 1 Estimated parameter values used as input for the nonpoint source derived TP export model for sensitive drainage basins (Grobler and Rossouw, 1988a).

| Drainage Basin | Reservoir | Gauging Station | Parameter | Estimate |
|---|---|---|---|---|
| Crocodile | Hartbeespoort Dam<br>Roodeplaat Dam<br>Rietvlei Dam | A2M13 | a<br>b | 0.160<br>1.280 |
| Upper Vaal | Grootdraai Dam<br>Vaal Dam<br>Vaal Barrage | C1M06<br>C1M07 | a<br>b | 0.275<br>1.347 |
| Lower Vaal | Bloemhof Dam | C4M04 | a<br>b | 0.422<br>1.255 |
| Olifants | Bronhorstspruit Dam<br>Loskop Dam | B1M05 | a<br>b | 0.129<br>0.992 |
| Umgeni | Midmar Dam | U2M13 | a<br>b | 0.002<br>1.953 |
| | Albert Falls Dam | U2M06 | a<br>b | 0.024<br>1.272 |
| | Nagle Dam | U2M12 | a<br>b | 0.032<br>0.302 |
| | Inanda Dam | U2M11 | a<br>b | 0.039<br>1.559 |
| Umlazi | Shongweni Dam | - | a<br>b | 0.039<br>1.559 |
| Buffalo | Laing Dam<br>Bridle Drift Dam | R2M06<br>R2M09 | a<br>b | 0.188<br>1.156 |

The calibrated model was used to simulate phosphorus export from runoff data which was then converted to phosphorus loads from a catchment. The load during month i was calculated as the product of monthly phosphorus export and the catchment area:

$$NPL_i = Pexport_i \times A \tag{4}$$

where $NPL_i$ is the nonpoint source derived phosphorus load, P $export_i$ is the phosphorus export from the catchment during month i, and A is the catchment area.

### 3.3 Upstream reservoirs

Upstream reservoirs which regularly release water to the reservoir of interest, are treated as point sources. If such releases represent a major source of inflow to the downstream reservoir it is advisable to apply the DSS to the upstream reservoir first so that a time series of P concentrations in the upstream reservoir can be generated. These P concentrations can then be used with the time series of reservoir discharges to calculate the P loads released from the upstream reservoir. If it is a minor source of discharge to the reservoir of interest, a constant mean P concentration can be assumed. This, with the time series of reservoir outflows, can be used to calculate the P loads from the upstream reservoir.

### 3.4 Total amount of P exported

The time series of monthly total phosphorus loads ($TL_i$) entering the receiving water body is obtained by adding, for each month, the monthly mean point source load, the varying monthly nonpoint source derived phosphorus loads and the loads from upstream reservoirs in the time series:

$$TL_i = PL + NPL_i + URL_i \tag{5}$$

where $TL_i$ is the total P load for month i, $NPL_i$ is the nonpoint source derived P load for month i, $URL_i$ is the P load derived from upstream reservoirs and PL is mean monthly P load derived from point sources after river losses were accounted for. The magnitude of PL is determined by the particular point source P control scenario being investigated.

## 4. MODELLING SUBSYSTEM 2

### 4.1 Fate of Phosphorus in Reservoirs

The fate of phosphorus in reservoirs is modelled with a phosphorus budget model which is based on the principle of conservation of mass (Grobler, 1985b), i.e.

$$\frac{dP}{dt} = P_{in} - P_{out} - P_{sed} \tag{6}$$

in which P is the mass of phosphorus stored in the water in a reservoir, $P_{in}$ is the mass of phosphorus entering the reservoir, $P_{out}$ the mass of phosphorus leaving the reservoir, and $P_{sed}$ the amount of phosphorus lost by sedimentation, during time interval dt.

$P_{in}$ and $P_{out}$ are obtained as measured or simulated time series phosphorus loads entering or leaving a reservoir, whereas $P_{sed}$ is simulated as a function of both the mass of phosphorus and the ambient phosphorus concentration in the reservoir, i.e.

$$P_{sed} = s \times P \tag{7}$$

$$s = k[P]^2 \tag{8}$$

where s is the phosphorus concentration dependent sedimentation rate, k the sedimentation parameter and [P] the ambient phosphorus concentration during dt. The parameter k is calibrated for a specific reservoir by solving the mass budget equation using time series data of observed dP/dt, $P_{in}$, and $P_{out}$.

The ambient phosphorus concentration during dt is calculated by dividing P by the volume of water stored during dt.

### 4.2 Water balance for the reservoir

The phosphorus concentration in a reservoir depends on the volume of water stored and on the mass of phosphorus in the water. Therefore, in order to simulate phosphorus concentrations, both the volume of water stored and the mass of phosphorus in a reservoir need to be simulated simultaneously in the phosphorus budget model. The volume of water stored in a reservoir is simulated as (Midgley *et al.*, 1983):

$$\frac{dV}{dt} = Q_{in} + Pt - E - Sp - Q_{out} \tag{9}$$

where V is the volume of water in the reservoir, $Q_{IN}$ is the inflow, Pt is the precipitation, E is the evaporation, Sp is the spillage and $Q_{OUT}$ is the water released from the reservoir, during dt.

To convert the areal rainfall and evaporation (mm) to a volume, the rainfall and evaporation are multiplied by the reservoir area. The reservoir area is calculated from the volume as:

$$Area = A \times V^{B} \tag{10}$$

where *A* and *B* are parameters which describe the bathymetric shape of the reservoir and V is the volume of water (Middleton *et al*, 1981).

The water balance can either be calculated as part of the simulation or it can be carried out outside the program with a hydrological simulation model. For a single catchment single reservoir system, the water balance can be computed within the DSS. The physical characteristics of the reservoir plus projected water demands and reservoir operating rules must be entered as input. However, for complex catchment-reservoir systems, such as the Vaal River system, where releases from upstream reservoirs are governed by water demands and water levels in Vaal Dam, it is advisable to do the system water balance outside the DSS with a hydrological model. The Department of Water Affairs often uses a systems analysis program for simulating the hydrology of complex systems. The simulated hydrological output, such as reservoir levels, outflows etc, can then serve as input for the DSS for eutrophication control.

### 4.3 Numerical solution technique for solving the differential equations

To simulate the fate of phosphorus in the reservoir requires the solution of the phosphorus budget and water balance equations. Both these equations are non-linear, first-order, ordinary differential equations (ODE). Originally, the trapezium rule was used to solve the equations (Grobler, 1985). However, it was found that when large changes in the reservoir volume took place, the solution technique became unstable. Under certain conditions, consecutive estimates of the reservoir phosphorus concentration started to oscillate between high and low concentrations instead of converging towards a minimum, in a given time step (Figure 3). This was typical of a stiff differential equation and it was suggested that an initial value technique for solving ODE's, like one of the Runge Kutta techniques be used. The method of Heun (Flanders, 1984) was therefore chosen to solve the phosphorus budget model in REMDSS.

The Heun method for solving ODE's uses a fixed step-size but it was found that the step size had to be reduced considerably to accommodate periods when rapid changes in the reservoir volume took place. This increased the execution time of REMDSS to levels where it became unacceptable. The National Research Institute for Mathematical Sciences was contracted to find an algorithm which was fast and accurate and which selected the time step automatically. Two solutions were proposed (Dell, 1987):

1. Modified Heun method which uses a variable step size.
2. An analytical approximation to the ODE's.

Although the analytical approximation technique was faster, it was (1) difficult to implement into the existing framework of the DSS and (2) to modify the program afterwards to add e.g. new operating rules, would require a new analytical approximation. The modified Heun method was therefore incorporated into the DSS to solve the phosphorus budget model. It had the following advantages:

1. It was a simple solution to implement into the framework of the DSS
2. The execution speed could be maintained under most circumstances and only when required is the step size reduced to maintain accuracy.

An ad hoc maximum step length (hmax) of 0.2 was chosen because it reduced the program execution time considerably without sacrificing accuracy. Up to the present, the method has been found to be stable for all the applications done with the DSS.

The Heun method is an initial value solution technique which means that it requires, as input, an initial phosphorus concentration. It was found that the method was insensitive to the initial value entered (Figure 4). A running in time of 36 months was built into the final version of the DSS for eutrophication control which relieved the user of the burden of entering an initial phosphorus concentration.

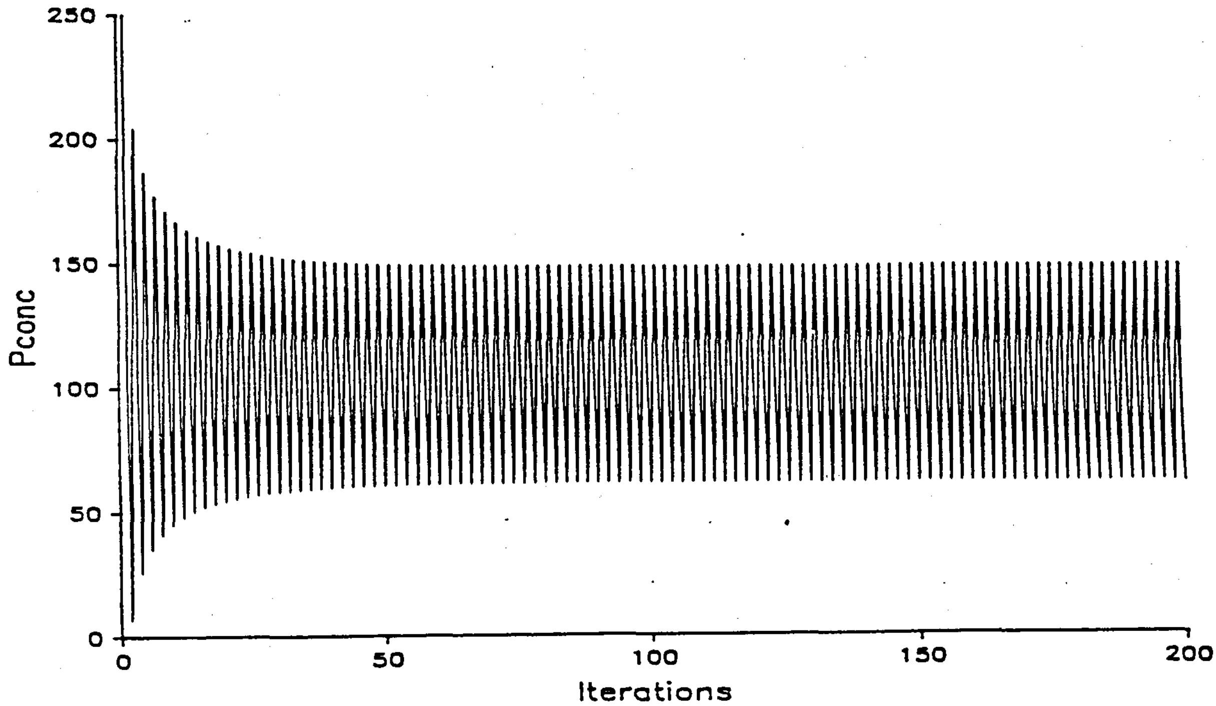


Figure 3 Graphical illustration of what happens when the numerical solution technique (trapezium rule) became unstable causing consecutive phosphorus concentrations to oscilate between high and low concentrations instead of converging towards a minimum.

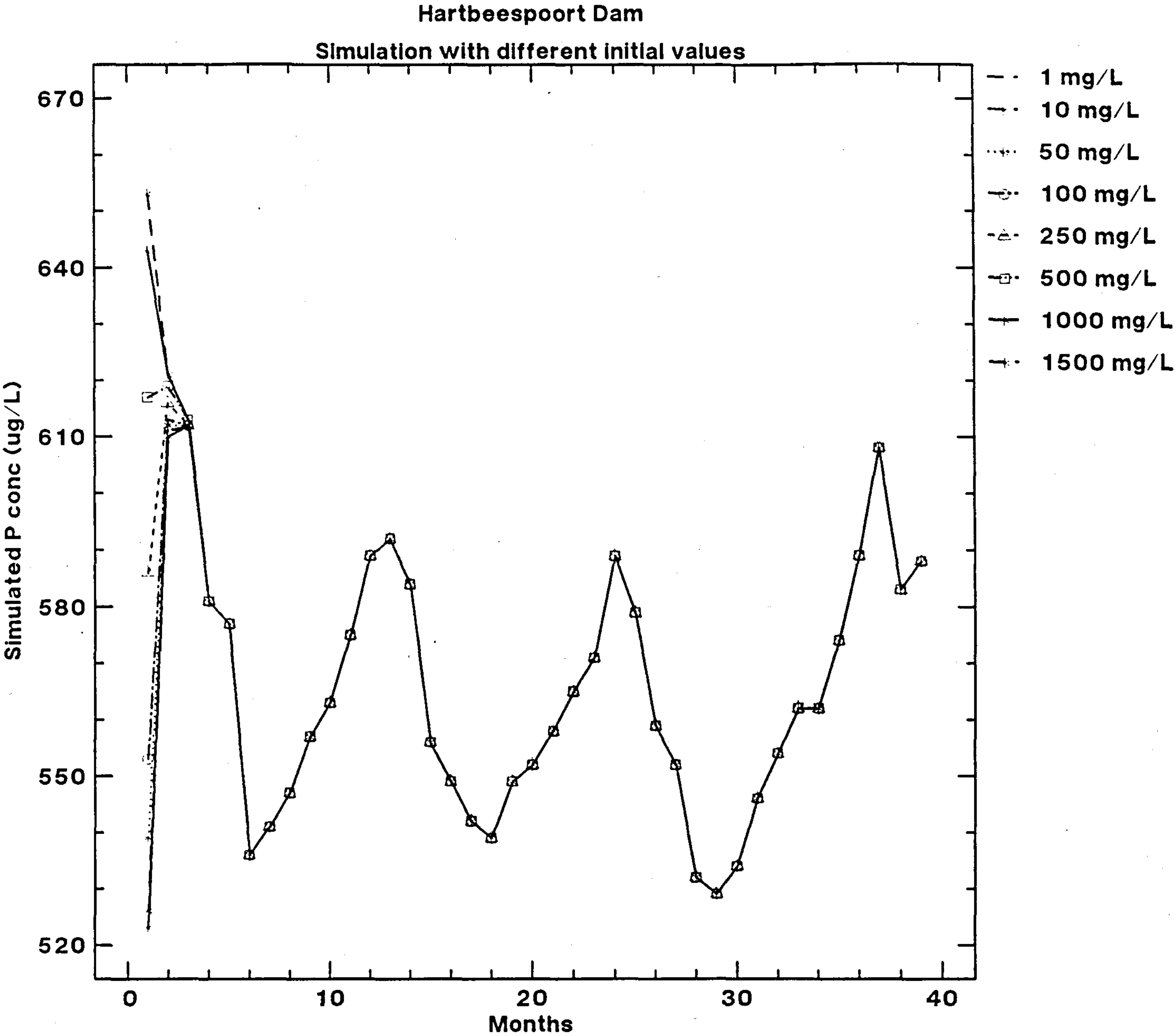


Figure 4 Graphical illustration of the insensitivity of the modified Heun method to the selected initial value.

### 4.4 Recalibration of the sedimentation parameter

In REM, the mass of phosphate in the reservoir is modelled as a function of the mass entering the reservoir minus the losses through the outflow minus all in-lake losses (Equation 6). All in-lake losses are conceptually lumped together into a process called sedimentation. In REM a concentration dependent sedimentation rate is used (Equation 8) which is calibrated for a specific reservoir by solving the mass budget equation using time series data of observed dP/dt, $P_{in}$, and $P_{out}$.

It was decided to recalibrate the sedimentation parameter because:

1. A new numerical technique is used for the solution of the P budget and water budget equations.
2. Data are now available for a longer period than was used in the original calibration of the sedimentation parameter. Grobler (1985) used about two years of data from Hartbeespoort Dam to calibrate the sedimentation parameter. In this calibration, eight years of data are used to calibrate the sedimentation parameter for Hartbeespoort Dam.

With the time available to the project team, the sedimentation parameter was only calibrated for Hartbeespoort Dam. The ideal would be to calibrate the parameter for a turbid reservoir as well. In this section the methods used to calibrate and verify the sedimentation parameter for Hartbeespoort Dam are discussed.

#### 4.4.1 Preparation of the calibration data

The data used to calibrate and verify the sedimentation parameter were collected as part of several projects on the eutrophication of Hartbeespoort Dam.

The inflows into Hartbeespoort Dam are gauged on the Crocodile River at A2M12 and on the Magalies River at A2M13. The Department of Water Affairs (Directorate of Hydrology) provided the measured in- and outflows, reservoir volume, rainfall and evaporation data for Hartbeespoort Dam. There was a good correspondence between the observed and simulated volumes (Figure 5). For 1988 no reservoir rainfall and evaporation data were available and instead the long term average rainfall and evaporation data were used (Department of Water Affairs, 1985). This explains the difference in the observed and simulated volumes for 1988.

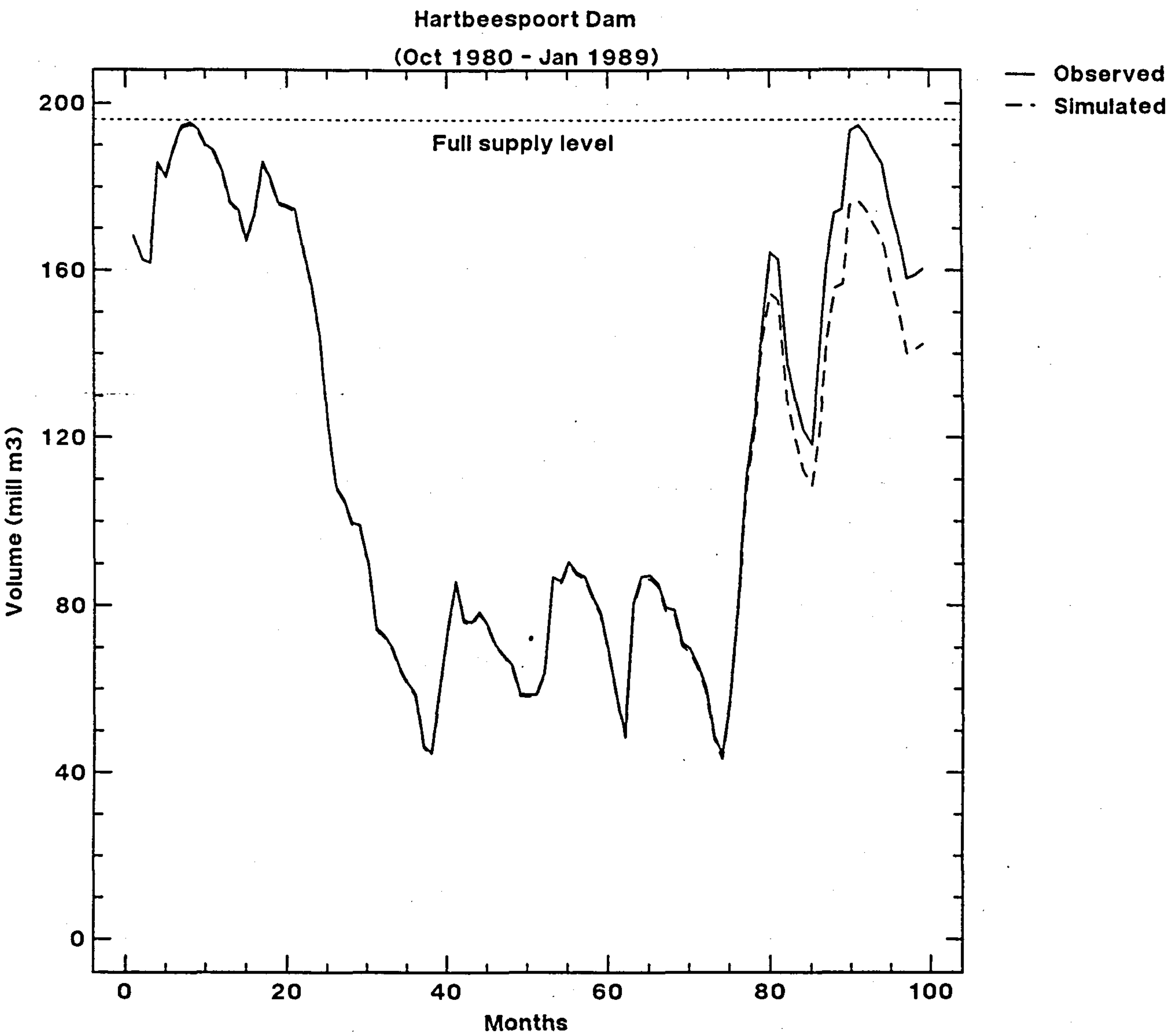


Figure 5 Comparison between the observed (solid line) and simulated (dashed line) water volumes in Hartbeespoort Dam. Month 1 = October 1980 and Month 99 = January 1989.

The P loads from the Crocodile River were estimated from daily P concentrations observed at A2M12 and the observed daily flows. For periods when only weekly samples were available, the FLUX model (Walker, 1987; Grobler and Rossouw, 1988a) was used to estimate the daily P flux from daily flows. The Crocodile River contributes more than 90% of the P load into Hartbeespoort Dam. The P loads from the Magalies river were estimated with the FLUX model using weekly P concentrations and daily flows. The total monthly P load was calculated as the sum of the loads from A2M12 and A2M13 during a specific month.

The observed reservoir P concentrations were depth-month averaged P concentrations, i.e. the average of 0m to 5m P concentrations were first calculated and then a monthly average was calculated of all depth averaged concentrations during the month. The 0-5m P concentrations were used because, for most of the time, it represented the P available to phytoplankton for growth.

The original data set was divided into two independent data sets; the first to be used for the calibration phase and the second to be used for the verification phase:

1. Calibration data (October 1980 to September 1984) - a 48 month period when the reservoir was almost full for half of the period.
2. Verification data (October 1985 to January 1989) - a 52 month period when the reservoir was mostly empty and only started to fill up in January 1987.

### 4.4.2 Conceptualization of the sedimentation process

According to the literature, phosphorus losses can be simulated using either a constant - or a concentration dependent sedimentation rate. It was decided to test both submodels on the Hartbeespoort Dam data.

Sedimentation submodel 1 uses a fixed sedimentation rate (Grobler, 1985), i.e. rewrite equation 8 as:

$$s = k' \tag{11}$$

where k' is a fixed sedimentation rate.

Sediment submodel 2 uses a concentration dependent sedimentation rate (Grobler, 1985) i.e. rewrite equation 8 as:

$$s = k1 \times [P]^{k2} \tag{12}$$

where k1 and k2 are the sedimentation parameters and s becomes a variable.

### 4.4.3 Selection of an objective function

It is important to express the correspondence between the model and system output with a statistical measure of the goodness-of-fit (Thomann, 1982; Reckhow and Chapra, 1983). An objective function is used to quantify the difference (error) between the model output and the system output. Calibration is the selection of parameter values to minimize the objective function. The Root Mean Square Error (RMSE) (Thomann, 1982) was used to express the goodness-of-fit:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Obs_i - Sim_i)^2}{N}} \tag{13}$$

where $Obs_i$ is the observed data, $Sim_i$ is the simulated data and N the number of paired data sets. The RMSE is statistically well behaved and provides a direct measure of the model error.

### 4.4.4 Calibration of the fixed sedimentation rate

Using the calibration data set, the parameter k' was estimated to minimize the RMSE. There was a good correspondence between the observed and simulated P concentrations in Hartbeespoort Dam using a fixed sedimentation parameter. There is no significant difference between the medians of two boxplots if the notches, which represent the 95% confidence limits around the median, overlap (Mc Gill *et al.*, 1978). There was no significant difference between the medians of the observed and simulated calibration data (Figure 6). The following results were obtained from the calibration (Table 2, Figure 7):

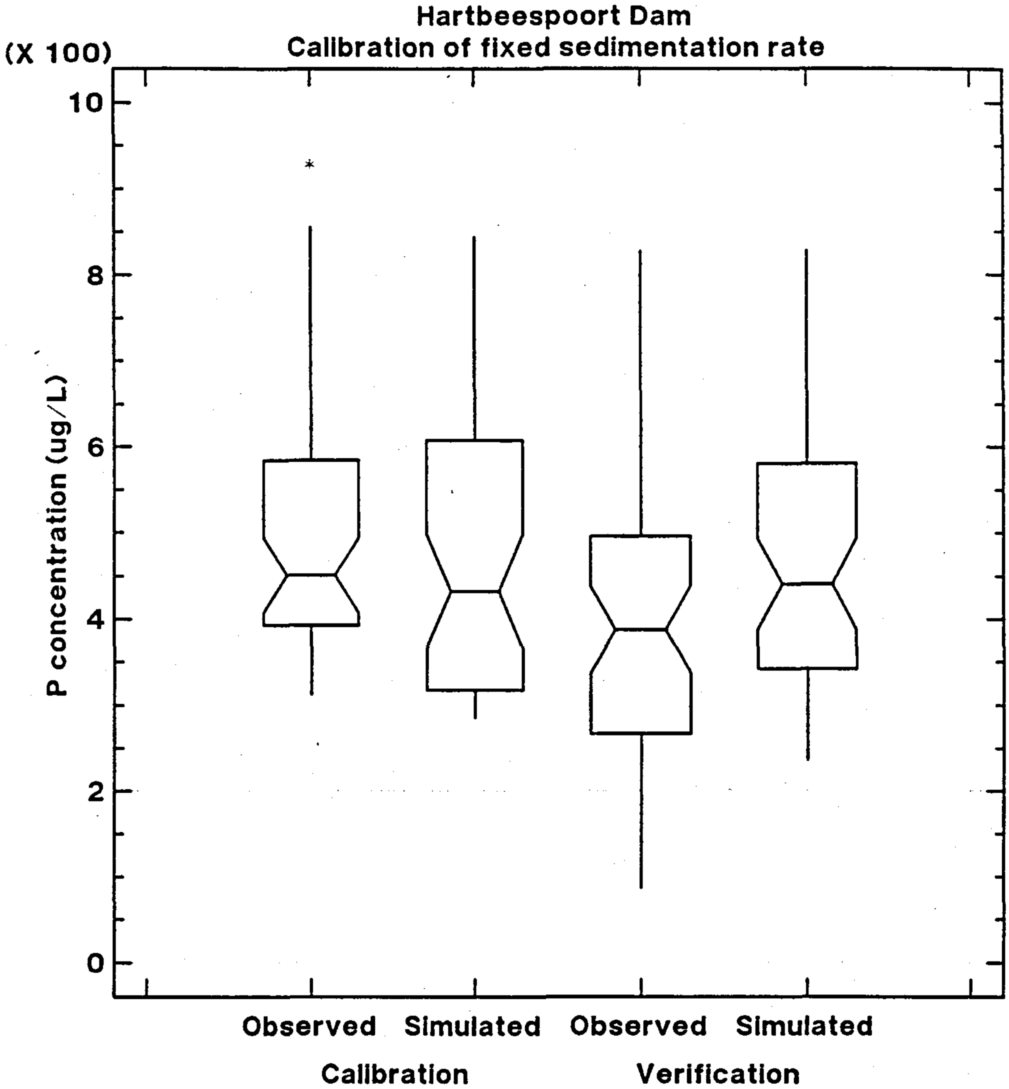


Figure 6 Boxplot showing the resemblance between the observed and simulated P concentration in Hartbeespoort Dam used for calibrating and verifying the fixed sedimentation parameter. The upper and lower bars of the box are the 75 and 25 percentiles. The interquartile range is the length of the box. The line in the middle of the box is the median while the notch represents the 95% confidence limits around the median. Extreme points beyond 1.5 times the interquartile range are plotted as individual points.

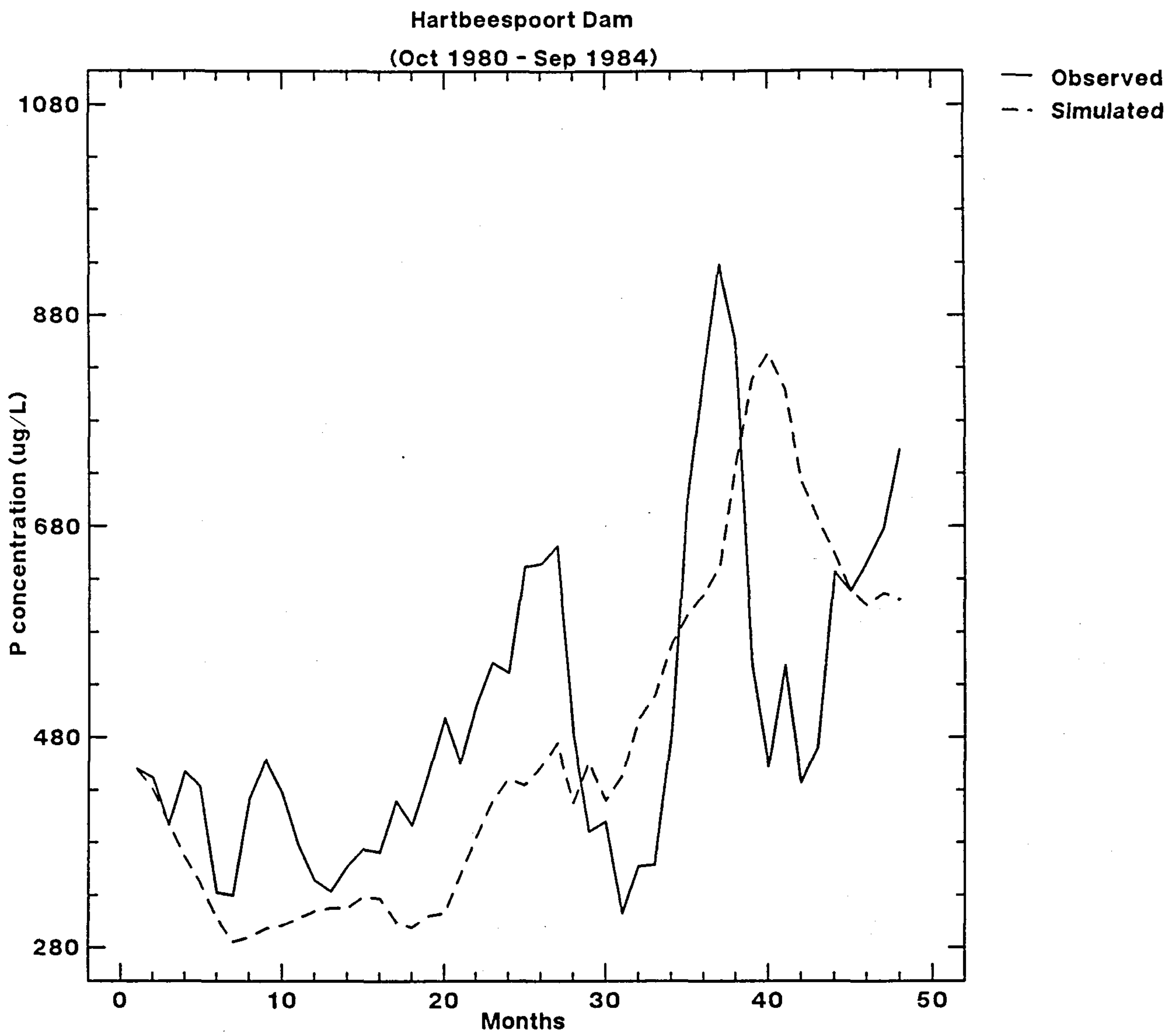


Figure 7 Diagram of the final calibration of the fixed sedimentation (k') parameter comparing the observed (solid line) and simulated (dashed line) P concentration in Hartbeespoort Dam.

Table 2 Estimated parameter values and results of the calibration and verification of the P budget model on Hartbeespoort Dam using a fixed sedimentation rate.

| Data Set | Calibrated parameter k' ($month^{-1}$) | RMSE |
|---|---|---|
| Calibration (10/80-9/84) | 0.28 | 145.22 |
| Verification (10/84-1/89) | 0.28 | 127.30 |

Once the best parameter value was found for the fixed sedimentation rate, it was used with the verification data set to verify the parameter value (Figure 8).

### 4.4.5 **Calibration of the concentration dependent sedimentation rate**

Originally the sedimentation parameter k2 was set to 2. However, it was argued that, for a specific reservoir, there is a unique combination of the k1 and k2 parameters which would yield the lowest value for the objective function. The value of parameter k2 was therefore varied between 1 and 2 in steps of 0.1 and for each k2 value, a k1 value was calibrated to minimize the RMSE (Table 3).

There does not seem to be a significant difference between the RMSE's of the different k1 and k2 parameter combinations. This is a characteristic of indeterminant parameters which is not limited to fixed values.

It was decided to set k2 = 2 (as was originally done) and calibrate only the k1 parameter (Table 4, Figure 10). The calibrated k1 and k2 parameters were then verified against the verification data set (Table 4, Figure 11).

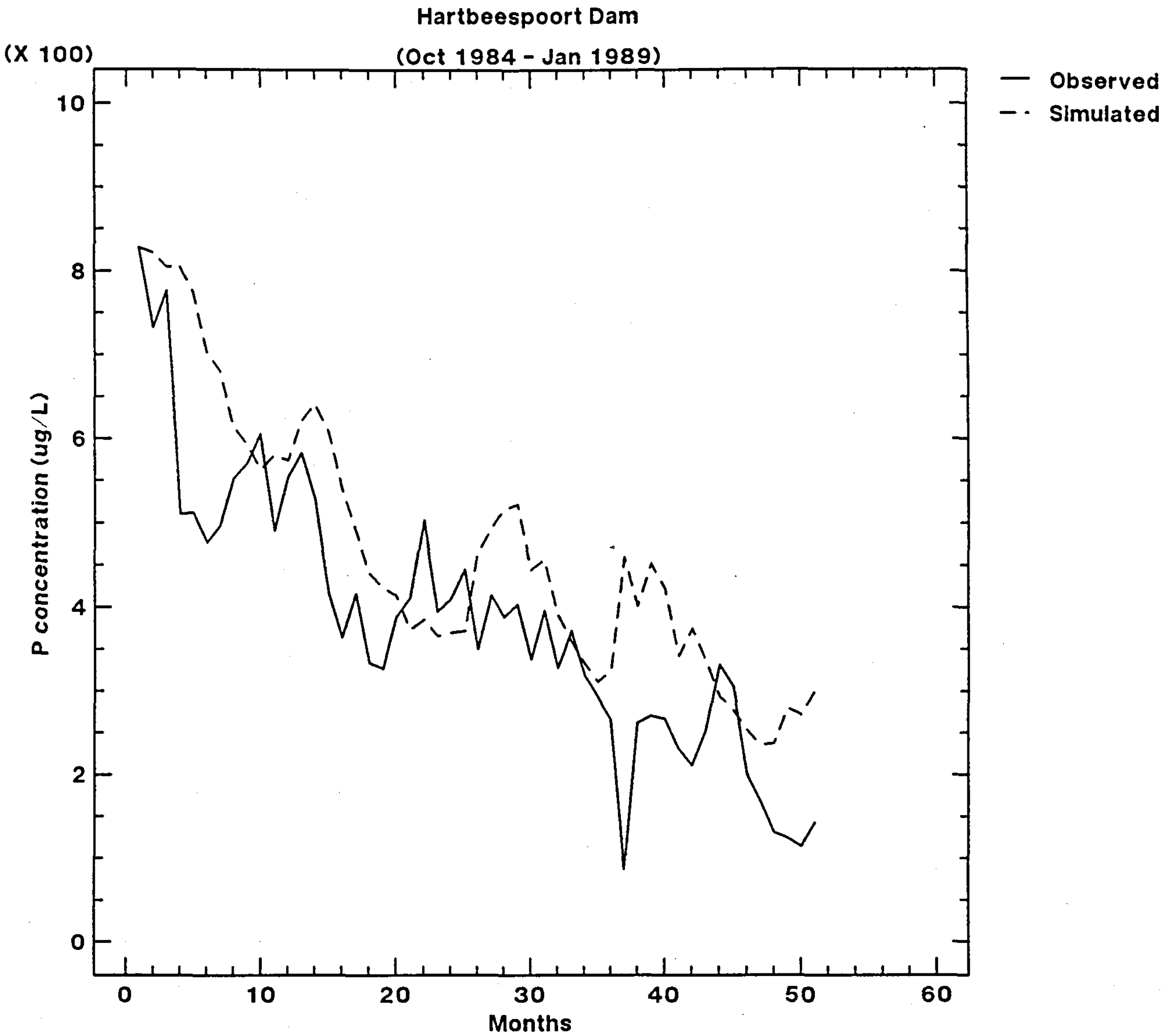


Figure 8 Diagram of the final verification of the fixed sedimentation parameter (k') comparing of the observed (solid line) and simulated (dashed line) P concentration in Hartbeespoort Dam.

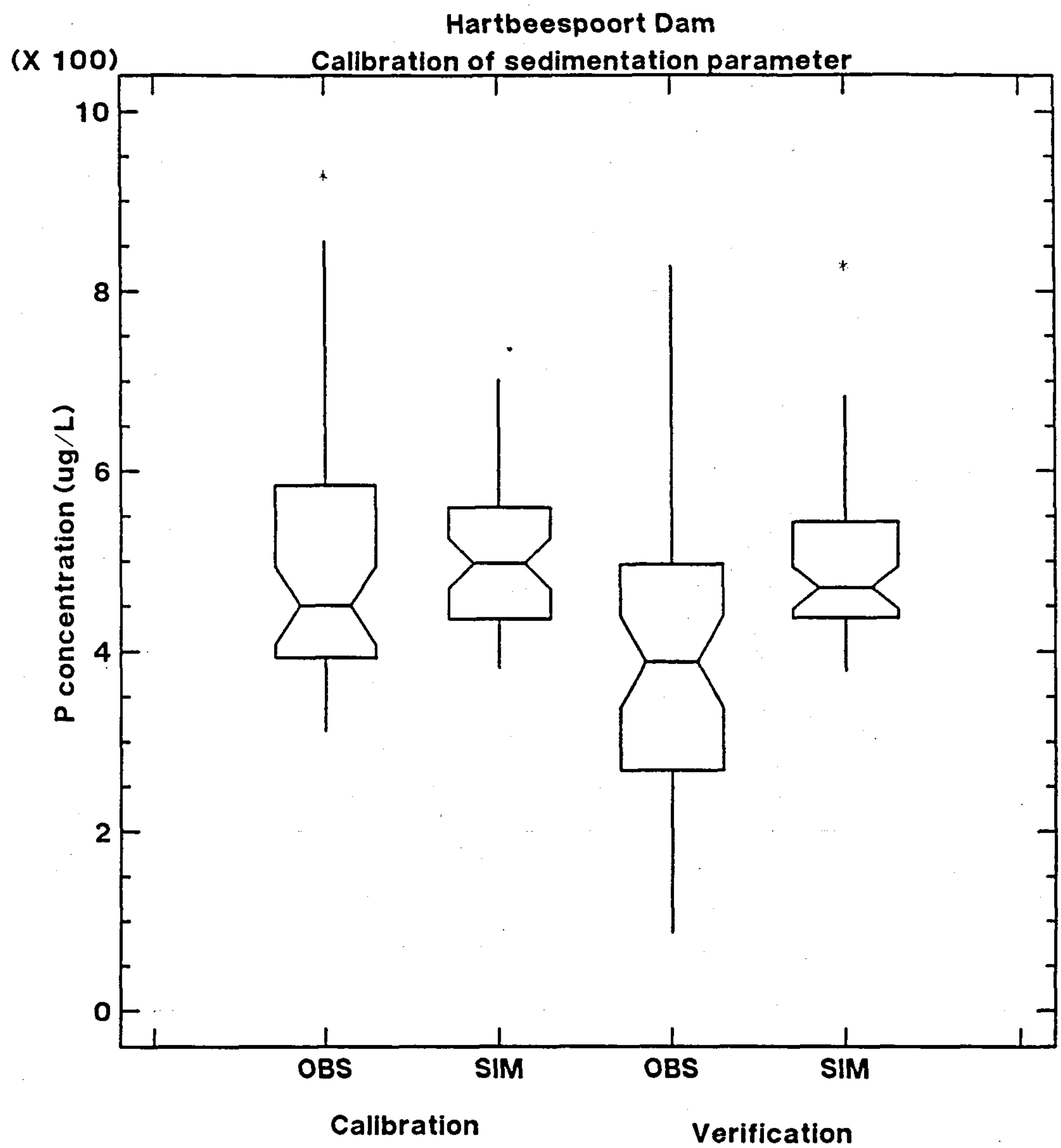


Figure 9 Boxplot showing the resemblance between the observed and simulated P concentration in Hartbeespoort Dam used for calibrating and verifying the constant sedimentation parameters, k1 and k2. The upper and lower bars of the box are the 75 and 25 percentiles. The interquartile range is the length of the box. The line in the middle of the box is the median while the notch represents the 95% confidence limits around the median. Extreme points beyond 1.5 times the interquartile range are plotted as individual points.

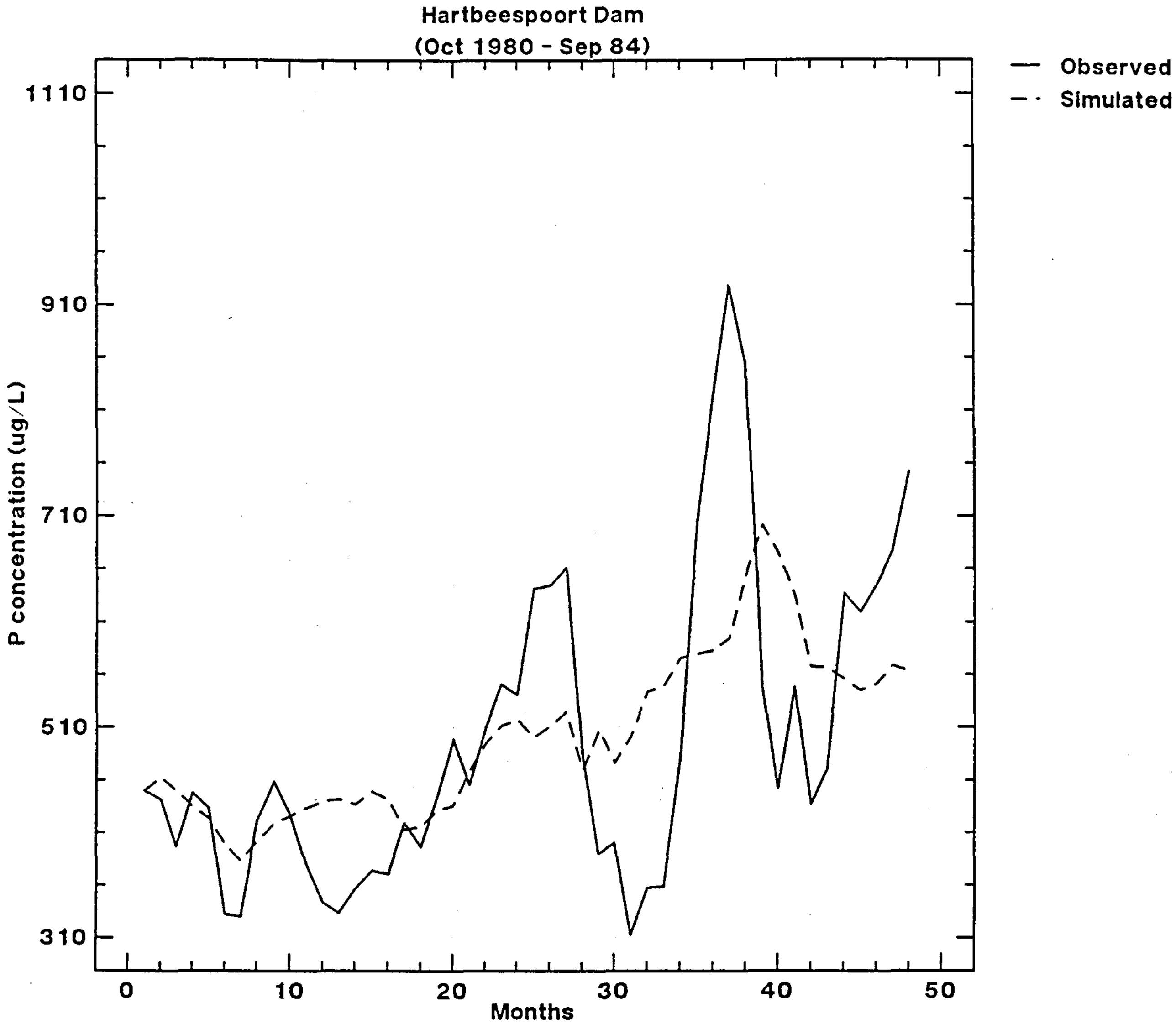


Figure 10 Diagram of the final calibration of the concentration dependent sedimentation parameters k1 and k2, comparing the observed (solid line) and simulated (dashed line) P concentrations in Hartbeespoort Dam.

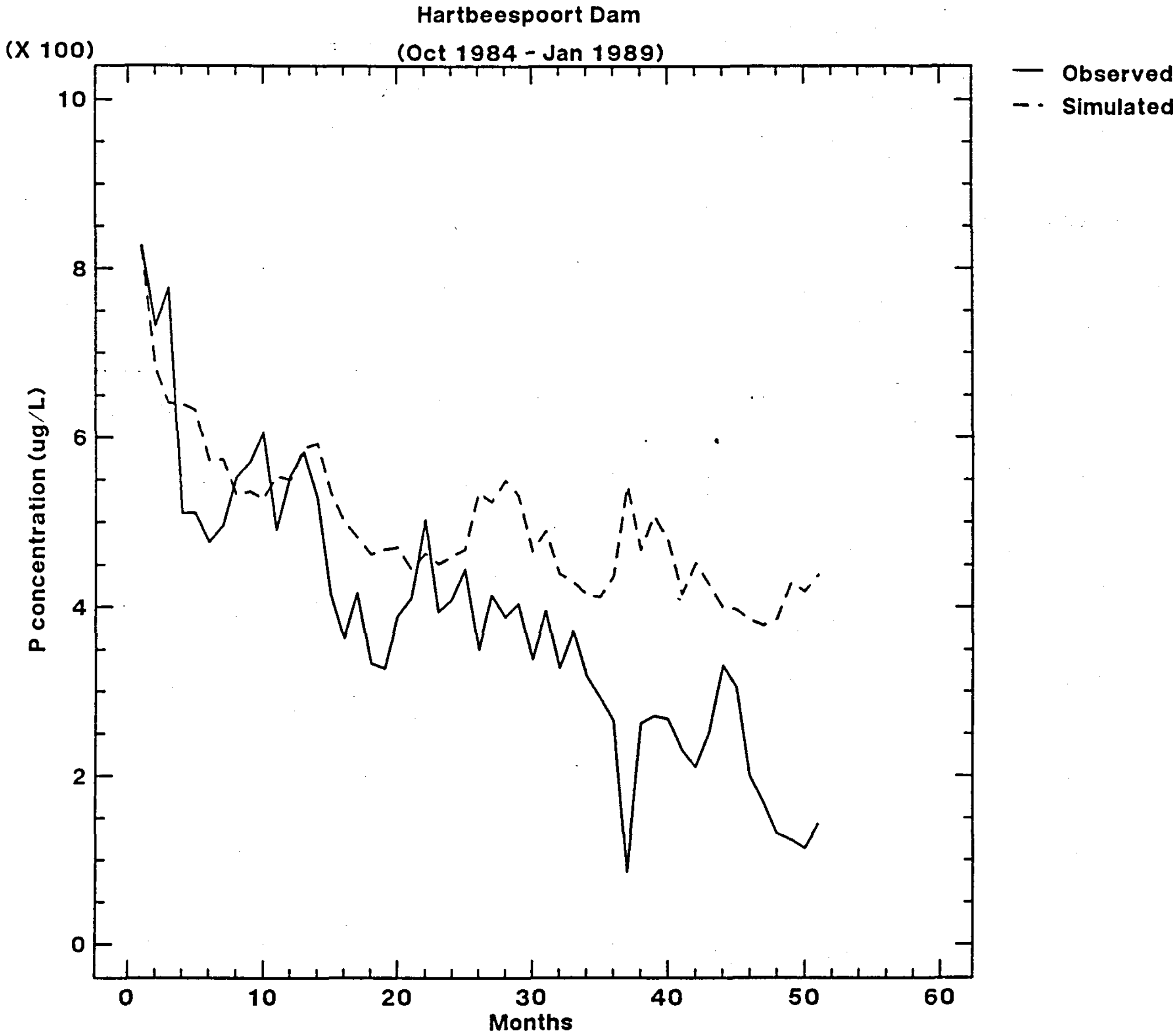


Figure 11 Diagram of the final verification of the concentration dependent sedimentation parameters k1 and k2, comparing the observed (solid line) and simulated (dashed line) P concentration in Hartbeespoort Dam.

Table 3 Estimated parameter values of k1 for a given k2 value, and RMSE's of the calibration of the P budget model on Hartbeespoort Dam using a concentration dependent sedimentation rate.

| k2 | k1 month$^{-1}$/(mg m$^{-3}$)$^2$ | RMSE |
|---|---|---|
| 1.0 | 5000.0 x $10^{-6}$ | 118.92 |
| 1.1 | 2700.0 x $10^{-6}$ | 118.15 |
| 1.2 | 1440.0 x $10^{-6}$ | 117.56 |
| 1.3 | 770.0 x $10^{-6}$ | 117.11 |
| 1.4 | 410.0 x $10^{-6}$ | 116.79 |
| 1.5 | 220.0 x $10^{-6}$ | 116.58 |
| 1.6 | 115.0 x $10^{-6}$ | 116.50 |
| 1.7 | 63.0 x $10^{-6}$ | 116.40 |
| 1.8 | 34.0 x $10^{-6}$ | 116.43 |
| 1.9 | 18.0 x $10^{-6}$ | 116.48 |
| 2.0 | 9.7 x $10^{-6}$ | 116.53 |

Table 4 Estimated parameter values and results of the final calibration and verification of the P budget model on Hartbeespoort Dam using a concentration dependent sedimentation rate.

| Data Set | Calibrated Parameters | | RMSE |
|---|---|---|---|
| | k1 month$^{-1}$/(mg m$^{-3}$)$^2$ | k2 | |
| Calibration (10/80-9/84) | 9.7 x $10^{-6}$ | 2.0 | 116.59 |
| Verification (10/84-1/89) | 9.7 x $10^{-6}$ | 2.0 | 157.20 |

There was no significant difference between the medians of the observed and calibration data sets using a concentration dependent sedimentation rate (Figure 9). However, the model failed to simulate the peaks in the observed calibration data (Figure 10). These peaks all corresponded to the onset of summer; in 1982 (months 25-27), in 1983 (months 35 - 38) and in 1984 (months 48 - 51). The P budget model responds to loads entering and leaving the reservoir. It is therefore clear that the observed peaks were caused by in- lake processes rather than increased loadings. The most likely process responsible for the observed peaks is resuspension. The peaks occurred when conditions occurred which were favourable for resuspension i.e. low reservoir volumes (shallow water depth) and a time of the year when moderate to high wind speeds are generally observed.

The verification of the concentration dependent sedimentation rate was less successful (Figure 9 & 11). There was a significant difference between the medians of the observed verification and simulated data sets. The simulated P concentration followed the same trend as the observed P concentration up to December 1986 (month 27) when the lines of the simulated and observed data started to diverge. This corresponded to the period when the reservoir started to fill up after the drought. Once again, the P budget model responded to P loads entering the reservoir. The loads did not differ significantly from the loads of previous years. It is assumed that the reduction in P concentrations was due to processes which were not previously dominant in the reservoir. A study is currently in progress to investigate the reasons for the reduction in the in-lake P concentrations.

The next step in the modelling process is to go back to the model structure identification phase. It is believed that a concentration dependent sedimentation rate which take the reservoir area into account, would be more successful in simulating the in-lake P losses. However, this task will be done in a future project which will also model the effects of nitrogen and suspended sediments on the eutrophication process.

## 5. MODELLING SUBSYSTEM 3

### 5.1 Conversion of phosphorus to chlorophyll

The final step in simulating the eutrophication process is to relate the ambient phosphorus concentration in a reservoir to the water quality variable of concern. Water quality problems associated with eutrophication are usually caused by the occurrence of undesirable quantities and/or species of algae. Therefore, the algal standing crop in a reservoir resulting from the ambient phosphorus concentration, usually expressed as chlorophyll concentration, is most often considered to be the water quality variable of concern. The trophic status is related to the mean annual concentrations of TP and chlorophyll (Walmsley and Butty, 1980):

| Trophic Status | TP concentration ($\mu g/\ell$) | Chlorophyll concentration ($\mu g/\ell$) |
|---|---|---|
| Oligotrophic | $<= 15$ | $< 3$ |
| Mesotrophic | 15 - 47 | 3 - 9 |
| Eutrophic | $> 47$ | $> 9$ |

From a management point of view, the frequency with which algal concentrations that result in nuisance conditions are experienced are of concern. Walmsley (1984) developed an aesthetic or use impairment classification system which was based upon mean annual chlorophyll concentrations observed in reservoirs:

| Chlorophyll ($\mu g/\ell$) | Impairment classification |
|---|---|
| 0 - 10 | No problems encountered |
| 10 - 20 | Algal scums can be present |
| 20 - 30 | Nuisance conditions can be expected |
| $> 30$ | Severe nuisance conditions can be expected |

Walmsley (1984) also developed a procedure to predict, from the mean annual chlorophyll concentration, the frequency with which each of these use impairment classes will occur in a reservoir. For example, the percentage time that chlorophyll concentrations can be expected to exceed 30 $\mu g/\ell$ and therefore result in severe nuisance conditions being experienced, is calculated as:

$$F - 1.19\ Chl - 5.36 \qquad (14)$$

where F is the frequency of occurrence of severe nuisance conditions, expressed as a percentage of a year.

Based on experience in South Africa and elsewhere in the world, the Department of Water Affairs provisionally adopted a general eutrophication management objective of ensuring that severe nuisance conditions in reservoirs should occur for less than 20 percent of the time. Using equation 14 this translates into maintaining a mean chlorophyll concentration of less than 21 $\mu g/\ell$. In turn, this translates into maintaining mean phosphorus concentrations (equation 15) at below 130 $\mu g/\ell$ in a clear water reservoir.

In a survey of 92 South African reservoirs, Walmsley and Bruwer (1980) found that 42% of the reservoirs had an average Secchi disk depth of less than 0.5m and could be classified as turbid. The geographical distribution of the turbid reservoirs agreed with the geographical distribution of sediment production indicating that suspended sediment is the factor influencing water transparency most. Low transparencies increased the ability of reservoirs to tolerate high nutrient loadings before severe eutrophication problems were experienced. These findings confirmed that a distinction had to be made between turbid and clear reservoirs in order to simulate changes in standing algal biomass (as chlorophyll) as a function of ambient phosphorus concentrations.

### 5.2 Conversion of phosphorus to chlorophyll a in clear water reservoirs

For the purpose of the DSS for eutrophication control, a clear water reservoir was defined as one where the extinction of light in the water column is dominated by algae and not by inorganic suspended solids. The OECD chlorophyll:phosphorus regression model (Jones and Lee, 1982; Grobler and Silberbauer, 1984) is used to relate mean summer and winter phosphorus concentration ($\mu g/\ell$) to the mean summer and winter chlorophyll concentration ($\mu g/\ell$) in clear water reservoirs :

$$Chl = 0.45[P]^{0.79} \tag{15}$$

where Chl is the chlorophyll a concentration ($\mu g/\ell$) and [P] the phosphorus concentration in $\mu g/\ell$. Grobler and Silberbauer (1984) confirmed that South African reservoirs responded in the same way as most other water bodies with regard to the OECD TP:chlorophyll relationship (Figure 12).

## 5.3 Conversion of phosphorus to chlorophyll a in turbid reservoirs

Reservoirs which receive high sediment loads pose additional problems to modelling water quality because there is evidence that high turbidity reduces the algal standing crop. The reasons for the reduction in algal standing crop and therefore chlorophyll a concentrations are:

1. Particulate phosphorus makes up a large proportion of the total phosphorus in the water. Particulate phosphorus is less available for algal growth and less algae (measures as chlorophyll) will be produced for a given total phosphorus concentration.

2. Inorganic suspended solids (ISS) are responsible for the high attenuation of light in the water column; the rapid decrease in the under water light intensity reduces algal growth rates.

It was found that the OECD chlorophyll:phosphorus regression model over estimated the chlorophyll concentration in turbid Australian reservoirs (Smith, 1982) and turbid South African reservoirs (this project). To make the DSS for eutrophication control as general as possible, it was important to use a chlorophyll:phosphorus model which takes turbidity or light attenuation into account.

Hoyer and Jones (1983) developed a multivariate model, on 96 midwestern U.S. reservoirs, to account for the effect of ISS on the chlorophyll:phosphorus relationship:

$$LogChl = 1.13Log[P] - 1.03\frac{[ISS]}{[P]} - 0.47 \tag{16}$$

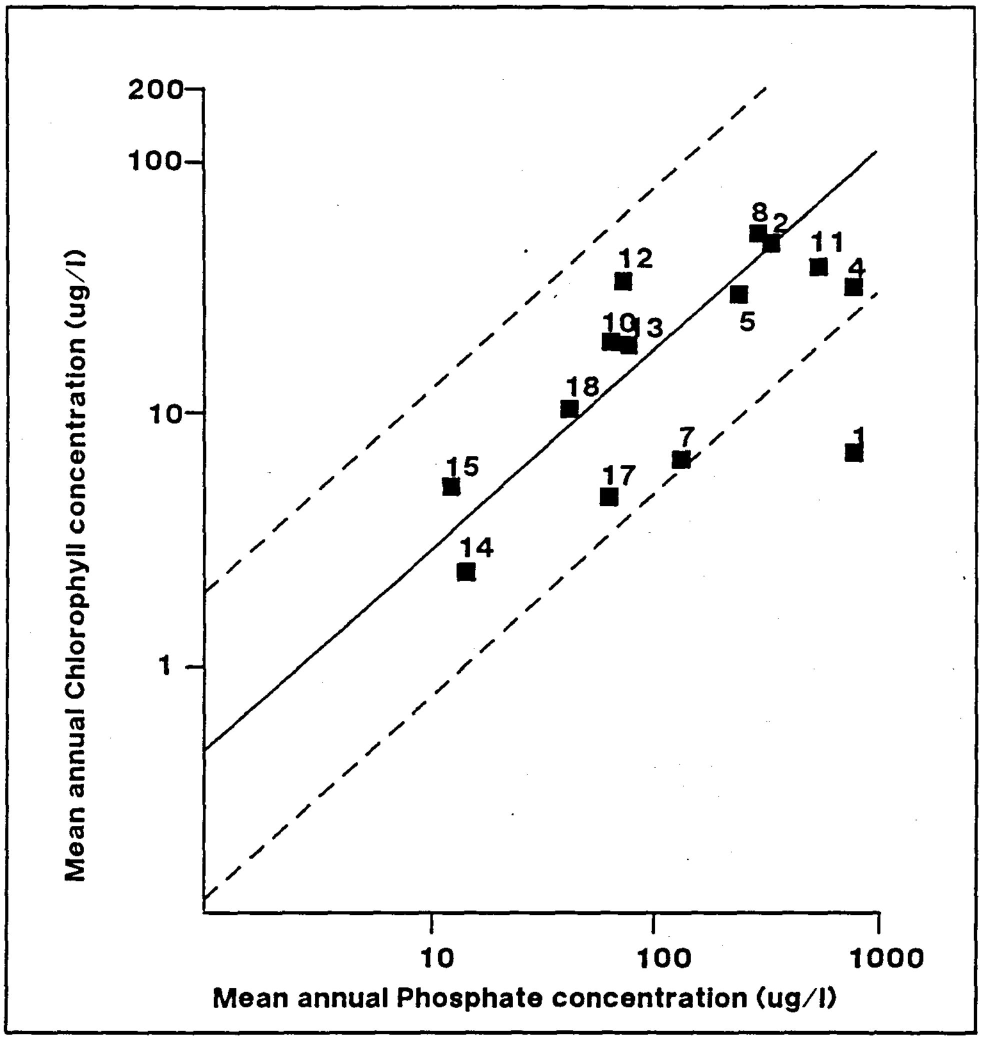


Figure 12 Chlorophyll - phosphorus relationships for South African reservoirs showing the OECD chlorophyll-phosphorus regression line with its 95% confidence interval. Most of the reservoirs plot within the 95% confidence intervals around the line of best fit. The reservoirs are:

| | | |
|---|---|---|
| (1) Rietvlei | (8) Vaal Barrage | (15) Albert Falls |
| (2) Hartbeespoort | (9) Koppies | (16) Inanda |
| (3) Roodekopjies | (10) Bloemhof | (17) Bronkhorstspruit |
| (4) Bon Accord | (11) Laing | (18) Loskop |
| (5) Roodeplaat | (12) Bridle Drift | (19) Misverstand |
| (6) Klipvoor | (13) Shongweni | |
| (7) Vaal | (14) Midmar | |

where [ISS] is the inorganic suspended solids concentration (mg/ℓ), Chl the chlorophyll concentration (μg/ℓ) and [P] the phosphorus concentration in (μg/ℓ). This model is used for turbid reservoirs, i.e. ones in which light extinction is dominated by mineral turbidity, to account for the large differences in light penetration in South African reservoirs.

Inorganic suspended solids (ISS) concentrations are generally not available for South African reservoirs. However, turbidity and Secchi disk depth are commonly used as measures of water transparency in most reservoirs. To be able to apply equation 16 to cases where only turbidity or Secchi depth measurements were available, the following classification system was developed and used to select the appropriate model for converting phosphorus to chlorophyll.

The first step in the development of the classification system was to divide reservoirs into light attenuation or turbidity classes and then to estimate an representative average Secchi depth, turbidity and suspended sediment concentration for each class.

Secchi depth was used as the reference measure of turbidity because it is the most common measurement of light attenuation used in reservoir studies and most water resource managers could relate to it.

The attenuation of light in water is described by the Lambert-Beer law. To graphically illustrate the relationship between the attenuation coefficient and Secchi depth (Figure 13), the following equation was used (Stefan *et al.*, 1983):

$$k = \frac{1.7}{SD} \tag{17}$$

where k = the attenuation coefficient ($m^{-1}$) and SD the Secchi depth (m).

The four turbidity (attenuation) classes were selected on an ad hoc basis using the following as guidelines :

1. The accuracy of Secchi disk measurements is 0.1 m. A class interval can therefore not be less than 0.1 m. On this basis the first two classes were selected for very turbid reservoirs (Figure 13).

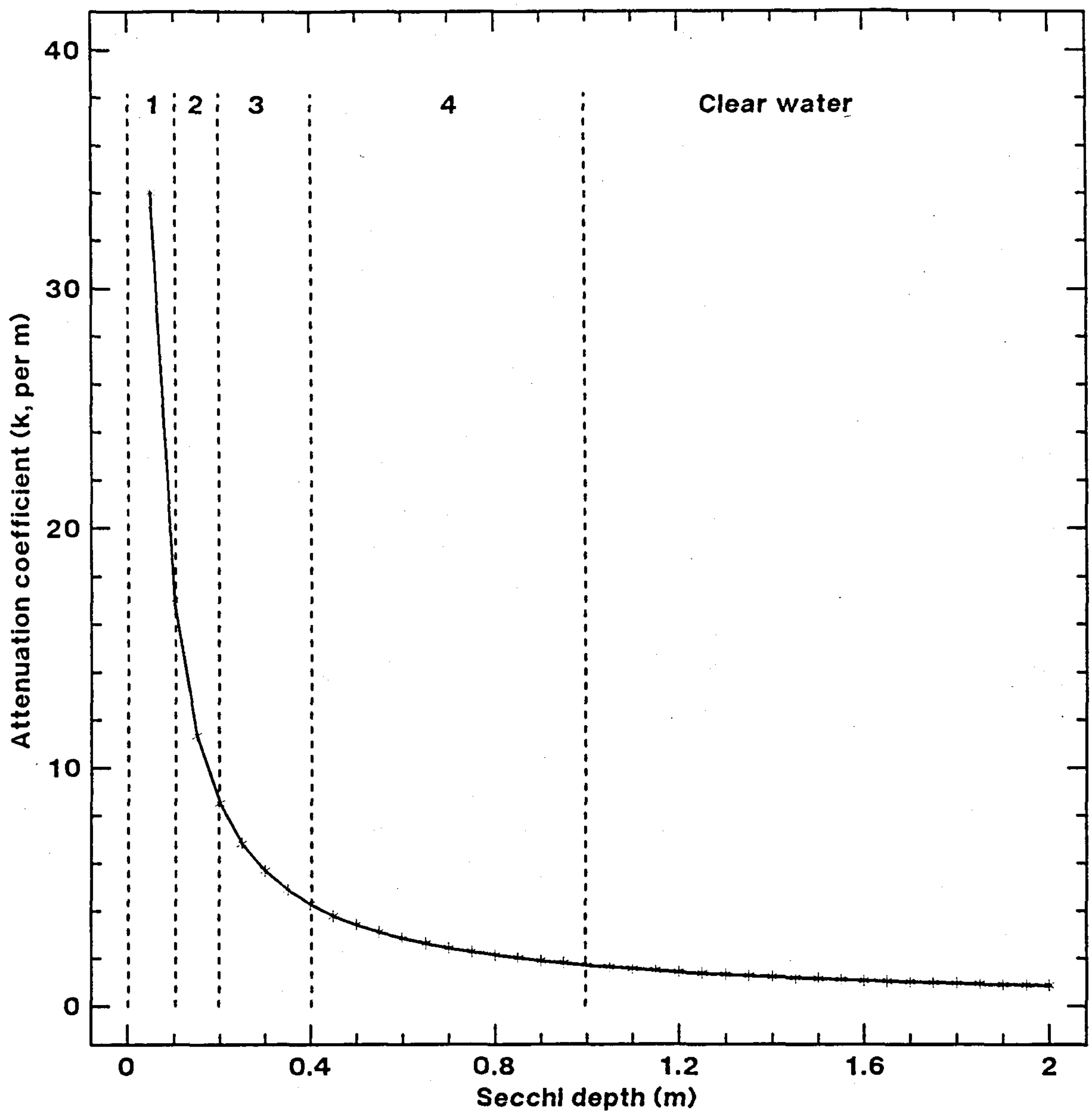


Figure 13 Graph of attenuation coefficient (k, m-1) against Secchi disk depth (m) showing the turbidity classes which were selected for the classification of turbid reservoirs.

2. The third and fourth class intervals were selected on the basis that the relationship (Figure 13) is nonlinear which would justify the use of unequal class intervals for the last two turbidity classes.
3. For the purpose of the DSS it was decided to classify all reservoirs with a Secchi depth greater than 1.0 m as "clear water" reservoirs and use the OECD Chl:P model to relate the phosphorus concentration to chlorophyll concentration (Figure 13).

Light attenuation in water is due to the processes of absorption and scattering. Absorption is due to organic substances, algae, coloured particles and water itself. Scattering is due to particles like algae and suspended solids. Turbidity is a measure of the scatter of light in the water column and is essentially insensitive to light absorption. A Secchi disk is a 20 cm black and white disk which is lowered into the water to a depth where it just disappears from view. Secchi depth is a function of both light scattering and light absorption. However, at high levels of scattering (as measured in turbid reservoirs), turbidity is a good predictor of Secchi depth (Effler, 1988).

A good relationship was found between turbidity and Secchi depth for Bloemhof Dam (Rossouw, 1986)

$$Turbidity = -2.067 + \frac{14.98}{SD} \quad (R^2=0.66) \tag{18}$$

Grobler *et al.* (1981) observed a good relationship between turbidity and suspended sediment in Bloemhof Dam:

$$Turbidity = 0.62 \times ISS - 0.51 \tag{19}$$

where Turbidity is in NTU, Secchi depth (SD) in metres and inorganic suspended solids (ISS) in mg/ℓ.

These relationships were used to estimate the turbidity and ISS concentrations for each of the four light attenuation classes used in the classification system for turbid reservoirs (Table 5).

Based on experience and knowledge of the reservoir, the user must classify the reservoir into one of the turbidity classes which will then automatically lead to the selection of the appropriate Chlorophyll:phosphorus model (Equation 16).

Table 5. Classification used to differentiate reservoirs into turbidity classes

| Turbidity class | Secchi Depth (m) | Turbidity (NTU) | Suspended sediment (mg/ℓ) |
|---|---|---|---|
| Highly Turbid | 0.0 - 0.1 | 260 | 419 |
| | 0.1 - 0.2 | 87 | 142 |
| Turbid | 0.2 - 0.4 | 44 | 72 |
| Less turbid | 0.4 - 1.0 | 19 | 32 |
| Clear water | > 1.0 | < 10 | < 10 |

# 6. INTEGRATED MODELLING APPROACH

## 6.1 Introduction

The control and management of eutrophication requires that the impact of alternative control measures be assessed to determine the most appropriate management strategy. Mathematical models have proved to be powerful tools for predicting the impact of alternative control measures. The models described in the previous sections simulate a large number of complex processes, some of which are highly stochastic in nature. One of the primary aims of this project was to integrate these models into a management-orientated eutrophication model to assess the impact of alternative control measures.

In eutrophication management, decision-making involves the structuring of information, which is essentially the analysis and synthesis of data, to form the foundation for choosing between different control measures. Decision support systems have been developed to help with the structuring of information in the decision-making process. It was therefore decided to incorporate the Reservoir Eutrophication Models into a Decision Support System for eutrophication control. The software package which was developed in the project was called REMDSS - Reservoir Eutrophication Model Decision Support System.

## 6.2 Introduction to Decision Support Systems

A **Decision Support System** (DSS) is defined as an interactive computer-based system that helps decision makers utilize data and models to solve unstructured problems (Sprague and Carlson, 1982). The objective is to evaluate "what if" questions regarding the operation of a system and simulate results in an effort to select the most appropriate solution (Koch and Allen, 1986). It can also assist the decision maker to interpret modelling results.

A DSS can be divided into a model base, a data base and the software system which provide the link between the user and each system (Figure 14). The software system can be divided into software which manage the model and data base and software which manages the interface or dialogue with the user (Sprague and Carlson, 1982).

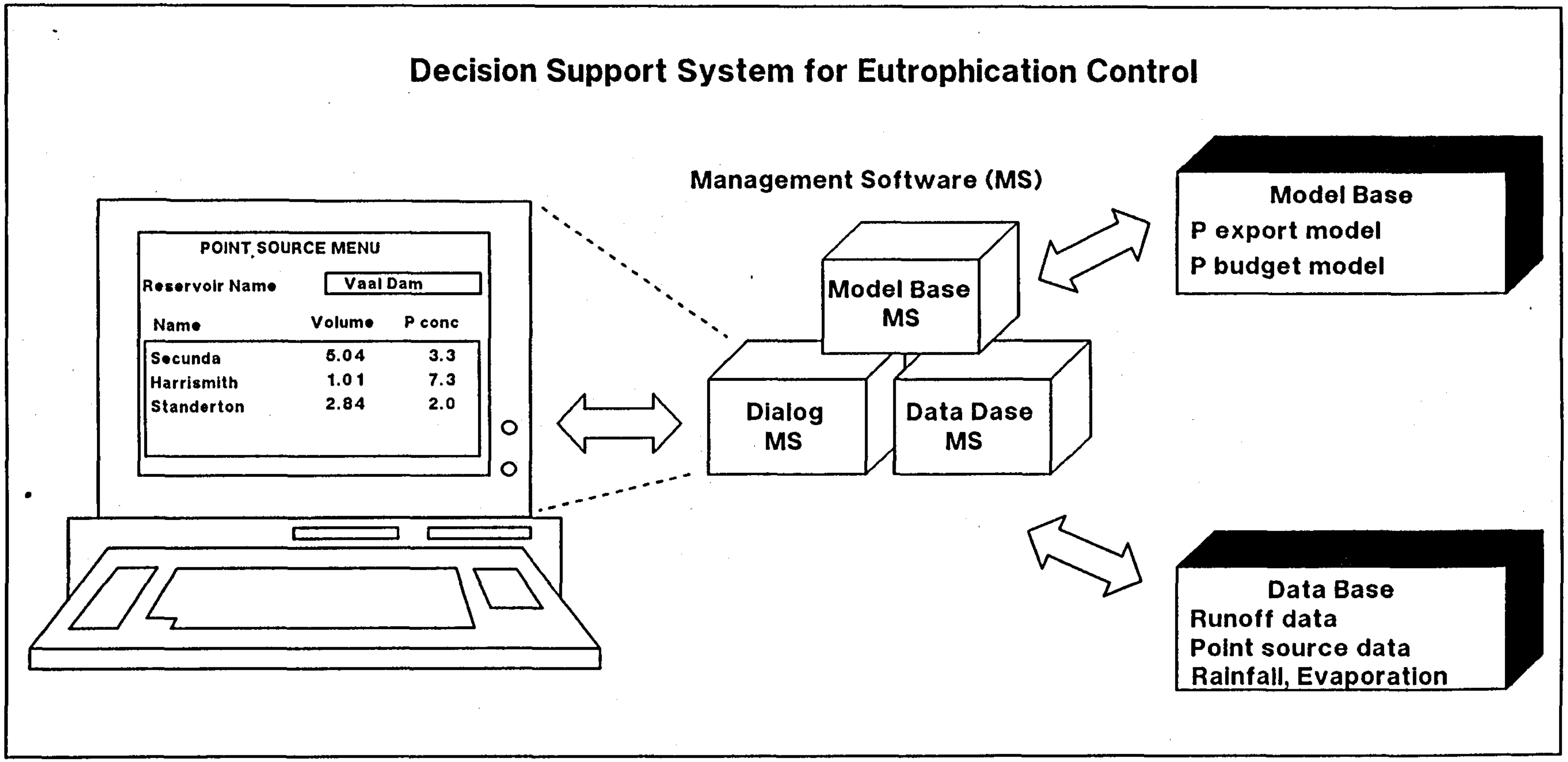


Figure 14 Diagram of the main components of the Decision Support System for Eutrophication control.

The **Dialogue system** is the most important feature of the DSS because it characterizes the power, flexibility and usability of the DSS. In the past, modellers were preoccupied with the structure of the model. Separate models were developed for each distinct part of the problem but were seldom integrated. Communication between the related models was left to the manager as a menial and frustrating process (Sprague and Carlson, 1982). The solution was to incorporate the models into a framework which performs the integration between the different models and the data as well as providing the interface with the user (Loucks *et al.*, 1985). The intelligent user interface must be easy to use, have opportunity to correct errors and be self teaching (Fedra, 1985). The interface must be largely menu driven and make ample use of graphics to display numerical data.

The **Data Base subsystem** consists of the data base and the data base management software (DBMS). In the data base the site specific input data and parameters which describe the physical system are stored (Fedra, 1985). The DBMS is responsible for retrieving and storing data, organizing interim results and preparing data for graphical displays.

The **Model Base subsystem** contains a set of simulation models which describe the individual processes of the problem situation (Sprague and Carlson, 1982). This is the key to the DSS because the models are embedded in an information system which performs the integration with the data base and therefore combines data retrieval and presentation with established models familiar to the decision maker.

## 6.3 The decision support system for eutrophication control (REMDSS)

The models described in chapters 3 to 5 were incorporated into a user friendly Decision Support System (DSS). A DSS consist of three components i.e. a model base, a data base and a computer program. The computer program links the model base and the data base and provides the interface with the user.

The model base contains the different REM submodels which were described in previous chapters. The data base contains the hydrological, point source, catchment and reservoir characteristic data of the reservoir. The DSS that was developed for REM is a program which helps the user prepare the input data to the models, then runs the models and displays the simulation results in different formats. It is responsible for storing and retrieving data, organizing interim results and displaying results in a graphical form. The interface with the user is a dialogue system which relies on menus which the user must complete. It then checks for errors, correcting these if necessary, and provides help facilities to new users.

The program runs on an IBM compatible personal computer under the MS-DOS operating system. All results are displayed on screen and the user has the option of displaying results on a printer or plotter. The program was developed with TURBO PASCAL (Borland International) and various third party supporting software.

## 6.4 Development of the DSS for eutrophication control

The development of a decision support system differs from the traditional systems design approach because the final system emerges through an adaptive process of design and usage (Ittman, 1985). One of the prerequisites in the development of decision support systems is that the user must be involved in the project from the start (Ittman, 1985; Loucks *et al.*, 1985). Provision must be made for rapid feedback from the user to ensure that the system meets the user's requirements and permits changes to be made easily. The steps in systems development - analysis, design, construction and implementation - are combined into one step which is repeated iteratively. Ittman (1985) stressed that success with any decision support system depends on picking the right problem and participants, setting the right targets, using the right processes and fitting the right tools to the task.

In the development of the DSS for eutrophication control, the following basic principles were applied (Rossouw and Grobler, 1987):

**User participation** - The first step was to identify the users of the DSS for eutrophication control. A technical subcommittee was appointed which consisted of the development team and the users from the Department of Water Affairs (Directorate of Water Pollution Control), under the chairmanship of the WRC research manager responsible for the project. The technical subcommittee met frequently in the early states of the project to clarify the user's needs and expectations, functional specifications, case studies etc. In the latter half of the project the functions of the subcommittee were replaced with direct interaction with the users during the application of the DSS.

**Correct tools** - It was decided to develop the DSS on an IBM compatible PC rather than a mainframe computer because recent advances in microcomputer technology made the PC a valuable aid to decision makers. It is easy to transport software between computers and graphic capabilities are better on PC's. Output devices such as printers and plotters are generally compatible.

The requirements of the development language were that it had to support structured programming, modular program development, have a good interface with screen graphics and with external files, have an efficient program editor with fast debug and compile facilities and support a maths coprocessor for speed of execution. TURBO PASCAL was found to fill all these requirements. It also conformed to the Department of Water Affairs' policy to standardize on TURBO PASCAL for all their scientific applications.

**Modular development** - The DSS was developed in modules which perform independent tasks such as drawing a graph or calculating a water balance. This not only increased readability of the program code but also made program maintenance easy. Ease of program maintenance is important during the iterative program development phase.

**Iterative development** - An important feature of the development of the DSS was the iterative development process in alliance with the users (Ittman, 1985; Loucks *et al.*, 1985). The users were presented at the earliest opportunity with a prototype of the DSS. Through using the system, the user fed back information on shortcomings experienced and enhancements required. These were taken care of in subsequent versions of the DSS which, upon completion, were passed back to the user for evaluation. The value of the user in this phase of the development should never be underestimated.

**Adaptive development** - the first prototypes of the DSS focused on very specific problems which only allowed the user to run the models for specific reservoirs. The intermediate versions were modified and adapted to user requests to run on more reservoir systems. The final version of REMDSS can be applied to a variety of catchment-reservoir systems and incorporates the latest user needs.

**User friendly interface** - The DSS for eutrophication control was designed to be applied in a process orientation (refer 6.5), where the decision maker personally uses the decision support system. This required a huge investment of resources. According to our experience, about 70% of the total resources were required for developing the user interface compare to about 30% required for the data and model base management systems.

The interface with the user is through a series of menu's, some of which are forms which have to be completed, and others which are merely choices between different options. The user fills in the forms using a full screen editor. Some of the fields are masked to guard against errors and inconsistencies. Some of the data in the input screens do not change from one run to another and are saved as "default values". The user only has to enter data into the fields he wishes to change and can then save it as a "standard file" for subsequent simulations. When the input has been prepared the management software runs the required models. In this process data files need to be accessed. For each file to be accessed, the user is prompted for a file name but is always presented with a default file name. If the file name specified for the output file corresponds with an existing file name, a warning is given and the user is asked whether or not the existing file can be overwritten. After running the models, the management software presents the user with a variety of options for viewing and displaying the output. The graphical outputs are always displayed on the screen. The user is then given the option of either printing the graph on a printer or plotting it on a plotter.

## 6.5 Utilization of the DSS for eutrophication control

Loucks *et al.* (1985) distinguish between two orientations in which decision support systems are applied; in a product orientation or in a process orientation. The definition of a decision support systems (6.2) emphasizes the interactive use of computers. However, whether the interactive use of computers plays a central role depends on the orientation in which it is applied and on the nature of the user interface (Figure 15).

### Product orientation

In product oriented applications, a technical expert applies the decision support system and then provides the decision-maker with the results who then includes these in the decision-making process. The interactive use of computers by the decision-maker therefore does not play a central role. The user interface is almost entirely in the form of verbal and written communication between the technical expert and the decision-maker. The communication between the

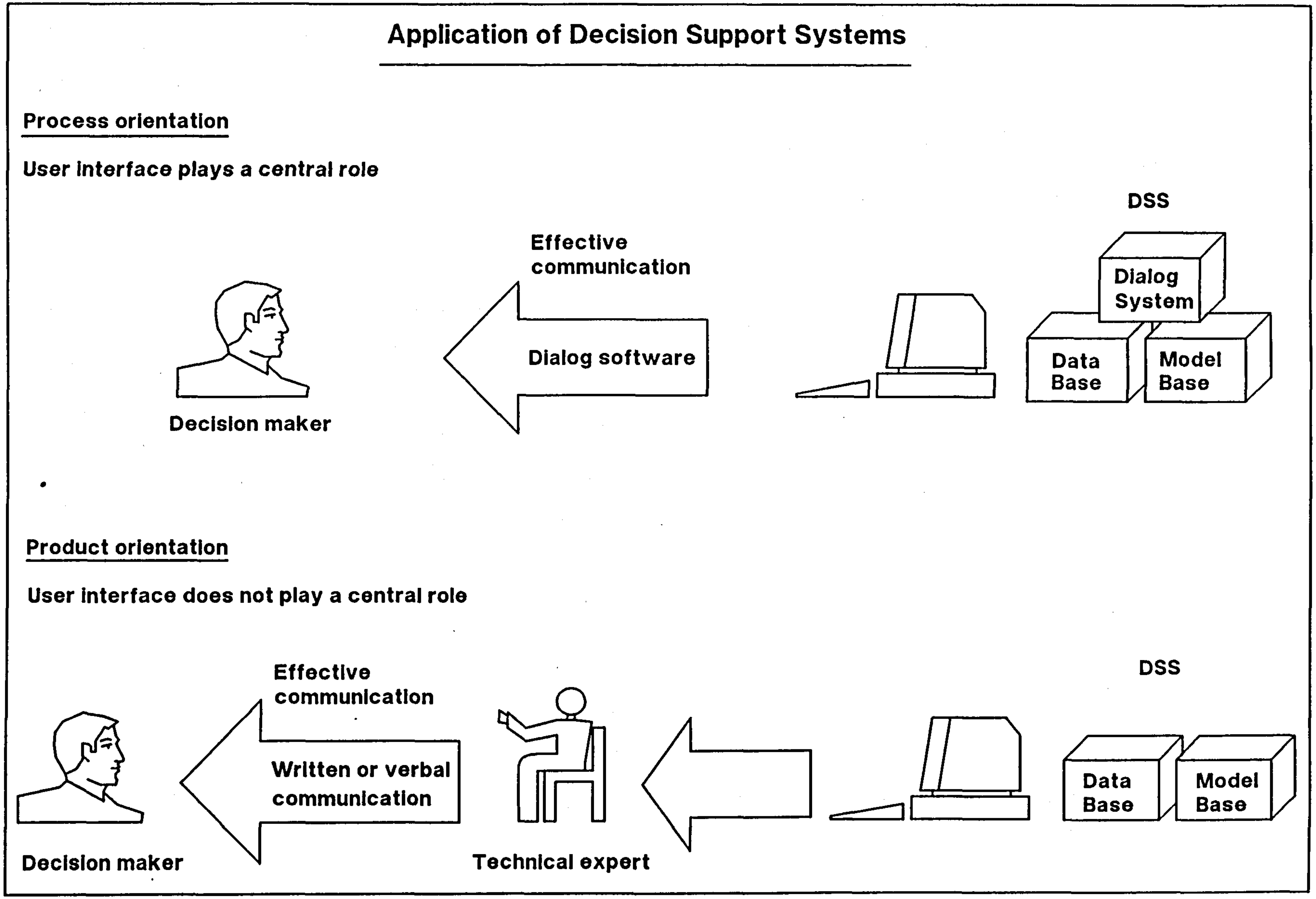


Figure 15 Graphical presentation of the two orientations in which Decision Support Systems are applied.

decision-maker and the technical expert must be effective to ensure successful application of the decision support system.

**Process orientation**

In process oriented applications, the interactive use of computers by decision-makers plays a central role. The user interface is handled almost entirely by computer software as described in 6.2. The decision-maker personally uses an interactive computer-based decision support system and then includes the results in the decision process. To ensure the successful application of the decision support system, the user interface between the computer and the decision-maker must be effective.

The decision support system for eutrophication control (REMDSS) was designed to be used in a process orientation. As a result, considerable resources were spent on the development of the computer based dialogue system as the user interface. However, when it was applied in practice, the decision support system was used in a product orientation (Grobler, 1988). The decision-makers relied on technical experts to apply the decision support system and synthesize the results. The apparent advantages of using REMDSS in a process orientation were therefore not realized for managers.

Grobler (1988) listed three probable reasons for this:

1. Running the simulation models was considerably simplified. However, the catchment-river-reservoir systems represented by the models were complex and required considerable insight from the user about the reasonableness of the inputs, assumptions and outputs for a given application. It was felt that decision-makers were uncomfortable with making judgments if these was outside their fields of expertise.
2. A decision-maker cannot afford to spend the long time required to do an analysis on one single problem. It required about two man years to apply REMDSS to seven catchments to assess the impact of different eutrophication control measures. This time was reduced to nine months by using more manpower. However, very few water resource managers in South Africa can afford to spend that amount of time in investigating one problem.
3. The investigations were essentially exercises in planning and policy analysis which seldom required decisions to be taken immediately.

The author believes that the amount of effort that went into the development of the user interface for REMDSS was justified because it made it easier to run the models. This was a great advantage to technical experts who were not computer literate. It also forced users to focus on important issues such as the accuracy of the input data, the assumptions made for a particular application and the reasonableness of the output data.

Although the REMDSS was not utilized by the decision makers as originally envisaged, it made the REM models accessible to the technical experts advising the decision makers, to whom the REM would otherwise have remained largely a closed book.

# 7. MANAGEMENT DECISION MODELS

## 7.1 Introduction

The decision support system described so far provides decision makers only with information about the predicted physical, chemical and biological response of the reservoir to different eutrophication control measures. In the selection of appropriate eutrophication control strategies, decision-makers are often faced with a multiplicity of conflicting objectives of a technological, financial, environmental, social and political nature. The problem decision makers are faced with is how to integrate quantitative and qualitative information in the same decision framework. A number of decision models have been developed to accomplish this and the Analytical Hierarchy Process (AHP) developed by Saaty (1982) is an excellent example.

Grobler *et al.* (1987) demonstrated how the AHP could be used to select the most appropriate phosphorus control option from several alternatives by performing a formal benefit:cost analysis. At the third steering committee meeting it was suggested that an actual case study be done to establish the usefulness of the AHP process for selecting the most beneficial eutrophication control measure. The AHP was therefore used in a practical application with the Department of Water Affairs to consider which one of four alternative control measures would be most appropriate for controlling eutrophication in Hartbeespoort Dam.

## 7.2 The analytical hierarchy process

The AHP is one of the operational research tools available for decision making in a complex environment. It is a multi-objective, multi-criterion decision- making system that employs a pairwise comparison procedure to arrive at a scale of preferences amongst sets of alternatives. The AHP is applied by conceptualizing the decision-problem as a hierarchy of decision elements. In short, it is a method of breaking down a complex, unstructured situation into its component parts; arranging these parts into a hierarchic order; assigning numerical values to subjective judgments on the relative importance of each variable; and synthesizing the judgments to determine which variables have the highest priority and should be acted upon to influence the outcome of the situation (Saaty, 1983).

AHP can cope with intuitive, rational and irrational judgments of measurable quantities and immeasurable qualities. This is a major advantage when applying the AHP in decision problems where quantitative as well qualitative information has to be considered (Figure 16).

It also provides an effective structure for group decision making by imposing a discipline on the group's thought processes. It requires a group to be small and well informed, highly motivated and in agreement on the basic question being addressed.

## 7.3 Evaluation of the AHP as a decision making model

To evaluate the AHP as a decision aid for eutrophication control, it was decided to invite only a small group of participants from the Department of Water Affairs who were directly involved with management decisions on Hartbeespoort Dam and its catchment. Large groups pose special problems (Saaty, 1982) because it can make the analysis unwieldy and time consuming. A number of people with specialized knowledge of the Hartbeespoort Dam system were also invited in an advisory capacity.

### 7.3.1 Participants

The following members of the Department of Water Affairs and advisors were present:

| | |
|---|---|
| Facilitator | |
| Dr.D C Grobler | Division of Water Technology, CSIR |
| | |
| Participants | |
| Mnr. W van der Merwe | Director: Water Pollution Control |
| Mnr. A Botha | Directorate of Strategic Planning |
| Mnr. H Muller | Directorate of Planning |
| Mnr. F van Zyl | Directorate of Planning |
| Mnr. E Braune | Director: Hydrological Research Institute |
| | |
| Advisors | |
| Dr. P Ashton | Division of Water Technology, CSIR |
| Mnr. N Rossouw | Division of Water Technology, CSIR |
| Mnr. M du Plessis | Water Research Commission |

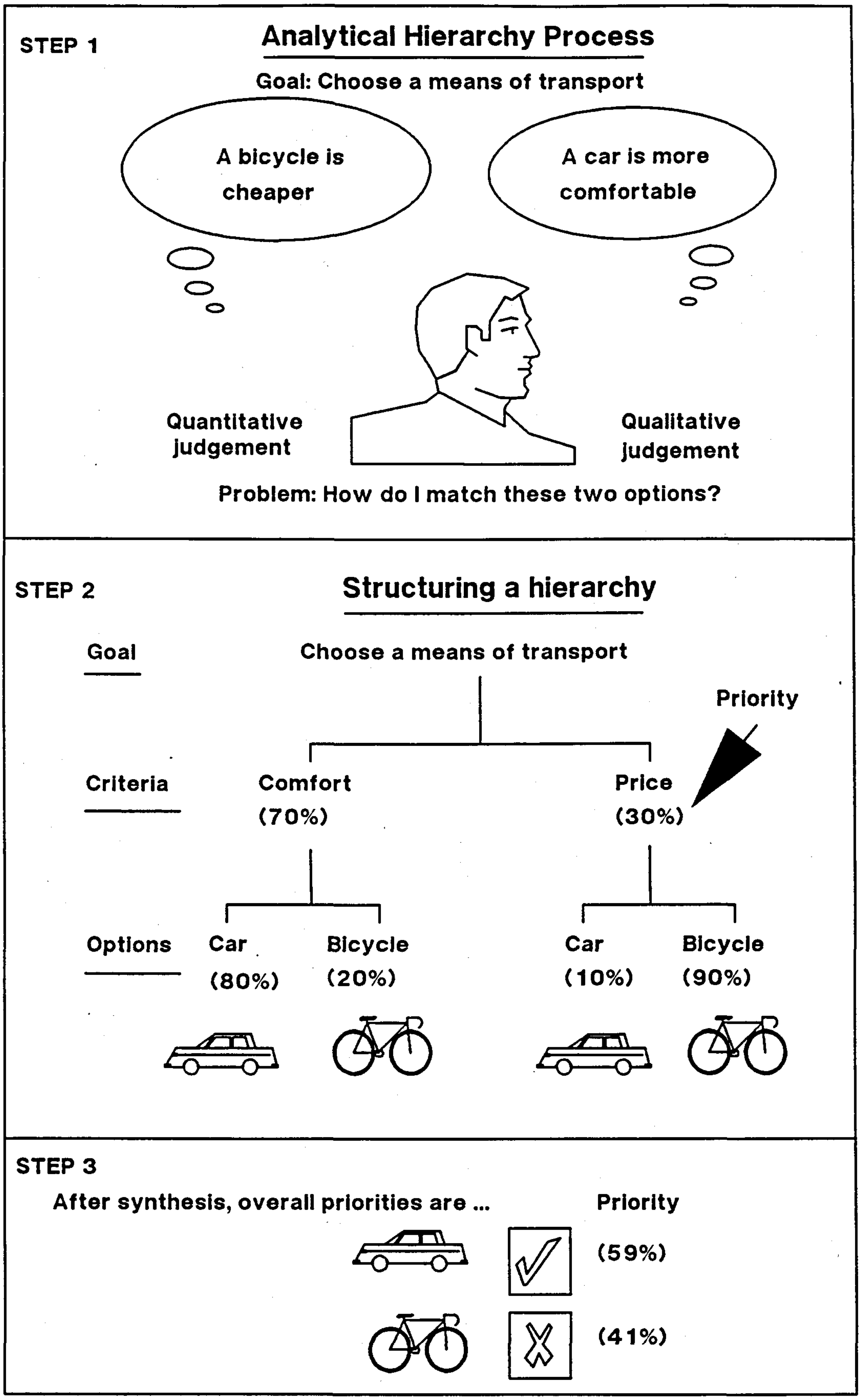


Figure 16 Graphical illustration of the Analytical Hierarchy Process (AHP). AHP is best applied to problems in which qualitative as well as quantitative information have to be considered. The first step is to define the problem, specify the solution desired, list all the alternatives and identify the main factors (criteria) influencing the decision. The second step is to construct a hierarchy and then do a pairwise comparison of all the elements at the same level of the hierarchy. The last step is a synthesis of all the weights to arrive at a scale of preferences amongst the sets of alternatives (options).

| | |
|---|---|
| Mnr. R Schwab | Directorate of Water Pollution Control |
| Mnr. F Vogel | Directorate of Planning |
| Mnr. P Howarth | Directorate of Water Pollution Control |

### 7.3.2 Selection of the best P control option for Hartbeespoort Dam

The first step in applying the AHP was to state the goal of the analysis as clearly as possible. In this case **the goal** was stated as:

*Select the one control measure, out of the four listed below, which would maximize the benefits and minimize the disadvantages to all the users and administrators of the water resources in the catchment.*

The four alternative phosphorus control strategies for Hartbeespoort Dam were derived from what is considered to be technologically feasible in terms of phosphorus removal from effluents, the role of effluents as a major resource in the long term development of the water resources of the region, and what is considered to be technologically feasible in terms of in-lake management procedures (Rossouw and Grobler, 1988). The four alternatives were:

1. **1 MG/L** - All point source effluents must comply to a 1 mg P/ℓ effluent standard. The technology for achieving this standard in effluents is well established in South Africa.

2. **0.1 MG/L** - All point source effluents must comply to a 0.1 mg P/ℓ standard. The technology is not well established and it is perceived to be considerably more expensive than option 1.

3. **RE-USE** - 60% of the effluent will be treated for direct re-use and would thus not be returned to the receiving waters. The technology for treating wastewater to potable standards is well established and economically feasible in South Africa. However, there is considerable public resistance to directly reusing treated wastewater.

4. **INLAKE** - All effluents must comply to a 1 mg P/ℓ standard and aeration/destratification

will be implemented as an in-lake management procedure to control some of the symptoms of eutrophication. The severity of the eutrophication-related water quality problems experienced in Hartbeespoort Dam is partly due to Microcystis being the dominant alga. It is believed that aeration/destratification is the only practical and economical in-lake management operation which could cause a shift from Microcystis dominance to more desirable algal species.

### 7.3.3 Construction of the hierarchy

The next step in the application was to identify the major factors affecting the decision, define each clearly and construct a hierarchy using all the relevant details to depict the problem. A software package "EXPERT CHOICE" (Decision Support Software, Inc.), which was developed for AHP applications, was used to structure the hierarchy and select the best control strategy.

It was widely debated whether the first level of the hierarchy should reflect the major concerns associated with Hartbeespoort Dam or the parties involved with problems. It was finally decided that the first level should in fact be the major parties who are involved with the eutrophication problems in Hartbeespoort dam (Figure 17). They were defined as:

**STATE** The government departments who are responsible for development of the water resources in the catchment and for maintaining appropriate water quality in Hartbeespoort Dam. They were the Department of Water Affairs and the Department of National Health and Population Development.

**POLLUTER** With the exception of AECI, these were the local authorities who operate sewage treatment plants in the Hartbeespoort dam catchment. Treated sewage is the biggest source of phosphates in the Hartbeespoort Dam catchment.

**USERS** Those who obtain water from Hartbeespoort dam for irrigation and treatment of potable water (municipalities of Schoemansville, Cosmos and Brits, farmers of the Hartbeespoort Dam irrigation scheme). It also includes recreation users (contact and non-contact users) and the property owners living along the shores of Hartbeespoort Dam.

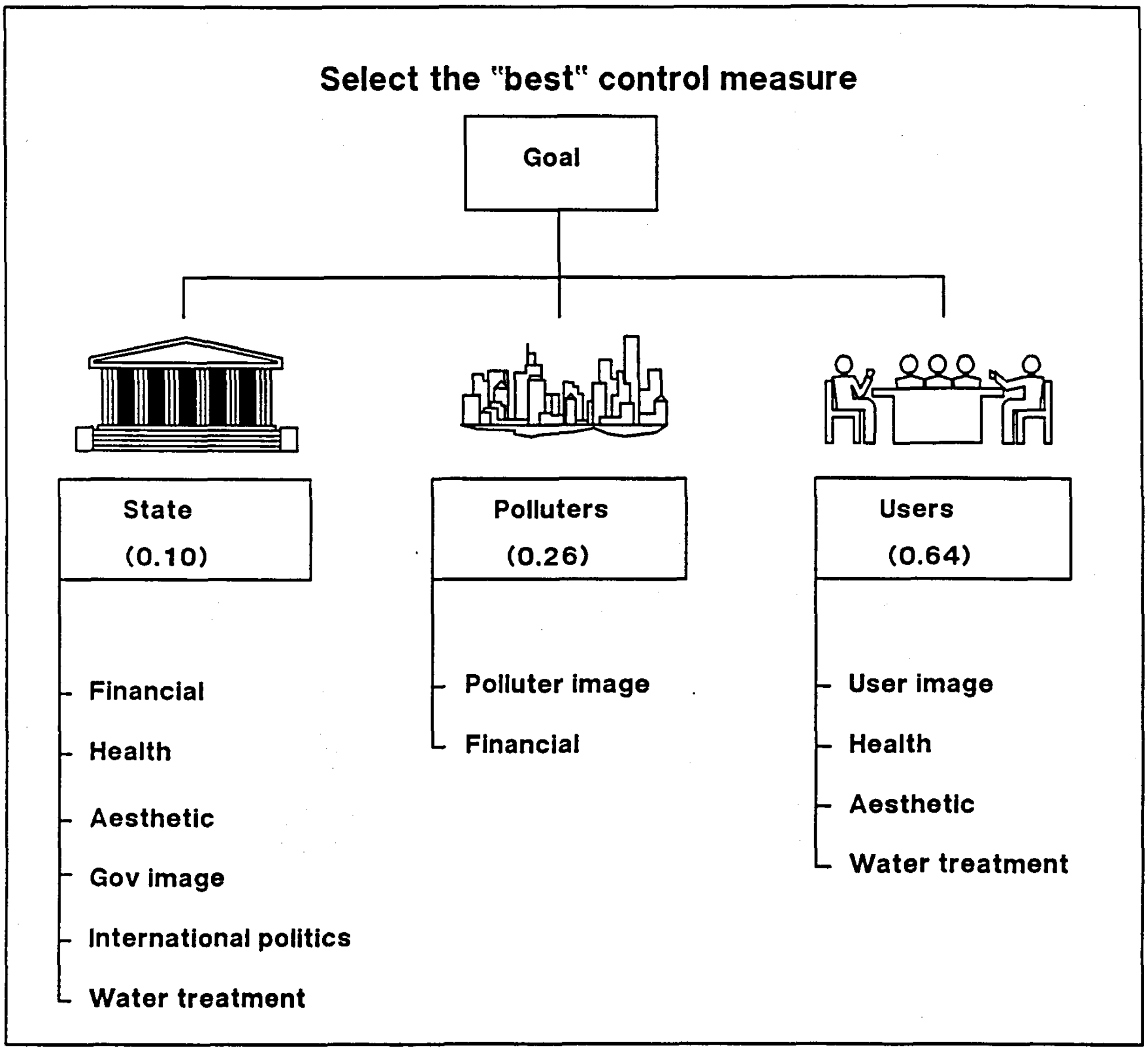


Figure 17 Diagram of the first level of the hierarchy (major parties) which was constructed to select the best eutrophication control measure for Hartbeespoort Dam.

The parties involved in the problems of Hartbeespoort Dam were compared to determine the relative importance of each party. The following priorities were derived from the comparisons:

| | |
|---|---|
| USERS | 64 % |
| POLLUTERS | 26 % |
| STATE | 10 % |

It was argued that the users were the most important party because they had to suffer the consequences of bad water quality in Hartbeespoort Dam.

The second level of the hierarchy was the concerns related to the selection of an optimum control strategy, for each of the major parties.

It was assumed that the **USERS** group would be concerned about (Figure 18):

**IMAGE** The perception with the general public that Hartbeespoort Dam is severely polluted and therefore poses a health risk for those who use it. This also includes the image of lake-side authorities who have a responsibility to their rate- payers for supplying drinking water and cleaning up the shore.

**HEALTH** The health risk involved users who utilize the water from Hartbeespoort Dam for potable water supplies and recreation. It also includes downstream users who withdraw water directly from the Crocodile River.

**AESTHETIC** The users perception of aesthetic considerations such as maintenance of a healthy ecosystem, the quality of recreation, and the value visitors and lake-side property owners attribute to the ecosystem.

**WATER TREATMENT** These are the financial costs to lake-side authorities and water boards of treating eutrophic water to drinking water standards.

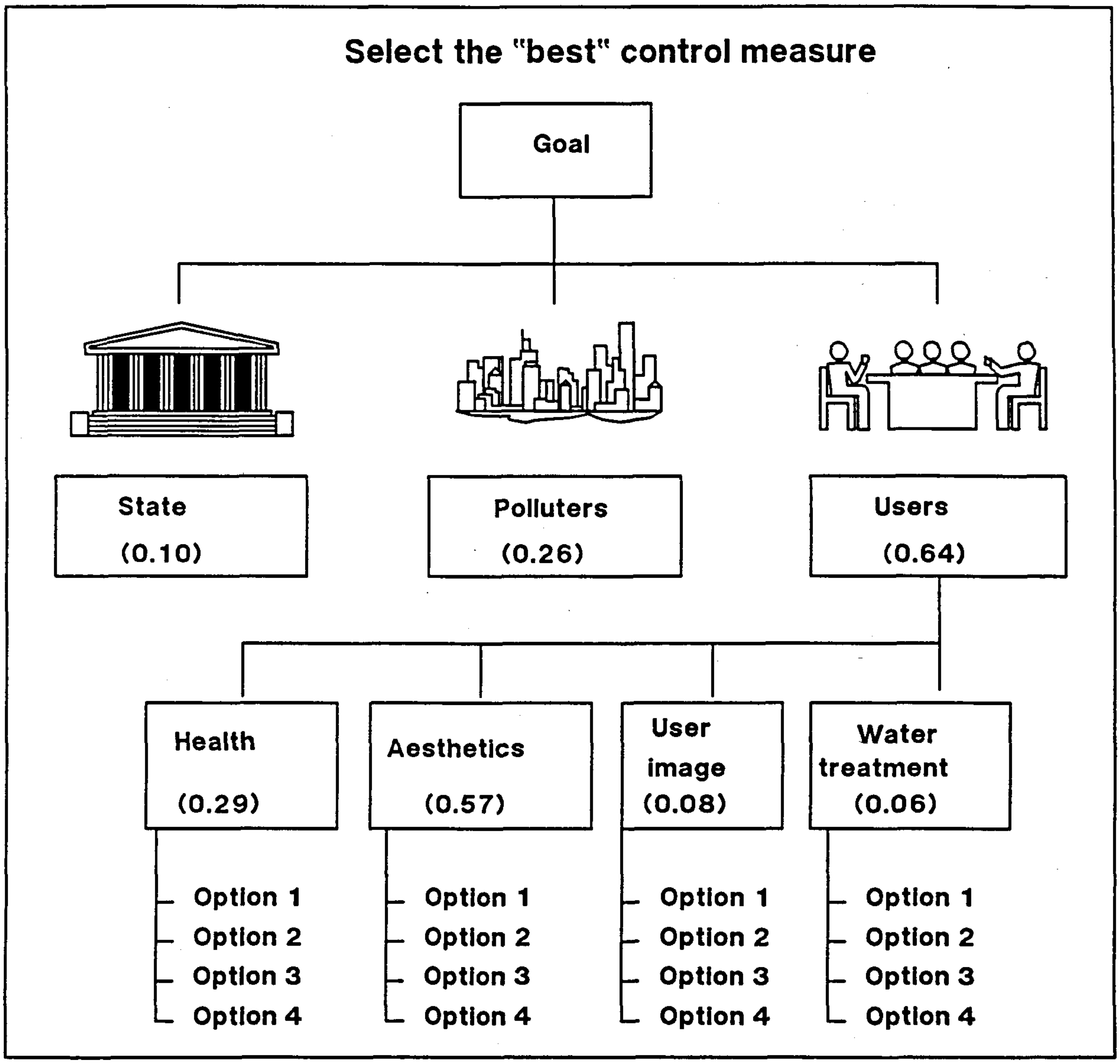


Figure 18 Diagram of the major factors which concern the users group in their decision to select the best eutrophication control measure for Hartbeespoort Dam.

It was assumed that the **POLLUTER** group would be concerned about (Figure 19):

**IMAGE** The image of the polluter (local authority) as an organization who has to treat sewage with the best available technology with the most cost effective method.

**FINANCE** The financial costs and effort to the polluter (local authority) to upgrade sewage works to remove phosphates to comply to the set standards.

It was assumed that the **STATE** group would be concerned about (Figure 20):

**IMAGE** The image of government departments who have moral and legislative responsibilities towards their tax payers, the scientific/ecological community and local authorities (polluters) in the catchment. This includes the risk of taking a wrong decision.

**FINANCE** The financial costs and effort to implement and police eutrophication control measures, including the costs of assessing the impact of different control measures.

**HEALTH** The responsibility of the state to ensure that safe drinking water and recreation standards are maintained in Hartbeespoort Dam.

**AESTHETIC** The responsibility of the state to maintain a healthy ecosystem, improve the quality of recreation and the value which visitors and lake-side property owners attribute to the Hartbeespoort Dam ecosystem.

**INTERNATIONAL POLITICS** The Crocodile River becomes an international river downstream of Hartbeespoort Dam and it is the responsibility of the state to ensure adequate water of acceptable quality to downstream users according to the Helsinki rules.

**WATER TREATMENT** The concern of the state about the financial costs to local authorities to treat Hartbeespoort Dam water to drinking water standards.

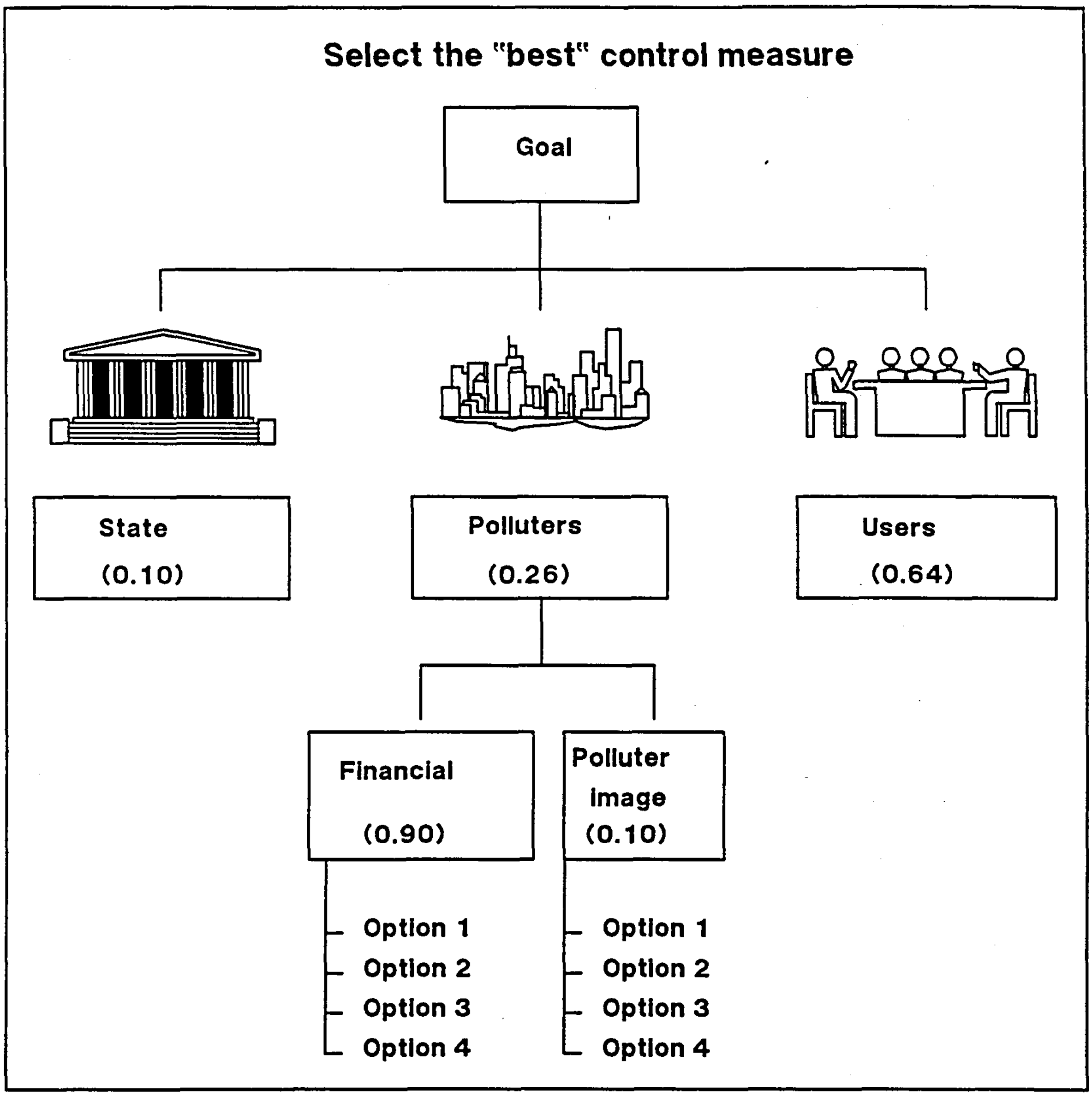


Figure 19 Diagram of the major factors which concern the polluters group in their decision to select the best eutrophication control measure for Hartbeespoort Dam.

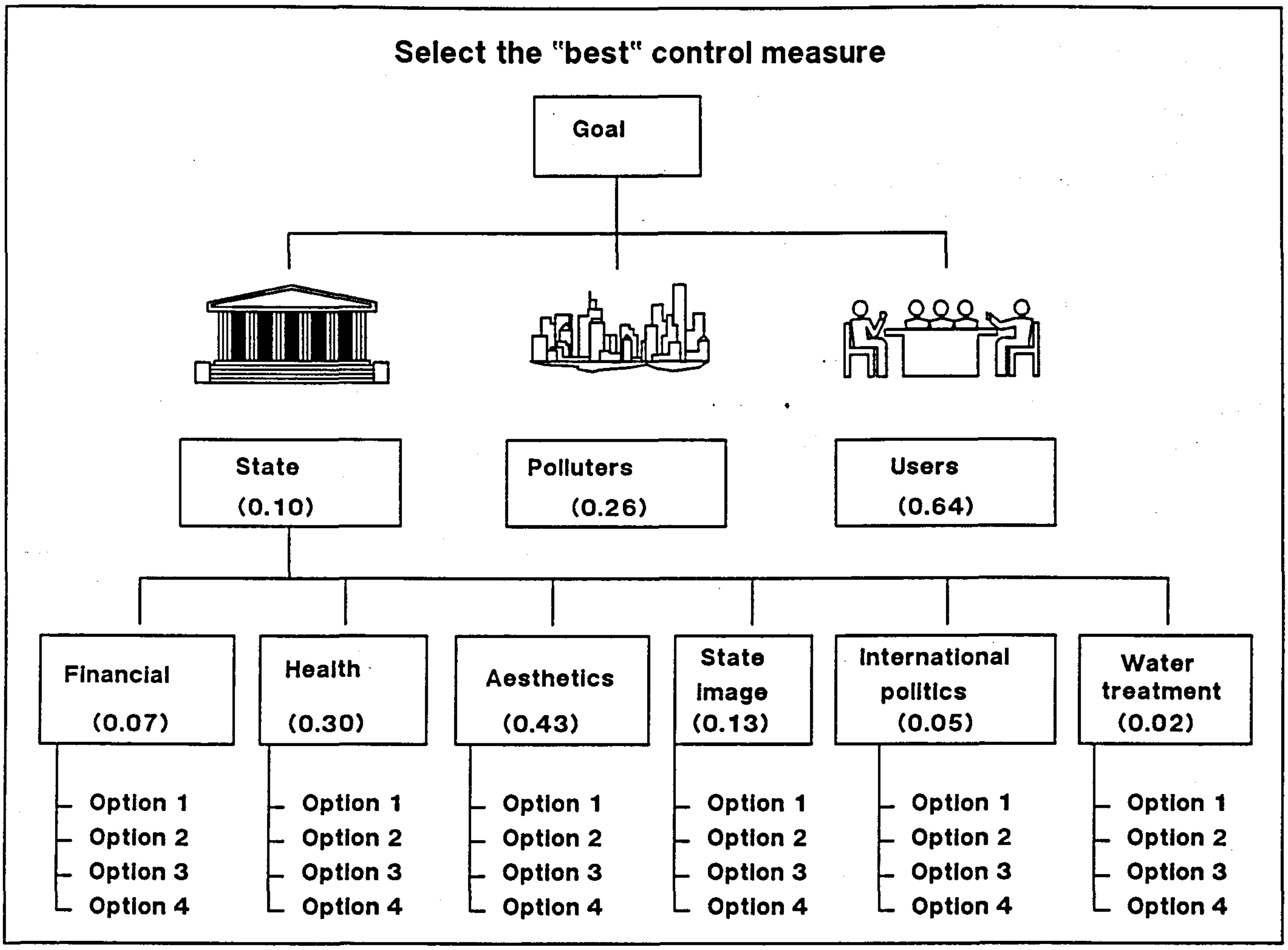


Figure 20 Diagram of the major factors which concern the state group in their decision to select the best eutrophication control measure for Hartbeespoort Dam.

The major concerns of each party were compared with each other to determine the relative importance of each concern. The following priorities were derived from the comparisons:

| Party | Concern | Priority |
|---|---|---|
| STATE | Aesthetic | 43 % |
| | Health | 30 % |
| | Image | 12 % |
| | Financial | 7 % |
| | International Politics | 5 % |
| | Water Treatment | 2 % |
| POLLUTER | Financial | 90 % |
| | Image | 10 % |
| USER | Aesthetic | 57 % |
| | Health | 29 % |
| | Image | 8 % |
| | Water Treatment | 7 % |

The final step in the application of the AHP was an overall synthesis of the priorities. The result of the overall synthesis were:

| Option No | Option | Preference |
|---|---|---|
| 3 | Re-use | 47 % |
| 2 | 0.1 mg/$\ell$ P standard | 29 % |
| 4 | 1 mg/$\ell$ P standard & In-lake management | 14 % |
| 1 | 1 mg/$\ell$ P standard | 10 % |

## 7.4 Discussion

From these results it is clear that an option where 60% of the sewage effluents are treated for direct re-use was the most preferred option. It was argued that by preventing the nutrients from entering the reservoir, a great number of problems are averted. It would also improve the aesthetic image of the reservoir which is important to the users and to state groups. It would also reduce the health risks and would be financially beneficial to the polluter group. However, water resources are limited in the region and downstream users have become dependent on return flows to Hartbeespoort Dam as a source of water. It is foreseen that Hartbeespoort Dam would in future become an important source of water to urban and industrial users. Therefore, even though the re-use option is preferred from a water quality management point of view, water quantity management may exclude this option.

The second most preferred option was implementation of the 0.1 mg/ℓ P standard. This option would reduce the amount of nutrients entering the reservoir without reducing the volume of water. It was therefore preferred from a water quality and quantity point of view. However, this is a long-term goal as the technology to consistently remove P from sewage effluents to such low concentrations is not well established yet.

The option of implementing a 1mg/ℓ P effluent standard as well as aeration/destratification as an in-lake management technique, was the most probable short term management strategy to be implemented.

In 1988 the Department of Water Affairs took the decision to strictly implement the 1 mg P/ℓ effluent standard in the Hartbeespoort Dam catchment from August 1988 and to apply aeration/destratification as an in-lake management option. Grobler and Rossouw (1989) later applied the AHP to a retrospective analysis of the decision which resulted in the particular control measure being selected. It was hoped that such an analysis would illuminate the factors, and their weights, which influenced the Department's decision. The information required for the analysis was acquired through interviews with those officials in the Department who were involved in arriving at the decision that was made.

Four eutrophication control measures were actually considered (Figure 21):

1. No control
2. Implementation of the 1 mg P/ℓ effluent standard
3. Implementation of a 0.1 mg P/ℓ effluent standard
4. Implementation of the 1 mg P/ℓ effluent standard and in-lake management options

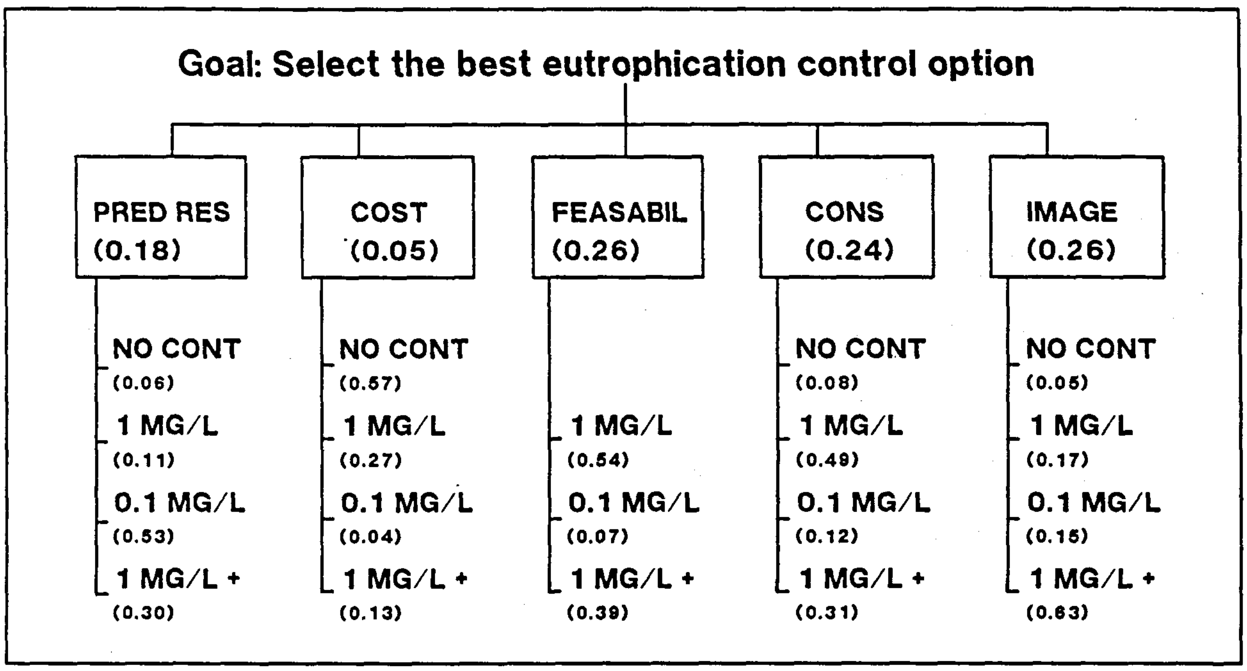


Figure 21 The decision hierarchy which was constructed in the retrospective analysis of the decision taken to control eutrophication in Hartbeespoort Dam. The relative weights associated with each factor or option are given in parentheses.

The re-use option was never seriously considered as a viable control measure because the Department would have difficulty in meeting the projected demands from Hartbeespoort Dam.

The major factors which affected the selection of a eutrophication control measure were built into the first level of the hierarchy (Figure 21):

1. The predicted water quality response which included the expert opinion of researchers who had studied the reservoir over several years.
2. The cost of implementing each option.
3. The feasibility of implementing each option.
4. Conservatism inherent in government institutions i.e. a tendency to prefer options which are proven, standard and not controversial.
5. The image of the Department i.e. concern on the one hand for the damage to the Department's image as a result of the present water quality and on the other hand, the image of the Department amongst polluters to be strict but fair.

A pairwise comparison was used to rate the various eutrophication control options in terms of preference under each of the major factors. Finally the relative weights associated with the factors in the first level had to be determined in order to arrive at the same decision in the retrospective analysis as the Department had originally arrived at.

The result of the analysis was a surprise because the factors which dealt with quantitative results ("predicted response" and "cost") carried less weight than any one of the remaining factors (Figure 21). This provided us with a healthy dose of modesty about the impacts that the output of the DSS have on the actual decisions that are made about eutrophication control. It must be stressed that the weights for the different factors depend very much on the particular local circumstances. At a different site or time, the weights for the factors and even the factors themselves, could be different to what they were found to be during the analysis.

# 8. APPLICATIONS OF REMDSS TO ASSESS EUTROPHICATION CONTROL MEASURES

One of the most important factors in the development of a DSS is the interaction with the user. During the development of the DSS for eutrophication control, the user was encouraged to apply the DSS to actual case studies. These applications not only demonstrated the capabilities of the DSS but also provided valuable feedback to the project team on problems experienced and enhancements required to the DSS.

The project team were also involved in a number of case studies to assess the impact of different eutrophication control measures.

## 8.1 Application of the DSS to assess the impact of the 1 mg P/ℓ phosphorus standard on sensitive catchments.

In 1987 the Department of Water Affairs approached the project team with a request to help the Department assess the impact of the 1 mg P/ℓ phosphorus standard on reservoirs in the seven sensitive catchments. It was estimated that the applications would take about 2 man years which could be reduced to about 9 months by deploying extra manpower. The Water Research Commission agreed to release the project team of their responsibility for the project for a period of 9 months. Together with members of the Department of Water Affairs (Directorate of Water Pollution Control), the assessments were carried out using the available data and the DSS for eutrophication control (Best, 1987).

The project team was responsible for applications in the Crocodile River catchment, Vaal River catchment and the Mgeni River catchment. The following reports were produced for the Department of Water Affairs:

GROBLER, D.C. and ROSSOUW, J.N. (1988). Nonpoint source derived phosphorus export from sensitive catchments in South Africa. Report to the Department of Water Affairs.

ROSSOUW, J.N. (1988). Evaluation of the impact of eutrophication control measures on water quality in: Rietvlei Dam. Report to the Directorate of Water Pollution Control, Department of Water Affairs.

ROSSOUW, J.N. and GROBLER, D.C. (1988). Evaluation of the impact of eutrophication control measures on water quality in: Hartbeespoort Dam. Report to the Directorate of Water Pollution Control, Department of Water Affairs.

ROSSOUW, J.N. and KELLY, H. (1988). Evaluation of the impact of eutrophication control measures on water quality in: The Umgeni River system. Report to the Directorate of Water Pollution Control, Department of Water Affairs.

ROSSOUW, J.N. and KELLY, H. (1988). Evaluation of the impact of eutrophication control measures on water quality in: Vaal Dam. Report to the Directorate of Water Pollution Control, Department of Water Affairs.

ROSSOUW, J.N. and KELLY, H. (1988). Evaluation of the impact of eutrophication control measures on water quality in: Bloemhof Dam. Report to the Directorate of Water Pollution Control, Department of Water Affairs.

GROBLER, D.C. (1988). Assessment of the implications of phosphorus control strategies on eutrophication related water quality in the middle Vaal River. Report to the Directorate of Water Pollution Control, Department of Water Affairs.

A copy of the Hartbeespoort Dam application is included in Appendix B as an example of how the DSS for eutrophication control was applied to case studies. The Department of Water Affairs (Directorate of Water Pollution Control) was responsible for the applications on the following reservoirs:

1. Roodeplaat Dam in the Pienaars River catchment.
2. Loskop Dam and Bronkhorstspruit Dam in the Olifants River catchment.
3. Shongweni Dam in the Umlaas River catchment.
4. Laing Dam and Bridle Drift Dam in the Buffalo River catchment.

## 8.2 Other applications of the DSS for eutrophication control

Botshabelo study - Botshabelo is a high-density low-cost housing project outside Thaba N'chu in the eastern Free State. Concern was expressed about the impact of the project on water quality in the Modder River downstream of Botshabelo. The DSS was applied to assess the impact of different point source and nonpoint source loads on the downstream reservoirs. This study resulted in a confidential report to the Department of Water Affairs, "Assessment of the impact of low-cost, high-density urban development at Botshabelo on water quality in the Modder River catchment" (Grobler *et al.*, 1987b).

Economic impact of eutrophication - The economic impact of eutrophication was the subject of an M.Sc study in which the DSS was applied to predict the water quality impact of different eutrophication control measures. The result was a thesis, "'n Ekonomiese evaluasie van beheermaatreëls vir eutrofikasie" (Botha, 1989).

# 9. UNCERTAINTY ANALYSIS

One of the goals in the original project proposal was to build in a procedure for uncertainty analysis to quantify the usefulness of predictions to management. It was foreseen that the procedure would be based on Monte Carlo simulations and/or the Bayes theorem. Two key issues were responsible for the lack of progress with this task.

The first key issue was that throughout the development phase of the project, the project team responded to user needs. This is a key feature in the development of decision support systems and was discussed in section 6.4. The question of uncertainty analysis was discussed at length at technical subcommittee level as well as with water resource managers at the Department of Water Affairs. There was always doubt in the minds of the users as to what might be expected from the uncertainty analysis and whether the analysis would only address one of the elements in a taxonomy of uncertainty (Figure 22), such as parameter uncertainty. It was felt that the predicted response of the system was only one of the many inputs into the decision making process. It was further reasoned that is was unnecessary to expend large resources on quantifying the uncertainty in the predictions when the uncertainty in the other main factors influencing the decision were perceived to be just as large or even greater by water resource managers. This perception of uncertainty analysis is understandable if the results of the retrospective analysis conducted on the factors which influenced the Departments's decision on Hartbeespoort Dam (section 7.4) is considered. It was clear that in order to develop realistic uncertainty analysis procedures, all the elements in the taxonomy of uncertainty (Figure 22) need to be addressed.

The second key issue which accounted for the lack of progress with uncertainty analysis was that it was realized from the beginning that an expert in the field of water quality uncertainty analysis was not available in South Africa. It was proposed to invite a leading expert in the field of uncertainty analysis from the U.S.A., to work on the project. The invitation was negotiated on several occasions but several factors prevented him from coming to South Africa. It was also unacceptable for the project team to contract this aspect to him in the USA because a transfer of technology would not really take place on that basis.

At the last steering committee meeting, the Department of Water Affairs indicated that they were satisfied with the product and expertise derived from this project. They felt that, from a user's point of view, the uncertainty analysis should have a low priority and should only be addressed if time was available after all the proposed changes to the DSS were completed. This suggestion was accepted by the steering committee.

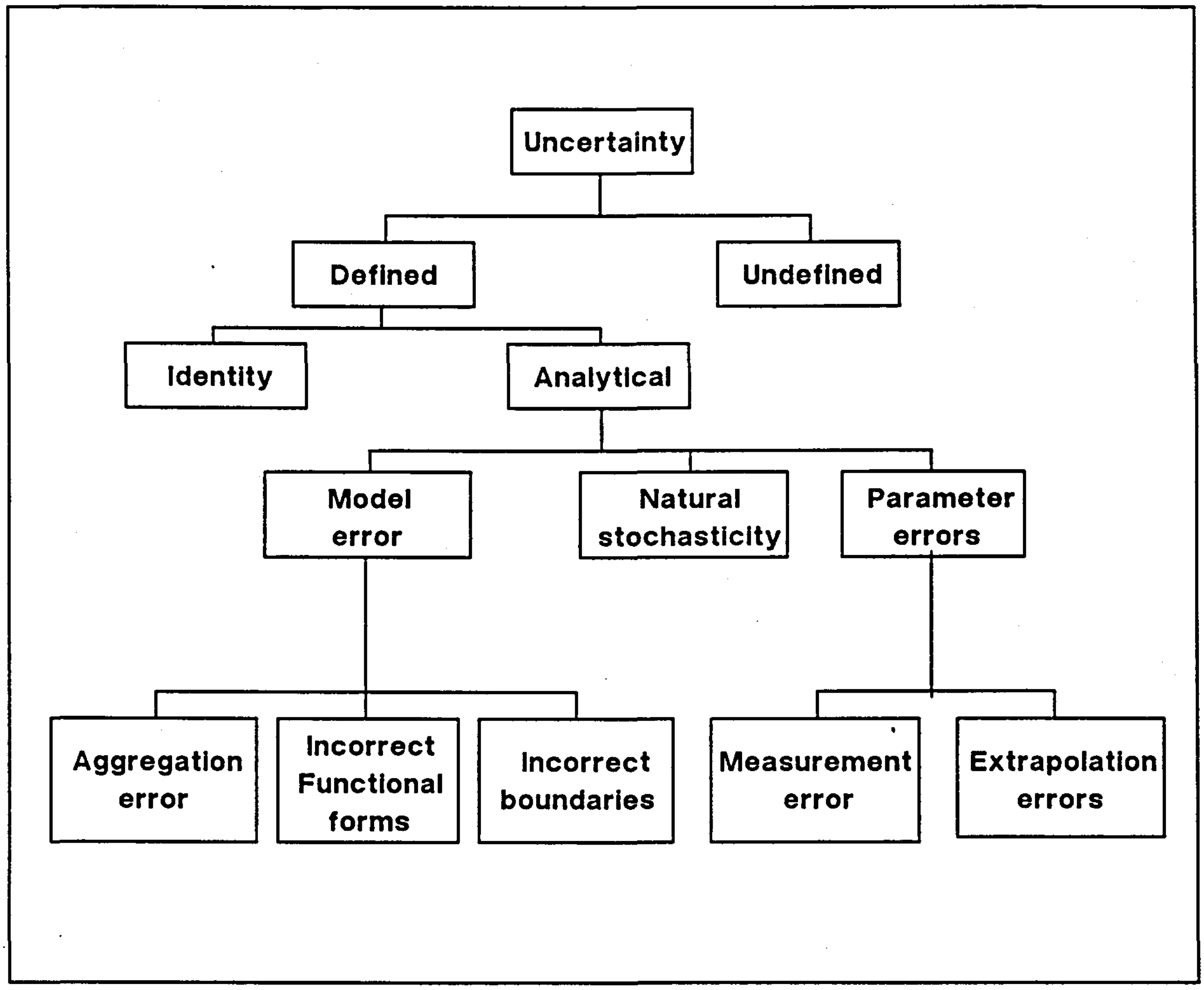


Figure 22 A taxonomy of uncertainty (Suter *et al.*, 1987).

## 10. RECOMMENDATIONS ON RESEARCH NEEDS

At present, the DSS only simulates the transport and fate of phosphates in catchment-river-reservoir systems. Phosphate was chosen as the nutrient of concern because it was found to be the nutrient which limits algal growth most frequently in freshwater systems and it is the only nutrient which can be controlled economically at waste water treatment plants.

The DSS has been applied to review present decisions about the implementation of the 1 mg P/ℓ standard by assessing the impacts of eutrophication control measures in sensitive catchments. In the course of these applications, four important limitations in the DSS were identified. In order to develop realistic eutrophication control strategies, these shortcomings must be addressed in future development work on management orientated models for eutrophication control.

### 10.1 Nitrogen limited systems

It was found that in some cases eutrophication related water quality in reservoirs were primarily regulated by factors other than phosphorus. In highly eutrophied reservoirs (Rietvlei Dam and to a certain extent Hartbeespoort Dam), it was found that nitrogen limited algal growth. An important question asked by water resource managers is "If P control measures were enforced on point sources in the catchment of a N-limited reservoir, what reductions in P concentrations are required for the reservoir to become P limited and therefore show a response to the eutrophication control measures?". In order to answer this question the export of N from catchment, its fate in water bodies and the biological response need to be simulated.

### 10.2 Light limited systems

It was found that in some cases eutrophication related water quality in reservoirs was regulated primarily by the availability of light for photosynthesis. The DSS could not adequately predict the impacts of control measures because it did not incorporate light or turbidity as a system variable.

In reservoirs where the growth of algae is limited by the availability of light as a result of high mineral turbidity, much higher nutrient concentrations can be tolerated than in clear water systems. However, the question which water resource managers ask is what would the impact be if the turbidity changes with time as a result of either increased salinity or the import of large quantities of low turbidity water through interbasin transfer schemes. In order to answer these questions, the simulation of turbidity needs to be incorporated in the DSS. This may require that attention be given to characterize the effects of salinity on turbidity.

The criteria for selecting appropriate models should be to select simple input-output models which describe the most important processes so that they can be used in a broad planning and management context. This aspect is of increasing importance to the Directorate of Water Pollution Control which is moving from an effluent based standard approach to a receiving water quality objectives approach in pollution control management. It will also be of value to the Directorate of Planning in assessing eutrophication related water quality problems in existing and future water resource development projects.

## 10.3 Spatial Variability in water quality

One of the limitations identified to the present REMDSS was that the REM model assumed waterbodies to be completely mixed. This assumption means that spatial variations in the water quality cannot be predicted and therefore limits the application of the DSS to cases where only information about the mean water quality in a waterbody is required. The reservoir eutrophication model also uses a monthly time step which means that it cannot be applied to highly dynamic systems such as barrages or weirs in rivers which are often used by Water Authorities for extracting their raw water supplies.

An important case where this limitation prevented the DSS from being used was for assessing the impact of eutrophication control measures on water quality in the Vaal Barrage and the middle Vaal River. These are two dynamic systems where severe eutrophication problems are already experienced. In both cases raw water is abstracted at positions other than the outlet of the water body (weir or barrage). Consequently it is important to know the spatial distribution in water quality because it is water quality at the treatment plant intakes rather than the mean water quality in the system that is of interest. The Department of Water Affairs needs modelling tools to develop eutrophication control strategies to address water quality problems in these systems. To accomplish this, methods should be investigated to adapt REMDSS to plug flow conditions so that it can adequately address both the highly dynamic state and the spatial variations in water quality of these waterbodies.

## 10.4 Sedimentation Release Processes

When the sedimentation parameter was calibrated on Hartbeespoort Dam (Section 4.4) it was found that neither sedimentation submodels could adequately describe P losses in the period following the filling of the reservoir. Methods should therefore be investigated to modify the sedimentation parameter to describe higher P losses after the sediment was exposed for a number of years, such as observed at Hartbeespoort Dam during the drought. This may require the incorporation of a factor into the parameter which takes the area of the sediment into account.

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## APPENDIX A

**Publications, conference papers and reports produced in the project.**

**Publications**

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ROSSOUW, J.N. (1988). *Evaluation of the impact of eutrophication control measures on water quality in: Rietvlei Dam*. Report to the Directorate of Water Pollution Control, Department of Water Affairs.

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GROBLER, D.C. (1988). *Assessment of implications of phosphorus control strategies on eutrophication related water quality in the middle Vaal River.* Report to the Directorate of Water Pollution Control, Department of Water Affairs.

# APPENDIX B

An example of the application of the DSS for eutrophication control to assess the impact of eutrophication control measures.

ROSSOUW, J.N. and GROBLER, D.C. (1988). Evaluation of the impact of eutrophication control measures on water quality in: Hartbeespoort Dam. Report to the Directorate of Water Pollution Control, Department of Water Affairs.

# EVALUATION OF THE IMPACT OF

# EUTROPHICATION CONTROL MEASURES ON

# WATER QUALITY IN :

# HARTBEESPOORT DAM

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Pretoria
August 1988

## Terms of Reference

This report was drawn up, at the request of Mr. W. van der Merwe, Director: Water Pollution Control Directorate of the Department of Water Affairs, to assess the impact of presently considered phosphorus control measures on water quality in Hartbeespoort Dam.

This report forms part of a contract between the Division of Water Technology and the Department of Water Affairs, whereby the Division assists the Department in assessing the impact of the special 1 mg/L phosphorus standard on eutrophication related water quality in sensitive catchments.

Specific instructions to the project team were:

1. Use the Decision Support System for eutrophication control to assess the impact of the special 1 mg/L phosphorus standard, or stricter standards, on reservoirs in the seven sensitive catchments.

2. Make recommendations about the implementation of the special 1 mg/L phosphorus standard. Where necessary, make recommendations about stricter standards and identify future research needs.

3. Use existing data available from the Directorates of Water Pollution Control, Hydrology, Planning and the Hydrological Research Institute. Take the most likely regional developments into account in the assessments.

4. Complete the investigations and recommendations before August 1988.

5. Ensure that all information relating to the terms and execution of the contract, as well as any correspondence generated in connection with the contract, are kept strictly confidential.

## CONTENTS

## 1. Executive summary

Eutrophication is the enrichment of water bodies with plant nutrients which lead to excessive growth of free floating algae and macrophytes. This in turn leads to eutrophication related problems such as increased water treatment costs, taste and odour problems, associated health risks and interference with recreation.

In 1980 an effluent phosphate (P) standard of 1.0 mg P/L was introduced in seven sensitive catchments to control eutrophication. Local authorities were given 5 years exemption when the standard was implemented in the Vaal Dam, Barrage, Roodeplaat Dam and Hartbeespoort Dam catchments only. This decision have to be reviewed by August 1988 on the basis of monitoring results as well as predictions of the impact of the standard on reservoirs with aid the Reservoir Eutrophication Model (REM).

This report is the assessment of the impact of eutrophication control measures on Hartbeespoort Dam.

Hartbeespoort Dam is:

1. Mainly a source of irrigation water to the Hartbeespoort Government water scheme.
2. A source of potable water for various urban and industrial users around and down stream of Hartbeespoort Dam.
3. An important recreation and nature conservation site.
4. Becoming an important source of water supply not only to the region north of Pretoria but, in the future, also to the north western Transvaal where water resources are already fully exploited .
5. Classified as hypertrophic which means that it is extremely enriched with plant nutrients, mainly N and P, which has led to a number of ecological, aesthetic, health and water treatment problems which are well documented.

The REM decision support system was used to predict the TP concentrations in Hartbeespoort Dam, for the 1990, 2000 and 2020 time horizons. Four point source control scenario's were evaluated for this investigation:

**Scenario 1** "Do nothing" scenario
Predict the impact if the concentrations in the point source effluents are maintained at present concentrations i.e. present conditions prevail. It was assumed that there were no P losses in the river.

**Scenario 2** 1 mg P/L standard scenario
Predict the impact of enforcing the existing 1.0 mg P/L effluent standard on all the point sources in the Hartbeespoort Dam catchment. It was assumed that there were no P losses in the river.

**Scenario 3** 0.1 mg P/L standard scenario
Predict the impact of enforcing a stricter standard of 0.1 mg P/L on all the point sources in the Hartbeespoort Dam catchment. It was assumed that there were no P losses in the river.

**Scenario 4** River P loss scenario
Test the sensitivity of predictions under scenario 2 (1.0 mg P/L standard

option) to P losses of 25% and 50% in the river.

The predicted TP and chlorophyll concentrations in Hartbeespoort Dam for the different control scenarios were:

**Scenario 1** **No P standard applied to point sources while point sources in Rietvlei Dam catchment comply to 1 mg P/L standard**

| | Time horizons 1990 | 2000 | 2020 |
|---|---|---|---|
| Nonpoint source TP load (Tons/a) | | | |
| Median load | 15.92 | 21.54 | 50.92 |
| Rietvlei Dam TP load (Tons/a) | | | |
| Median load | 6.67 | 15.31 | 51.90 |
| Point source TP loads (Tons/a) | | | |
| Total point load | 857.61 | 1388.10 | 3160.80 |
| Predicted TP concentration (μg/L) | | | |
| Average | 568 | 659 | 856 |
| Predicted Chlorophyll concentration (μg/L) | | | |
| Average | 67 | 76 | 93 |

**Scenario 2** **1 mg P/L standard applied to point sources and point sources in Rietvlei Dam catchment comply to 1 mg P/L standard**

| | Time horizons 1990 | 2000 | 2020 |
|---|---|---|---|
| Nonpoint source TP load (Tons/a) | | | |
| Median load | 15.92 | 21.54 | 50.92 |
| Rietvlei Dam TP load (Tons/a) | | | |
| Median | 6.67 | 15.31 | 51.90 |
| Point source TP loads | | | |
| Total point load | 140.96 | 227.50 | 518.00 |
| Predicted TP concentration (μg/L) | | | |
| Average | 297 | 334 | 418 |
| Predicted Chlorophyll concentration (μg/L) | | | |
| Average | 41 | 44 | 53 |

**Scenario 3** **0.1 mg P/L standard applied to point sources, point sources in Rietvlei Dam catchment comply to 0.1 mg P/L standard**

| | Time horizons 1990 | 2000 | 2020 |
|---|---|---|---|
| Nonpoint source TP load (Tons/a) | | | |
| Median load | 15.92 | 21.54 | 50.92 |
| Rietvlei Dam TP load (Tons/a) | | | |
| Median | 2.89 | 6.04 | 17.61 |
| Point source TP loads | | | |
| Total point load | 14.03 | 22.75 | 51.80 |
| Predicted TP concentration (µg/L) | | | |
| Average | 144 | 146 | 158 |
| Predicted Chlorophyll concentration (µg/L) | | | |
| Average | 23 | 23 | 25 |

**Scenario 4** **25% and 50% P losses in the river while point sources in Rietvlei Dam catchment comply to 1 mg P/L standard**

| Time horizons | 1990 | | 2000 | | 2020 | |
|---|---|---|---|---|---|---|
| Loss | 25% | 50% | 25% | 50% | 25% | 50% |
| Nonpoint source TP load (Tons/a) | | | | | | |
| Median load | 15.92 | 15.92 | 21.54 | 21.54 | 50.92 | 50.92 |
| Rietvlei Dam TP load (Tons/a) | | | | | | |
| Median | 5.00 | 3.34 | 11.49 | 7.66 | 38.92 | 25.95 |
| Point source TP loads | | | | | | |
| Total point load | 105.18 | 70.13 | 170.64 | 113.75 | 388.51 | 259.00 |
| Predicted TP concentration (µg/L) | | | | | | |
| Average | 263 | 226 | 296 | 250 | 365 | 301 |
| Predicted Chlorophyll concentration (µg/L) | | | | | | |
| Average | 37 | 33 | 40 | 35 | 48 | 41 |

**Conclusions and recommendations**

1. The 1 mg P/L effluent standard would reduce reservoir TP and chlorophyll concentrations by about 50% but that the predicted chlorophyll concentration would still result in nuisance conditions being experienced for 50% of the time. It is recommended, that as a starting point, the 1 mg P/L standard be enforced in the Hartbeespoort Dam catchment.
2. It is predicted that a stricter effluent standard of 0.1 mg P/L would result in chlorophyll concentrations which border on nuisance conditions. It is recommended that a stricter standard than the present 1 mg P/L standard be considered for implementation as soon as possible.
3. If P control measures are enforced in the catchment, Hartbeespoort Dam should move from a N limited reservoir (N:P ratio < 7:1) to a P limited reservoir (N:P ratio > 7:1).
4. River losses should be viewed as an ecological safety margin.

## 2. Introduction

Eutrophication is the enrichment of water bodies with plant nutrients which lead to excessive growth of free floating algae (phytoplankton) and floating and rooted macrophytes. This in turn leads to eutrophication related problems such as increased water treatment costs, taste and odour problems, associated health risks and interference with recreation.

Eutrophication is a problem in South Africa due to increased return flows to reservoirs, of nutrient rich treated sewage effluents. These sources of nutrients are commonly referred to as point sources, which can be controlled, in contrast to nonpoint sources (natural & agricultural sources) which are difficult to control. Authorities have adopted a policy that the polluter must pay i.e. treat the causes of eutrophication rather than the consequences.

An effluent standard of 1 mg P/L was promulgated on 1 August 1980 as the first step in long-term eutrophication control. The standard was introduced in seven sensitive catchments but local authorities were given five years grace to upgrade effluent treatment plants. In 1985, local authorities were forced to curtail capital expenditure due to a downturn in the economy and the Department was asked for a further extension of the implementation date. The Department decided to :

1. Implement the standard in the Vaal River catchment upstream of the Barrage as well as the Crocodile and Pienaars River catchments upstream of their confluence.
2. Grant exemption from the standard, for a further three years, to local authorities in the other five sensitive catchments and the Vaal River downstream of the Barrage.

These decisions have to be reviewed by August 1988 on the basis of monitoring results as well as predictions of the impact of the standard on the receiving water bodies in the sensitive catchments with the aid of the dynamic Reservoir Eutrophication Model (REM) (Best, 1987). A review of all the reservoirs in the sensitive catchments is being undertaken to assess the impact of eutrophication control measures on reservoir water quality. This investigation was initiated in September 1987 by the Department of Water Affairs and the participants are the Directorate of Water Pollution Control and the National Institute for Water Research. The impact assessment is being done with the aid of the reservoir eutrophication model (REM) with data currently available from various sources.

Hartbeespoort Dam is one of three major reservoirs of concern in the catchment which lies upstream of the confluence of the Crocodile and Pienaars Rivers (Figure 1), and serves three important purposes namely:

1. Its main purpose is a source of irrigation water to the Hartbeespoort Government Water Scheme.
2. It is a source of potable water for various urban and industrial users around and down stream of Hartbeespoort Dam.
3. It is an important recreation and nature conservation site.

Although Hartbeespoort Dam was built for irrigation purposes it is becoming an important source of water supply not only to the region north of

Pretoria but, in the future, also to the north western Transvaal where water resources are already fully exploited (Van Zyl and Blersch, 1987).

There is a direct relationship between increased treatment costs of potable water and increased levels of eutrophication (Viljoen and Haynes, 1985). Hartbeespoort Dam is a hypertrophic reservoir (extremely enriched with nutrients) and lowering the eutrophication levels as a result of P control measures in the catchment, may not only result in big savings in the treatment of potable water but also lead to a reduction in the harmful consequences of eutrophication such as the formation of trihalomethane precursors.

**The aim of the report**

This report is part of a series of reports, produced under contract to the Directorate of Water Pollution Control, on the evaluation of P control measures in the seven sensitive catchments. The aim is to report the assessment of the impact of eutrophication control measures on Hartbeespoort Dam. The report starts with a short introduction to the REM models and the Decision Support System (DSS) which forms the user friendly framework for these models. This is followed with a short description of the characteristics of Hartbeespoort Dam, its catchment and the present eutrophication status of the reservoir. A detailed description of the model inputs, and sources of information, used to simulate the impact of different eutrophication control scenario's is then given. The simulation scenario's and the assumptions for simulating the impact of the different control strategies are also discussed. Finally, the simulation results are discussed which are followed by conclusions and recommendations about the most suitable eutrophication control scenario's.

# 3. Decision Support System for eutrophication control

The aim of this chapter is to give the reader background information on the models which was used in this investigation. The reader may page directly to chapter 4, which is the description of the reservoir under investigation, if he is familiar with the models or if the background information is not important at this stage.

The eutrophication process consists of three components, namely:

1. the export of phosphorus (P) from the catchment of a reservoir,
2. the processes which determine the fate of phosphorus in the reservoir
3. the conversion of the ambient phosphorus concentration in the reservoir to some measure of the algal biomass such as chlorophyll.

The Reservoir Eutrophication Model (REM) (Grobler, 1985; Grobler, 1986) was developed to simulate each of the three components. This model was incorporated into a Decision Support System (DSS) which forms a user friendly framework for the different REM models. The models used to simulate the three components of the eutrophication process will be discussed separately in this chapter.

## Export of P from catchments

### Hydrology

The hydrological regime of the reservoir has a large effect on the phosphorus exported from the catchment and on the fate of phosphorus in the reservoirs. It is difficult to predict what the hydrology would be for a certain date in the future. However, it is possible to predict the future changes in the catchment which would influence the runoff, such as increased demands, increased urbanization etc. Using this knowledge we can simulate a representative range of hydrological conditions (time series of runoffs) which will contain both dry and wet cycles. Such a representative range of hydrological conditions can be used to predict a range of trophic responses of the reservoir to different phosphorus loads.

### P export from catchments

P can be derived from point sources (e.g. urban and industrial effluent) and nonpoint sources (e.g. virgin and agricultural runoff). The point source information, such as effluent volumes and P concentrations, form part of the DSS data base for each reservoir.

### P export from nonpoint sources

Nutrients derived from nonpoint sources are mainly transported by overland runoff associated with high flow. Consequently, the P load derived from nonpoint sources is highly variable and depends largely on hydrological conditions. Nonpoint source derived P loads are simulated as a function of runoff (Grobler and Silberbauer, 1985)

$$Pexp = a\ R^{b} \qquad \text{..........................(1)}$$

where Pexp is the mass of nonpoint source derived P exported from a catchment (kg km$^{-2}$ month$^{-1}$), R the runoff (mm month$^{-1}$) and a and b are export parameters.

The parameters a and b are calibrated for each catchment using observed runoff and load data collected in a subcatchment which is not significantly affected by point sources. The calibration process intrinsically takes into account the man made influences, such as export from agriculture (cultivated fields, grazed veldt etc.), and natural influences such as erosion processes. Because there is such a close relationship between runoff (both annual and monthly) and the amount of nonpoint source derived P exported, a representative range of nonpoint source loads can be simulated using a long (i.e. 55 years) historical time series of natural runoffs.

**P export from point sources**

The most important point sources of plant nutrients in South African catchments are effluents from domestic and industrial wastewater treatment plants. The volume of these effluents can be measured fairly accurately and future volumes can be estimated, in the case of domestic wastewater, as a function of population growth rates and, in the case of industrial or mining effluents, according to planned future activities.

For each point source the user must estimate the future effluent volumes and P concentration. Effluent volumes are assumed to be independent of hydrological conditions i.e. they do not vary as a function of the time of the year. The P load associated with a given point source is estimated as the effluent volume times the mean P concentration in the effluent. Through assuming different effluent volumes and mean P concentrations in effluents the user can generate scenarios reflecting different control strategies for point source derived P.

Not all the P released from point sources into rivers actually reaches downstream reservoirs. In some cases losses of as much as 50% of the original amount of P entering the river have been measured. The DSS makes provision for these losses by allowing the user to state, as input, the percentage P lost through river processes for each point source in the catchment. The worst possible case can be simulated by assuming no P losses in the river.

**P export from upstream reservoirs**

Upstream reservoirs from which water is released regularly to the reservoir of interest are treated as point sources. If such releases represent a major source of inflow to the reservoir it is advisable to apply the DSS to the upstream reservoir first so that a time series of P concentrations in the upstream reservoir can be generated. These P concentrations are then used in conjunction with the time series of reservoir outflows to calculate a time series of P loads released from the upstream reservoir. Otherwise a constant mean P concentration can be assumed which in conjunction with the time series of reservoir outflows can be used to calculate a time series of released P loads.

**Total amount of P exported**

The predicted P load from all the point sources is a fixed amount, e.g. 5 tons per month by the year 2000, whereas the P load derived from nonpoint sources and upstream reservoirs are simulated as a time series, i.e. 55 years of monthly loads. The total amount of P reaching the reservoir is then represented as a time series of P loads obtained by adding the loads derived from nonpoint sources, upstream reservoirs and point sources, i.e.

$$L_i = Lnp_i + Lur_i + Lp \qquad \text{................(2)}$$

where $L_i$ is the total P load for month i in the time series, $Lnp_i$ is the nonpoint source derived P load for month i, $Lur_i$ is the P load derived from upstream reservoirs for month i and Lp is the fixed monthly P load derived from point sources after river losses was accounted for. The magnitude of Lp is determined by the particular P control scenario being investigated.

## 3.2 The fate of P in the reservoir

The fate of P in the reservoir is simulated with a P budget model which states the conservation of mass of P in a reservoir (Grobler, 1985; Grobler, 1986) as the differential equation

$$dP/dt = W - (Q_{OUT}/V)P - s.P \qquad \text{....................(3)}$$

where P is the mass of P in the reservoir, t is time, W the phosphate loading rate, $Q_{OUT}$ the outflow rate, V the volume and s the phosphate sedimentation rate.

The sedimentation of P is assumed to be concentration dependent and be a third order reaction (Grobler, 1985)

$$s = k(P/V)^2 \qquad \text{....................(4)}$$

where s is the sedimentation rate, k is the sedimentation parameter and V the volume.

The P concentration in a reservoir depends on the volume of water stored and on the mass of P dissolved or suspended in the water Therefore, simulating P concentrations requires that both the volume of water stored and the mass of P in a reservoir are simulated simultaneously in the P budget model. The volume of water stored in a reservoir is simulated as

$$dV/dt = Q_{IN} + Pt - E - Sp - Q_{OUT} \qquad \text{............(5)}$$

where V is the volume of water, $Q_{IN}$ is the inflow, Pt is the precipitation, E is the evaporation, Sp is the spillage and $Q_{OUT}$ is the water released from the reservoir.

The time series of inflows and total P loads are used as input to the P budget model for simulating a representative time series of P concentrations in a reservoir reflecting a particular P control strategy.

## 3.3 The biological response to ambient P concentrations in reservoirs

The final step in applying REM is the interpretation of predicted reservoir P concentrations in terms of eutrophication related water quality. Water quality problems associated with eutrophication are usually caused by the occurrence of undesirable quantities and/or species of algae. The trophic response of reservoirs to changes in TP concentrations is therefor usually measured in terms of chlorophyll concentration which is an indication of algal biomass.

Walmsley (1984) has emphasized the importance of providing an indication of how much of the time one can expect nuisance conditions in an impoundment. He developed an aesthetic or use impairment classification system which was based upon chlorophyll:

| Chlorophyll (µg/L) | Rating |
|---|---|
| 0 - 10 | No problems encountered |
| 10 - 20 | Algal scums present |
| 20 - 30 | Nuisance conditions |
| > 30 | Severe nuisance conditions |

Walmsley (1984) provided an equation to predict the percentage time that chlorophyll concentrations will exceed 30 µg/L and result in severe nuisance conditions being experienced :

$$F = 1.19 \text{ (mean chlorophyll)} - 5.36 \quad \ldots\ldots\ldots\ldots\ldots\ldots(6)$$

where F is the frequency of occurrence of severe nuisance conditions, expressed as a percentage of the year. It is recommended that nuisance conditions for 20% of the time should be used as the threshold between acceptable and unacceptable water quality. This translates (Equation 6) to a mean chlorophyll concentration of 21 µg/L which would translate (Equation 7) to a mean TP concentration of 130 µg/L in a clear water reservoir.

In REMDSS, two chlorophyll:P relationships are used, one for clear water reservoirs and one for turbid reservoirs.

**Clear water reservoirs**

For the purpose of this investigation, a clear water reservoir was defined as one where the extinction of light in the water column is not influenced by inorganic suspended sediments. The OECD chlorophyll:P relationship (Jones and Lee, 1982; Grobler and Silberbauer, 1984) is used to relate mean seasonal chlorophyll concentration (µg/L) to the mean seasonal TP concentration (µg/L) in clear water reservoirs :

$$\text{Chl} = 0.45[\text{TP}]^{0.79} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

where Chl is the chlorophyll concentration (µg/L) and the TP concentration in µg/L. Grobler and Silberbauer (1984) have confirmed that South African reservoirs respond in the same way as most other water bodies with respect to the OECD chlorophyll:P relationship.

**Turbid reservoirs**

For the purpose of this investigation, a turbid reservoir was defined as one where the extinction of light is largely influenced by the presence of inorganic suspended sediments. For turbid reservoirs, the model formulated by Hoyer and Jones (1983) is used to relate chlorophyll to TP concentrations. This model uses the inorganic suspended sediment concentration (ISS) as a measure of turbidity in the reservoir :

$$\log Chl = 1.13 \log TP - 1.03\ (ISS/TP) - 0.47 \ldots\ldots\ldots\ldots (8)$$

where Chl is the chlorophyll concentration (µg/L), TP is the Total P concentration (µg/L) and ISS is the suspended sediment concentration (mg/L).

Suspended sediment concentrations are not generally available for South African reservoirs but turbidity measurements, and in most cases, Secchi disk depths, which are commonly used measures of water transparency, are available for most reservoirs. The user is given the option of choosing between four classes of reservoirs which range from very turbid to less turbid. Each class is characterized by Secchi disk depth, turbidity and suspended sediment concentration (Table 1).

Table 1. Classification used to differentiate reservoirs into turbidity classes

| Turbidity class | Secchi Depth (m) | Turbidity (NTU) | Suspended sediment (mg/L) |
|---|---|---|---|
| Highly turbid | 0.0 - 0.1 | 260 | 419 |
| | 0.1 - 0.2 | 87 | 142 |
| Turbid | 0.2 - 0.4 | 44 | 72 |
| Less turbid | 0.4 - 1.0 | 19 | 32 |
| Clear Water | > 1.0 | <10 | <10 |

Based on knowledge of the reservoir, and data available on the reservoir, the user must classify the reservoir being investigated into one of the turbidity classes which will then automatically lead to the selection of the most appropriate chlorophyll:P model.

### 3.4 The Decision Support System for the REM models

The models described in the previous sections were incorporated into a user friendly Decision Support System (DSS). A DSS is defined as an interactive computer based system that helps decision makers utilize data and models to solve problems. A DSS consist of three components i.e. a model base, a data base and a computer program which link these two components and provide the interface with the user.

The model base contains the different REM submodels which was described in the previous sections. The data base contains the hydrological, point source, catchment and reservoir characteristics data of the reservoir under investigation. The DSS that was developed for REM is a program which helps the user prepare the input data to the models, then runs the models and display the simulation results in different formats. It is responsible for storing and retrieving data, organizing interim results and displaying results in a graphical from. The interface with the user is in a form of a dialog system which relies on menus which the user must complete, do error checking and correction and provide help facilities to new users.

The program runs on a IBM compatible personal computer under the MS-DOS operating system. All results are displayed on screen and the user has the option of displaying results on a printer or plotter. The program was developed with TURBO PASCAL (Borland International) and various third party supporting software.

## 4. Description of Hartbeespoort Dam and its catchment

### Introduction and hydrology

Hartbeespoort dam, which lies 37 km west of Pretoria on the Crocodile River, was completed in 1925. It was constructed to supply irrigation water to the Hartbeespoort Government Water Scheme near Brits. Although irrigation water supply is still the most important purpose of the reservoir, other aspects, such as potable water supply, industrial and mining water supply, substantial recreation use, waterfront township development and flood control, are increasing in importance. In 1971 the wall was fitted with radial crest gates which increased the capacity of the reservoir from 168 x $10^6$ $m^3$ to 195 x $10^6$ $m^3$.

The main inflowing rivers are the Crocodile River and its tributaries, which supply over 90% of the inflow into the reservoir, and the Magalies River (Figure 1). The upper reaches of the Crocodile River drains parts of Krugersdorp, Randfontein and Roodepoort while the Jukskei tributary drains the Johannesburg Northern suburbs and the Hennops tributary drains Kempton Park, Tembisa, Midrand and Verwoerdburg.

The main physical and hydrological characteristics of the reservoir are listed in Table 2.

Table 2. Main physical and hydrological characteristics of Hartbeespoort Dam.

| | |
|---|---|
| Geographical location | 25° 43' S; 27° 51' E |
| Catchment type | Urban & Industrial, Rural |
| Usage of reservoir | Irrigation, potable water & recreation |
| Catchment area (total) | 4112 $km^2$ |
| Catchment area (without Rietvlei) | 3633 $km^2$ |
| Main inflowing river | Crocodile River |
| Dam wall completed | 1925 (Modified 1971) |
| FSL volume | 194.63 x $10^6$ $m^3$ (post 1971) |
| FSL area | 2034 HA |
| FSL max depth | 32.5 m |
| FSL mean depth | 9.6 m |
| Mean annual runoff (natural) | 163 x $10^6$ $m^3$ (* 147 x $10^6$ $m^3$) |
| Mean annual precipitation | 703 mm |
| Mean annual evaporation (S pan) | 1684 mm |

* MAR from catchment without Rietvlei Dam
Source: Department of Water Affairs, 1986

The landuse in the Hartbeespoort Dam catchment (excluding the Rietvlei Dam catchment), can be divided into rural and urban landuse. About 12.5% of the catchment is classed as urban, the bulk being within the Crocodile River catchment. The remaining 87.5% is rural of which only 1.5% is under irrigation. The rest is principally used for grazing or natural reservoirs.

Van Zyl and Blersch (1987) list the local water demands from Hartbeespoort Dam (Table 3). However, in the future, Hartbeespoort Dam may supply water to areas as far as Thabazimbi and Ellisras in the north west, Zeerust and

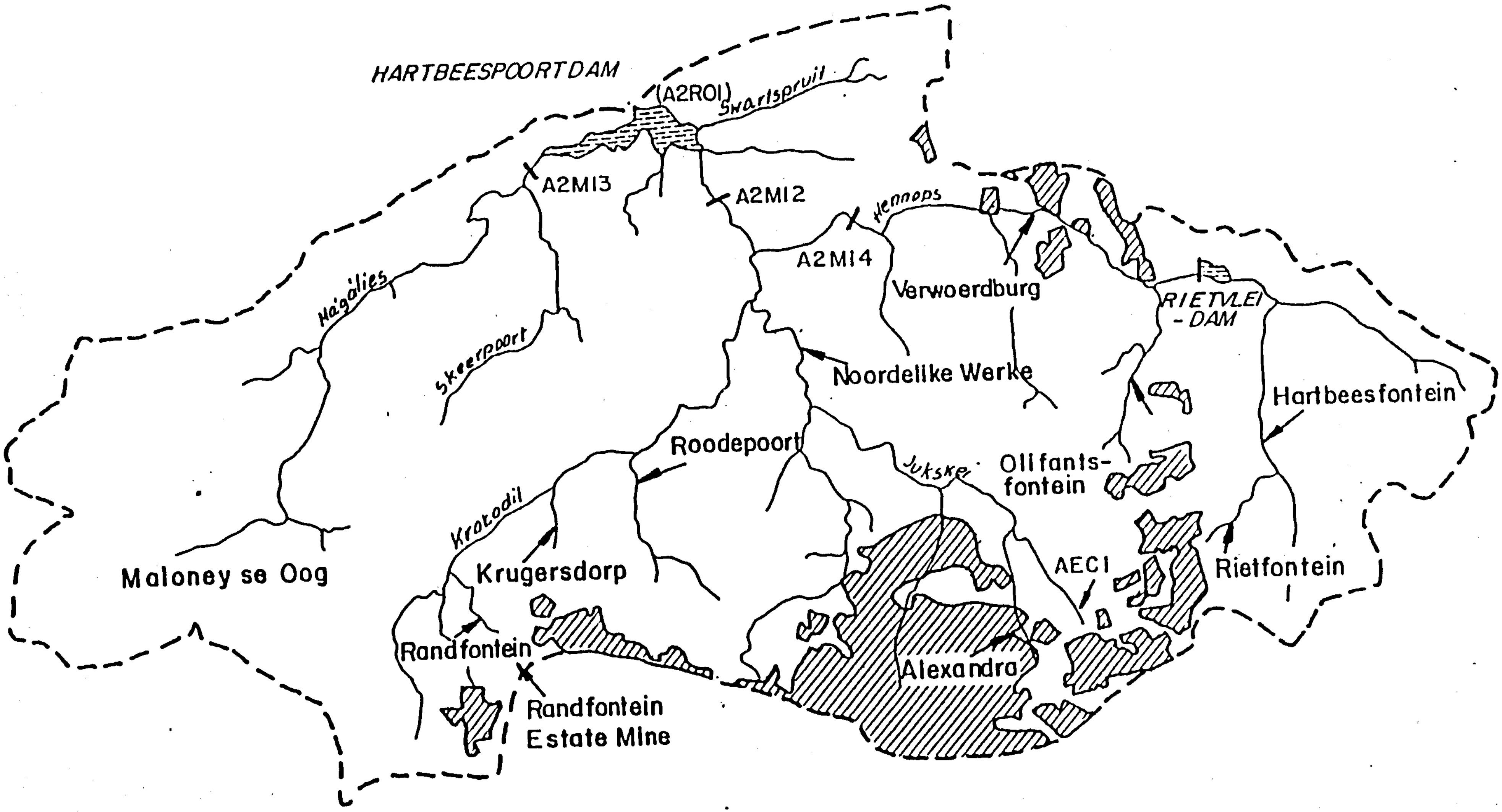


Figure 1 Map of the Hartbeespoort Dam catchment showing the location of the main inflowing rivers as well as the point sources in the catchment.

Mmabatho and Pietersburg in the north (Van Zyl and Blersch, 1987).

Table 3. Summary of average annual local water demands (existing and projected) from Hartbeespoort Dam (x $10^6$ $m^3$) (Van Zyl and Blersch, 1987)

| Description | Year 1985 | 1990 | 2000 | 2020 |
|---|---|---|---|---|
| **Irrigation** | | | | |
| RSA | 120 | 120 | 120 | 120 |
| Bophuthatswana** | 0 | 0 | 1.6 | 1.6 |
| Sub total | 120 | 120 | 121.6 | 121.6 |
| **Urban and Industrial** | | | | |
| Vaalkop | 1 | 10.8 | 22.6 | 45.2 |
| Brits municipality | 4 | 5.4 | 8.4 | 14.3 |
| Sonop & Losloperfontein | 0.4 | 0.4 | 0.6 | 0.6 |
| Lethlabile | 0.5 | 2.4 | 3.8 | 6.1 |
| Bophuthatswana (existing) | 0.6 | 0.7 | 0.9 | 1.0 |
| Bophuthatswana (expected)** | 1 | 1.4 | 1.9 | 2.8 |
| Hartbeespoort & Cosmos | 1.1 | 1.4 | 2.3 | 4.2 |
| Losses | 0.4 | 1.1 | 2.0 | 3.7 |
| Sub total | 9 | 23.6 | 42.5 | 77.9 |
| **Total demand** | | | | |
| Present consumers only | 127.2 | 142.2 | 160.5 | 195.0 |
| Expected consumers included | 129.0 | 143.6 | 164.1 | 199.5 |

** Expected consumers

Due to the rapid increase in urbanization and the associated increase in runoff and return flows, inflows into Hartbeespoort Dam has increased steadily. This resulted in an increase in the firm yield of the reservoir (Van Zyl and Blersch, 1987).

**Effects of eutrophication on Hartbeespoort Dam**

Hartbeespoort Dam is classified as hypertrophic, which is a water body that is extremely enriched with plant nutrients, mainly N and P (NIWR, 1985). This has led to a number of ecological problems (Jarvis, 1987) such as:

1. An anaerobic hypolimnion develops in the summer due to very high chemical and biological oxygen demand which is the consequence of extensive decomposition processes. This condition generally develops in September and can persist until turnover in late March/April. Under these anaerobic conditions, P release from the sediments increase five fold.

   During mid summer the top of the anaerobic zone is located between 10m to 15m below the surface. This restricts the distribution of zooplankton communities and increases grazing pressure on these communities. The shallow warm epilimnion also favors undesirable angling fish species such as barbels.

2. Several factors, such as high nutrient concentrations in Hartbeespoort Dam, favor the growth of the blue green alga, Microcystis, which form large buoyant colonies which at under certain conditions have developed into dense hyperscums at sheltered sites. These scums have led to public complaints about impaired recreation, foul smelling gases and adverse aesthetic considerations.

3. Although the fish biomass and yield are high, species diversity and abundance of desirable angling fish are very low. Populations of fish such as bass have declined as a result of high pH and fluctuating dissolved oxygen concentrations.

4. The hypertrophic conditions have promoted the development of macrophytes such as water hyacinth which had to be eradicated at great cost.

The following problems which have been associated with the hypertrophic state of Hartbeespoort Dam are described in greater detail in Thornton and Walmsley (1987) and in an excellent overview by Blersch et al (1987):

1. Potable water treatment - increased treatment costs, formation of THM precursors, taste and odour problem.
2. Health aspects - health risks associated with indirect reuse of treated sewage effluents, toxic algae, blackflies.
3. Recreation - impairment of water sports, poor quality shoreline.

**Present trophic status of Hartbeespoort Dam**

Hartbeespoort Dam is classified as a hypertrophic system which means that it is extremely enriched with nutrients. The present nutrient status of Hartbeespoort Dam is covered to serve as a reference when evaluating the predicted impact of P control measures in the catchment. The nutrient data were collected as part of an intensive study on Hartbeespoort Dam since 1980 by the NIWR (NIWR, 1985).

The median whole lake TP concentrations have been affected by the recent drought in the area (Table 4). The present (1986) median TP concentrations seem to be at the same level ( ≈ 470 µg/L) as before the drought (1980/81). During the drought, median TP concentrations increased to 770 µg/L (1984) as a result of low water levels and sewage effluents making up the bulk of the inflow into Hartbeespoort Dam. Since then the median TP concentration dropped as a result of dilution with rainfall runoff (Figure 2). During the study period 1980 to 1986 (Figure 2), Hartbeespoort Dam went through a wet and dry (1982-85) hydrological cycle which also had an influence on the reservoir TP concentrations.

The median whole lake TN concentrations were about 2000 µg/L and have not been affected as much by the drought as has been observed with the TP concentrations (Figure 3). This was probably due to N being lost to the atmosphere through denitrification processes. No data were available for 1986.

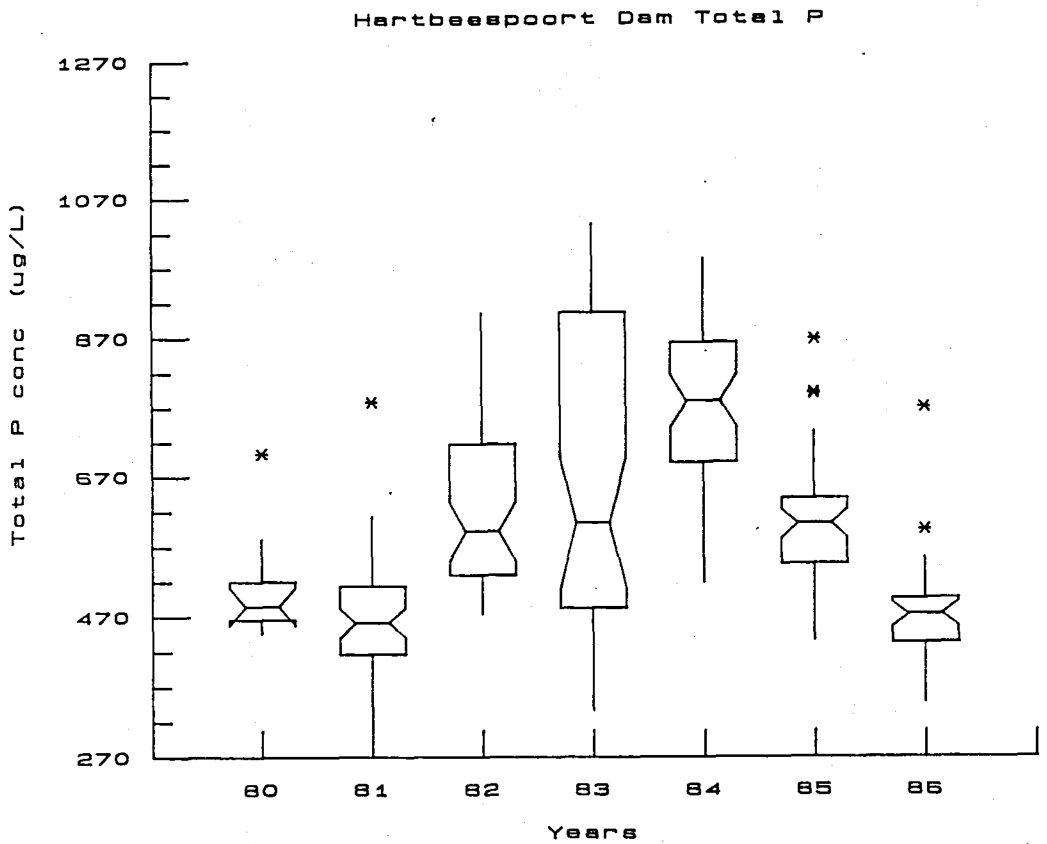


Figure 2 Boxplot of TP concentrations (μg/L) observed in Hartbeespoort Dam during 1980 to 1986. Extreme points beyond 1.5 times the interquartile range (box length) are plotted as individual points.

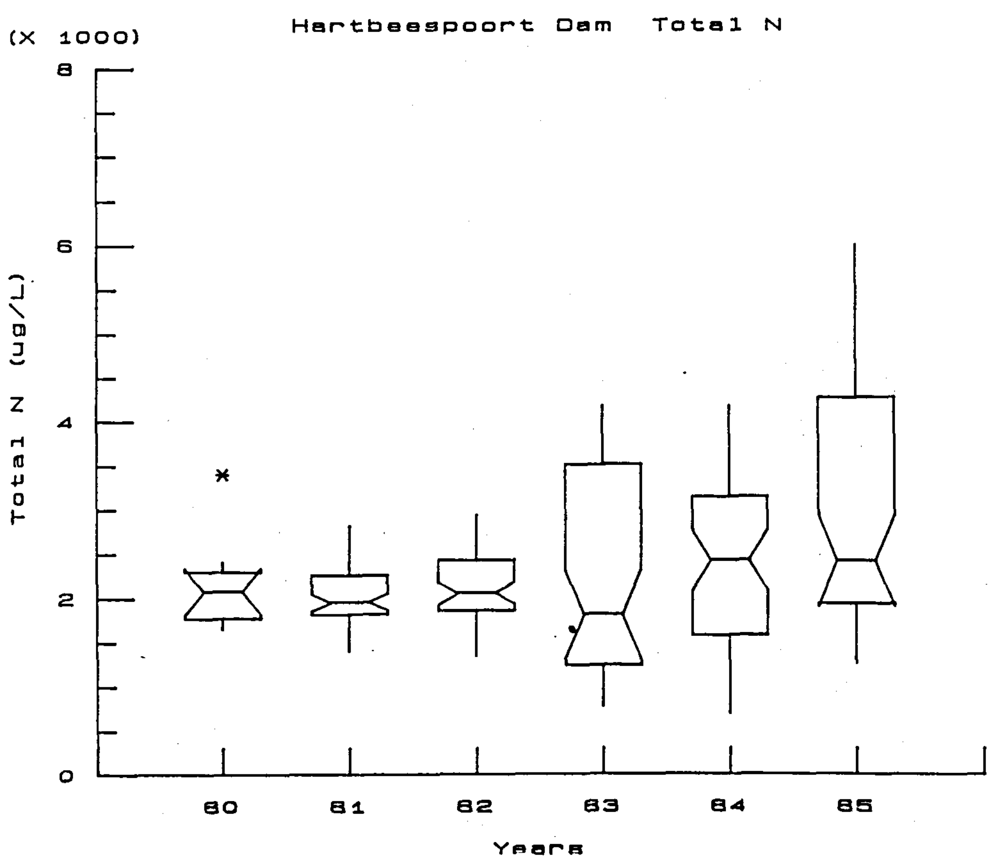


Figure 3 Boxplot of TN concentrations (μg/L) observed in Hartbeespoort Dam during 1980 to 1985. Extreme points beyond 1.5 times the interquartile range (box length) are plotted as individual points.

Table 4. Median chemical and biological characterize of Hartbeespoort Dam. Concentrations in µg/L

| | 1980 | 1981 | 1982 | 1983 | 1984 | 1985 | 1986 |
|---|---|---|---|---|---|---|---|
| Median TP conc | 485 | 462 | 592 | 605 | 780 | 604 | 473 |
| Median SRP conc | 381 | 346 | 455 | 431 | 570 | 444 | 329 |
| Median TN | 2077 | 1955 | 2053 | 1812 | 2422 | 2415 | - |
| Median Diss-N | 1974 | 1877 | 1939 | 1661 | 2278 | 2292 | - |
| Median Chlorophyll a | - | - | 119 | 158 | 165 | 110 | 111 |
| Secchi depth (m) | | | | | | | |
| N:P ratio | 4.2 | 4.5 | 3.4 | 3.2 | 3.2 | 5.1 | - |

TP = Total phosphate SRP = Soluble reactive phosphate (dissolved P)
TN = Total nitrogen Diss-N = Dissolved nitrogen

Hartbeespoort Dam is characterized by dense algal populations due to warm water, high insulation and high nutrient concentrations (NIWR, 1985). The reservoir is dominated by a single blue-green alga, Microcystis aeroginosa. This species has a buoyancy mechanism that allows it to float to the surface and form algal mats (scums) during calm periods. The mean chlorophyll concentration in Hartbeespoort Dam in 1986, integrated over the light penetration zone, was 135 µg/L which is high compared to other reservoirs in the region (Roodeplaat Dam = 18 µg/L; Rietvlei Dam = 28 µg/L (Van Ginkel and Theron, 1987)). Due to the buoyant nature of the algae, surface chlorophyll concentrations higher than 1000 µg/L have often been observed. During prolonged calm periods, Microcystis colonies have accumulated in wind protected bays forming a foul smelling mass of decomposing algae which may be up to a meter thick and exceed a hectare in area (NIWR, 1985).

**Nutrient limitation**

The N:P ratio of the water environment is often used to indicate which nutrient potentially limits algal growth in a water body. A N:P ratio of 7:1 normally occurs in the environment. A N:P ratio higher than 7:1 indicates potential P limitation and a ratio lower than 7:1 indicate potential N limitation. The N:P ratio in Hartbeespoort Dam was in the order of 4:1 (Table 4) which would indicate N limitation. However, if the amount of P reaching the reservoir is restricted through the introduction of effluent P standards, the N:P ratio will increase to levels where P is the limiting nutrient. This is because the process by which P is removed from the effluent does not remove significant amounts of N. The effluent N concentrations can be expected to remain the same, or grow in parralel with the effluent volume, while the P concentrations in the effluents are reduced.

## 5. Input data preparation for simulating Hartbeespoort Dam

### 5.1 Point sources

There are nine sewage treatment plants in the Hartbeespoort Dam catchment. (Figure 1). Future effluent discharges from these sewage treatment plants

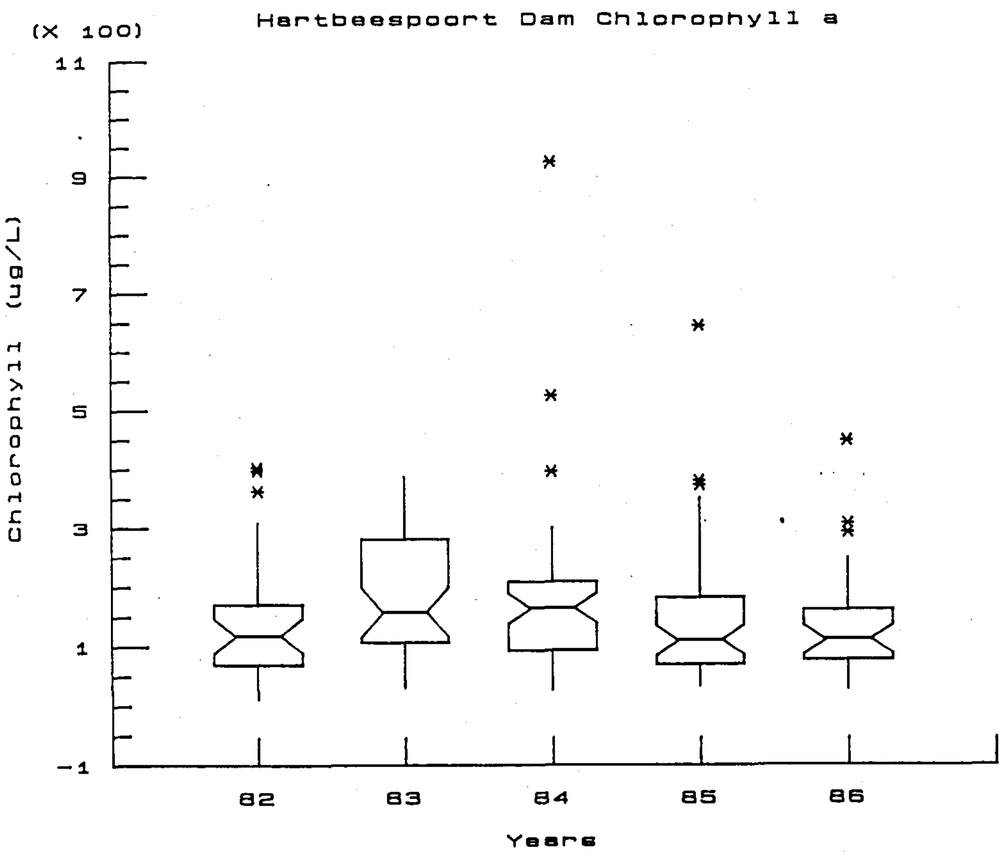


Figure 4 Boxplot of chlorophyll concentrations (µg/L) observed in Hartbeespoort Dam during 1980 to 1986. Extreme points beyond 1.5 times the interquartile range (box length) are plotted as individual points.

are expected to grow in parallel with the projected water demand in the entire RWB area of supply. The 1980/81 hydrological year was taken to be representative for projection purposes because the MAR for more recent years were below the long-term mean (Stewart, Sviridov and Oliver, 1986). It was assumed that there will be a growth rate of 5% per annum for the time horizons 1990 to 2005 which will then drop to 4% per annum for 2010 and 2020 (Table 5).

Table 5. Projected effluent volumes for sewage treatment plants in the Hartbeespoort Dam catchment (volumes in $10^6$ $m^3$).

| Sewage works | Time horizons 1980 | 1990 | 1995 | 2000 | 2005 | 2010 | 2020 |
|---|---|---|---|---|---|---|---|
| Tembisa | 4.29 | 7.10 | 9.12 | 11.50 | 14.05 | 17.70 | 26.10 |
| Verwoerdburg | 4.24 | 7.00 | 8.99 | 11.30 | 13.80 | 17.40 | 25.80 |
| Alexandra | 9.57 | 15.90 | 20.42 | 25.60 | 31.27 | 39.40 | 58.30 |
| AECI | 12.83 | 21.30 | 27.35 | 34.30 | 41.89 | 52.80 | 78.20 |
| JHB Northern Works | 39.19 | 65.10 | 83.59 | 104.90 | 128.13 | 161.30 | 238.90 |
| Roodepoort | 1.77 | 2.90 | 3.72 | 4.70 | 5.74 | 7.30 | 10.80 |
| Krugersdorp | 7.32 | 12.20 | 15.67 | 19.60 | 23.94 | 30.10 | 44.60 |
| Randfontein | 4.89 | 8.10 | 10.40 | 13.10 | 16.00 | 20.10 | 29.80 |
| Midrand | 0.00 | 0.66 | 2.00 | 2.50 | 3.00 | 4.50 | 5.50 |
| Total effluent vol | 84.10 | 140.26 | 181.26 | 227.50 | 277.82 | 350.60 | 518.00 |

The type of sewage treatment plant and the background TP concentrations in the effluents was:

| **Plant** | **TP concentration** | **Type** |
|---|---|---|
| Tembisa | 10.0 mg/L | BF |
| Verwoerdburg | 10.0 mg/L | BF, AS |
| Alexandra | 6.0 mg/L | AS |
| AECI | 1.0 mg/L | |
| JHB Northern Works | 6.0 mg/L | BF, AS |
| Roodepoort | 10.0 mg/L | AS(NR) |
| Krugersdorp | 8.0 mg/L | BF |
| Randfontein | 10.0 mg/L | AS |
| Midrand | 3.2 mg/L | |

where BF is a biological filter plant, AS is a activated sludge plant and (NR) is where nutrient removal is practiced.

## 5.2 Hydrology

### Natural Runoff

A time series of naturalized runoffs from the Hartbeespoort Dam catchment, excluding the Rietvlei Dam catchment, was simulated by Dr. Pitman of SS&O (Pitman, 1986). The natural runoff for the different time horizons (1990 to 2020) was adjusted for the projected changes in landuse in the Hartbeespoort Dam catchment (Table 5).

Table 5. Projected changes in the Hartbeespoort Dam catchment (excluding the Rietvlei catchment) which will change the future runoff

| Year | 1984 | 1990 | 1995 | 2000 | 2005 | 2010 | 2020 |
|---|---|---|---|---|---|---|---|
| Natural MAR ($10^6$ $m^3/a$) | 147 | 147 | 147 | 147 | 147 | 147 | 147 |
| Irrigation area (HA) | 53.0 | 54.8 | 56.7 | 58.5 | 60.3 | 62.1 | 65.8 |
| Irrigation ($10^6$ $m^3/a$) | 37.5 | 38.4 | 39.3 | 40.2 | 41.1 | 42.0 | 43.9 |
| Urban area (HA) | 456 | 621 | 787 | 995 | 1284 | 1657 | 2748 |
| Urban runoff ($10^6$ $m^3/a$) | 30.7 | 41.8 | 53.0 | 67.0 | 86.5 | 111.6 | 185.1 |
| Total runoff ($10^6$ $m^3/a$) | 142.2 | 150.4 | 160.7 | 173.8 | 192.4 | 216.6 | 288.2 |

## Reservoir characteristics

### Physical dimensions

To simulate a water balance for Hartbeespoort Dam, the following parameters were used to describe the physical dimensions of the reservoir:

| | |
|---|---|
| Full supply volume | $192.7 \times 10^6$ $m^3$ |
| Dead storage volume | $9.3 \times 10^6$ $m^3$ |

(Source: Department of Water Affairs, Reservoir records DW320)

The two parameters which were used to calculate the evaporation area from the volume were

$$\text{Area} = A * (\text{Volume})^B \qquad \text{where } A = 1.080 \text{ and } B = 0.53$$

(Source: Middleton <u>et al</u>, 1981)

### Abstractions

Van Zyl and Blersch (1987) (Table 3) gives a breakdown of the compensation releases from Hartbeespoort Dam to the different downstream urban, industrial and irrigation users. However, the total projected water demand from Hartbeespoort Dam is less than the yield of the reservoir. The Department felt that the difference between the yield and the projected demand will be used so that the reservoir will be operated at maximum yield. The compensation demands was therefor increased to represent the difference between the total yield and the irrigation demands. It was assumed that there is no seasonal pattern in the compensation extractions.

The projected irrigation water demands (Table 7) of the Hartbeespoort Government Water Scheme is expected to remain constant at $120 \times 10^6$ $m^3$ and the projected irrigation demands of Bophuthatswana from 1995 onwards is expected to remain constant at $1.6 \times 10^6$ $m^3$ (Van Zyl and Blersch, 1987). The seasonal pattern of irrigation extractions (Table 6) were supplied by the Directorate of Planning, Department of Water Affairs.

Table 6. Monthly compensation and irrigation release pattern from Hartbeespoort Dam expressed as a percentage of the annual demand.

| Seasonal Release Pattern as % of demand | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | Oct | Nov | Dec | Jan | Feb | Mch | Apr | May | Jun | Jul | Aug | Sep |
| Compensation | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 | 8.3 |
| Irrigation | 11.7 | 6.7 | 6.3 | 6.1 | 6.2 | 5.3 | 3.7 | 5.6 | 11.9 | 8.4 | 12.8 | 15.3 |

Table 7. Projected mean monthly compensation and irrigation releases from Hartbeespoort Dam ($10^6$ $m^3$) (Van Zyl and Blersch, 1987).

| Year | Probable maximum yield | Compensation Demands | Irrigation Demands |
|---|---|---|---|
| 1990 | 224 | 104.0 | 120.0 |
| 1995 | 273 | 151.4 | 121.6 |
| 2000 | 336 | 214.4 | 121.6 |
| 2005 | 409 | 287.4 | 121.6 |
| 2010 | 493 | 371.4 | 121.6 |
| 2020 | 730 | 608.4 | 121.6 |

**Rainfall and Evaporation**

To calculate the water balance, the average rainfall, symonspan evaporation and pan factor data for 1925/26 to 1979/80 (Table 8) was used (Department of Water Affairs, 1985).

Table 8. Rainfall (mm), Evaporation (mm) and pan factors used to simulate a water balance for Hartbeespoort Dam.

| Month | Oct | Nov | Dec | Jan | Feb | Mch | Apr | May | Jun | Jul | Aug | Sep |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Rainfall | 59 | 113 | 112 | 130 | 99 | 85 | 48 | 21 | 8 | 7 | 6 | 15 |
| Evaporation | 194 | 193 | 200 | 189 | 155 | 143 | 107 | 85 | 67 | 78 | 114 | 158 |
| Pan factor | .8 | .8 | .7 | .6 | .6 | .8 | .8 | .9 | .8 | .8 | .8 | .7 |

**Operating rule**

The operating rule for Hartbeespoort Dam (Directorate of Planning, per. com.) is based on an allocation of water which is revised on a yearly basis and depends largely on the amount of water in the reservoir in September each year. However, in the model the allocation of water is revised on a monthly basis. The operating rule was translated to:

| Reservoir level (% of FSL) | Compensation restriction | Irrigation restriction |
|---|---|---|
| | (% of mean use allowed) | |
| 100 | 100 | 100 |
| 60 | 100 | 70 |
| 40 | 60 | 50 |
| 20 | 30 | 10 |

### 5.3 Upstream reservoirs - Rietvlei Dam

Rietvlei Dam is upstream of Hartbeespoort Dam on the Hennops River tributary. For the purpose of this investigation Rietvlei Dam was treated as an upstream reservoir with a variable outflow and P load. The water levels and TP concentrations of Rietvlei dam was simulated (Rossouw, 1987) and the outflow volumes and TP concentrations were used to calculate the P load from Rietvlei Dam. For these simulations it was assumed that all the point sources in the Rietvlei Dam catchment comply to the 1 mg P/L standard. The median monthly Rietvlei Dam outflow volumes and loads which were used for simulating Hartbeespoort Dam, was :

| Time horizon | Volume ($10^6$ $m^3$) | P Load (Tons/m) |
|---|---|---|
| 1990 | 1.28 | 0.914 |
| 2000 | 2.62 | 1.277 |
| 2020 | 7.30 | 4.325 |

### 5.4 Nonpoint sources

The export parameter values used in equation 1 to calculate the monthly nonpoint source TP export (kg/km²/month) as a function of total runoff (mm/month), was :

$$\text{TP export} = A * \text{Runoff}^{B}$$

where

Parameter A = 0.163
Parameter B = 1.288

These parameters were calibrated on load and flow data for 1979 to 1986 collected in the Magalies River catchment (A2M13) which forms part of the Hartbeespoort Dam catchment (Grobler and Rossouw, 1988). There is no significant point sources in the Magalies catchment. The monthly TP export per $km^2$ was multiplied by the catchment area of 3633 $km^2$ to calculate the total monthly nonpoint source TP load from the whole catchment.

The median loads and flows for the different time horizons were:

| Time horizon | Median Flow ($10^6$ $m^3$/annum) | Median TP load (tons/annum) |
|---|---|---|
| 1990 | 81.60 | 15.92 |
| 2000 | 103.08 | 21.54 |
| 2020 | 200.88 | 50.92 |

### 5.5 Sedimentation

To simulate the monthly sedimentation losses of TP in Hartbeespoort Dam, a concentration dependent sedimentation rate of $2.0 \times 10^{-6}$ $month^{-1}/(mg\ m^{-3})^{2}$ was used in equation 4. There was sufficient observed data available on Hartbeespoort Dam to calibrate this parameter (Grobler, 1985).

### 5.6 Chlorophyll : P relationship

Hartbeespoort Dam can be classified as a clear water reservoir because the extinction of light in the water is mainly due to suspended algae and not suspended sediment (NIWR, 1985). The mean secchi depth was and the OECD chlorophyll:P relationship (Equation 7) was used to relate the mean seasonal TP concentrations in Hartbeespoort Dam to mean seasonal chlorophyll a concentration.

## 6. Simulation of the impact of different P control measures on Hartbeespoort Dam

### 6.1 Description of the phosphate control scenario's

**Scenario 1** "Do nothing" scenario

This is the "do nothing" option i.e. effluent volumes are expected to increase in the future but the P concentrations in the effluents will remain the same as it is at present (see section 5.1). It was assumed that there were no P losses in the river between the point sources and Hartbeespoort Dam and that a 1.0 mg P/L standard is enforced in the Rietvlei Dam catchment.
(Time horizons = 1990, 2000, 2020)

**Scenario 2** 1 mg P/L standard scenario

In this scenario the impact of enforcing the existing 1.0 mg P/L effluent standard on all the point sources in the Hartbeespoort Dam catchment was evaluated. It was assumed that there were no P losses in the river between the point sources and Hartbeespoort Dam and that a 1.0 mg P/L standard is enforced in the Rietvlei Dam catchment.
(Time horizons = 1990, 2000, 2020)

**Scenario 3** 0.1 mg P/L standard scenario

In this scenario the impact of enforcing a stricter standard of 0.1 mg P/L on all the point sources in the Hartbeespoort Dam catchment was evaluated. It was assumed that there were no P losses in the river between the point sources and Hartbeespoort Dam and that a 0.1 mg P/L standard is enforced in the Rietvlei Dam catchment.
(Time horizons = 1990, 2000, 2020)

**Scenario 4** River P loss scenario

In this scenario the sensitivity of predictions under scenario 2 (1.0 mg P/L standard option) to P losses of 25% and 50% in the river, between the point of discharge and the reservoir, were evaluated. It was assumed that the TP loads from Rietvlei Dam were also subject to the same river processes and the loads were therefor also reduced by 25% and 50%.
(Time horizons = 1990, 2000, 2010)

### 6.2 Simulation results and discussion

The input data described in chapter 5 were used as input to the REM decision support system and the TP concentrations in Hartbeespoort Dam were simulated, subject to the various point source P control scenario's. Rietvlei Dam was treated as an upstream reservoir which discharges into Hartbeespoort Dam and its catchment area was therefore excluded when the nonpoint source P export was calculated.

The results were summarized as boxplots (Figure 5) and the detailed results of each simulation scenario reported in appendix A to D. Boxplots were used because it is a convenient way to summarize the time series of TP

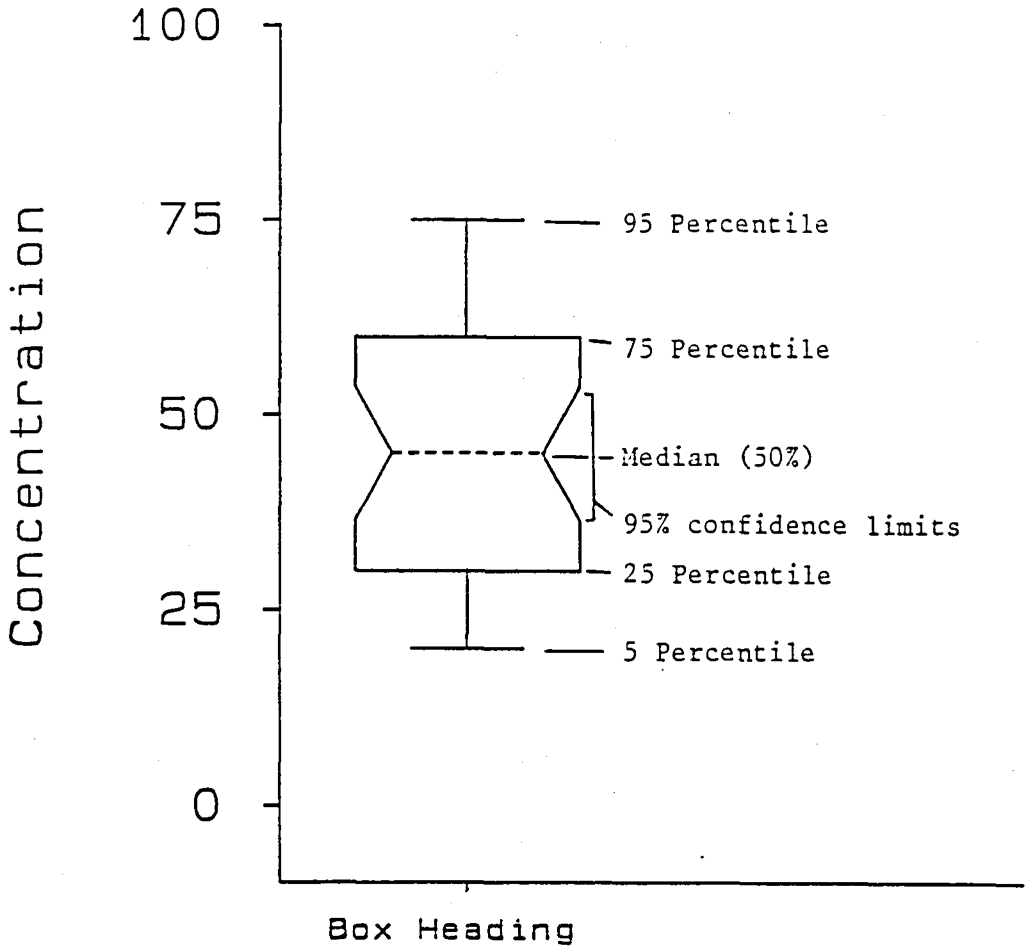


Figure 5 Information presented in each of the notched boxplots. The upper and lower sides of the box represent the 75 and 25 percentiles and the length iof the box is the interquartile range (i.e. 50% of the values fall within the upper and lower sides). The broken line is the median (50 percentile) and the notch represents the 95% confidence limits around the median. The upper and lower bars are the 95 and 5 percentiles respectively.

concentrations and therefor give an indication of the range of concentrations which can be expected as well as the distribution of the data round the median concentration. The median loads and flows from the catchment and upstream reservoirs were reported in the appendixes because the it represents the most likely expected load or flow at any given time which is more representative than the average due the skewed distribution of the load and flow time series.

No physical meaning should be attached to the actual years which the time horizons represent. It is assumed that, in the future, there will be changes in the catchment which will influence the trophic status of the reservoir. This is of importance in a catchments where developments such as urbanization and afforestation are taking place. These changes can be quantified by assuming annual growth rates for variables such as sewage effluent volumes, urban development, reservoir abstractions etc. If the actual growth rates are lower than those assumed for e.g. 1995, the conditions predicted for 1995 might only materialize by 2010. If the actual growth rates are higher than those assumed for e.g. 2000, the conditions predicted for 2000 might already materialize by 1990 or 1995.

### 6.2.1 Scenario 1 "Do nothing" option

The aim of evaluating a "Do nothing" scenario was to predict the impact on the water quality in Hartbeespoort Dam if the present P control measures remain as the were in 1987 i.e. effluent P concentrations remain the same. It was assumed that there were no P losses in the river between the point sources and the reservoir and that the point sources in the Rietvlei Dam catchment conform to the special 1.0 mg P/L standard.

If the present P control measures on point sources in the Hartbeespoort Dam catchment are maintained, the total point source P load to the reservoir will be about 860 tons/a for 1990 conditions which can increase to 3160 tons/a for 2020 conditions (Appendix A). The point source loads are about 50 to 60 times larger than the median nonpoint source P loads of 15.9 tons/a for 1990 and 50.9 tons/a for 2020. The large point source loads would result in average reservoir TP concentrations of about 570 µg/L for 1990 and 860 µg/L predicted for 2020 conditions (Figure 6a). These concentrations are much higher than the average TP concentrations (≈ 470 µg/L) observed in 1986 in Hartbeespoort Dam.

If the mean summer TP concentrations are converted to chlorophyll (Equation 6), the average summer concentrations would vary from about 70 µg/L for 1990 to 90 µg/L for the 2020 conditions (Figure 6b). This means that nuisance conditions are likely to occur for 78% of the time for 1990 and 100% of the time for 2020 conditions. The predicted chlorophyll concentrations are lower than the present chlorophyll concentrations observed in Hartbeespoort Dam (≈ 135 µg/L in 1986).

At present Hartbeespoort Dam is a nitrogen limited reservoir and using the OECD chlorophyll:P relationship to relate TP concentrations to chlorophyll concentrations would result in an over estimation of the chlorophyll concentrations. However, the predicted chlorophyll is lower than the observed chlorophyll concentrations because Hartbeespoort Dam is dominated by the blue-green alga, Microcystis, which is highly competitive under N limited conditions.

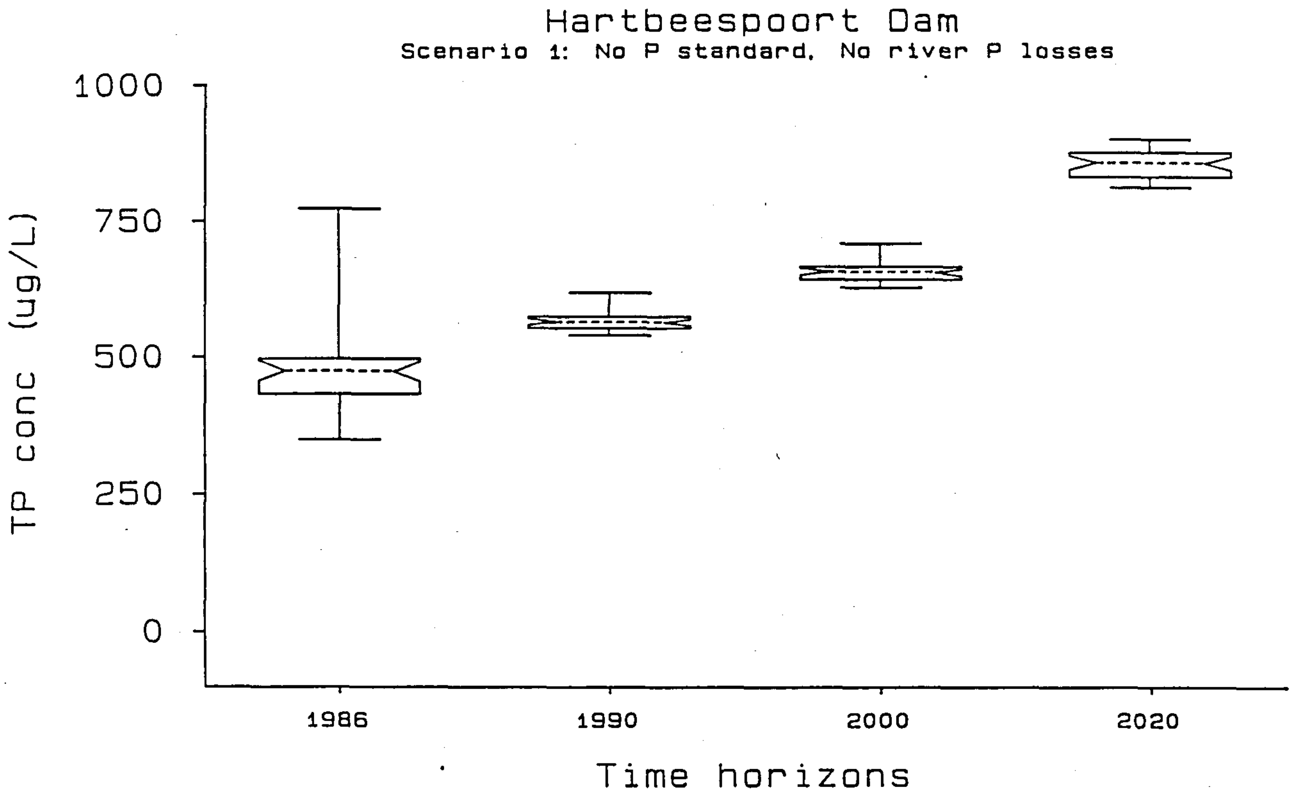


**Figure 6a** Boxplot of predicted TP concentrations in Hartbeespoort Dam for the different time horizons if no P control is enforced on point sources in the catchment.(1986 is observed concentration)

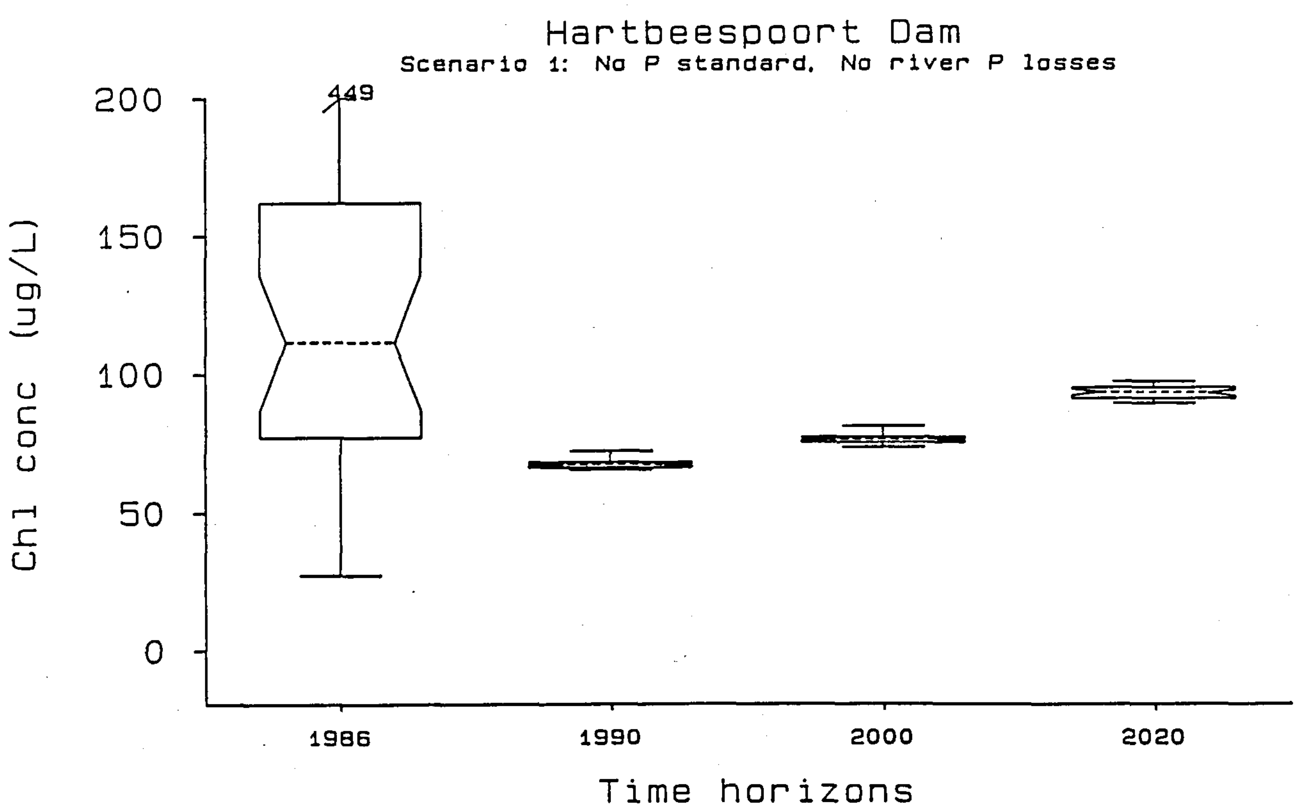


**Figure 6b** Boxplot of predicted chlorophyll concentrations in Hartbeespoort Dam for the different time horizons if no P control is enforced on point sources in the catchment.(1986 is observed concentration)

### 6.2.2 Scenario 2 1.0 mg P/L standard option

The aim of evaluating this scenario was to predict the reservoir TP concentrations if all the point sources in the Hartbeespoort Dam catchment conformed to the special 1.0 mg P/L effluent standard. It was assumed that no losses of P took place between the point sources and the reservoir and that point sources in the Rietvlei Dam catchment conform to the special 1.0 mg P/L standard.

If all the sewage treatment plants in the Hartbeespoort Dam catchment conform to the special 1.0 mg P/L effluent standard, the total point source load would vary between 141 tons/a for 1990 to 518 tons/a for 2020 conditions. This is about 8 to 10 times larger than the median nonpoint source load of 15.9 tons/a for 1990 and 50.9 ton/a for 2020. It is predicted that these loads would result in average TP concentrations varying between about 300 µg/L for 1990 and 420 µg/L for the 2020 conditions respectively (Figure 7a) which are lower than the observed (1986) average TP concentration of 470 µg/L.

If the mean seasonal TP concentrations are converted to chlorophyll, the mean summer concentrations would vary between about 40 µg/L for 1990 and 50 µg/L for 2020 (Figure 7b) which means that nuisance conditions are likely to occur for 42% of the time for 1990 and 54% of the time for the 2020 conditions. This is lower than the observed (1986) chlorophyll concentrations in Hartbeespoort Dam of 135 µg/L because Hartbeespoort Dam is dominated by the blue-green alga, Microcystis, which is dominant for about 8 to 10 months of the year. Microcystis is dominant in Hartbeespoort Dam because it is more competitive under N limited conditions and it is able to utilize the light regime in Hartbeespoort Dam more successfully due to its ability to adjust its buoyancy and therefor select most favorable conditions.

### 6.2.3 Scenario 3 0.1 mg P/L standard option

The aim of evaluating this scenario was to predict the reservoir TP concentrations if all the point sources comply to a standard stricter than the 1 mg P/L standard. It is technologically possible, with no great increase in cost, to treat effluents to meet a 0.1 mg P/L standard. The 0.1 mg P/L standard option predicts a better situation than the "Do nothing" option and the 1 mg P/L standard option. This scenario illustrates the outcome of the best option that is technically possible. It was assumed that no river P losses take place and that point sources in the Rietvlei Dam catchment also conformed to a stricter standard of 0.1 mg/l P standard.

If all the sewage treatment plants in the Hartbeespoort Dam catchment conform to a 0.1 mg P/L effluent standard, the total point source load would increase from 14 tons/a for 1990 to 52 tons/a for 2020 conditions. This is about equal to the median nonpoint source load of 16 tons/a for 1990 and 51 tons/a for 2020 conditions. It is predicted that these loads would result in average TP concentrations of 144 µg/L for 1990 and 158 µg/L for 2020 conditions (Figure 8a) which is much lower than the observed (1986) average TP concentration of 470 µg/L.

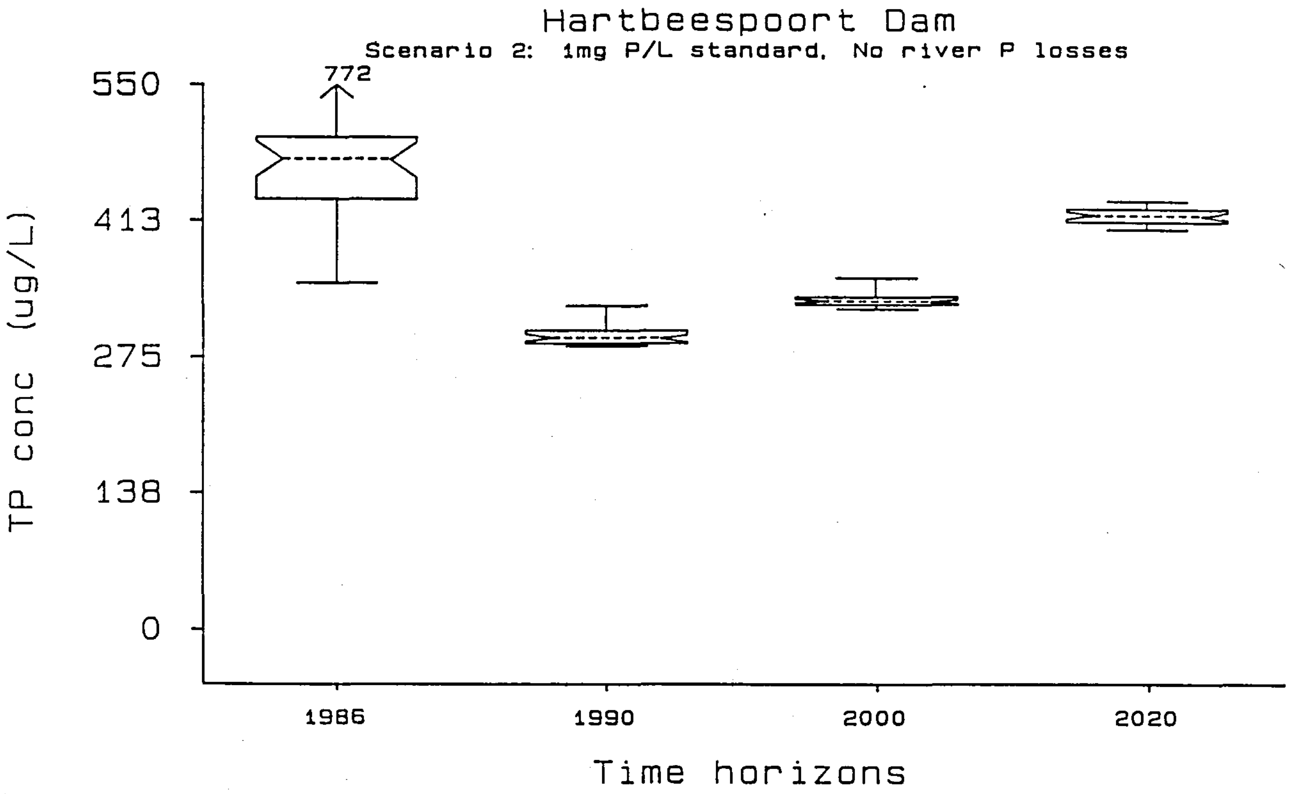


Figure 7a Boxplot of predicted TP concentrations in Hartbeespoort Dam for the different time horizons if the 1 mg P/L standard is enforced on point sources in the catchment.(1986 is observed concentration)

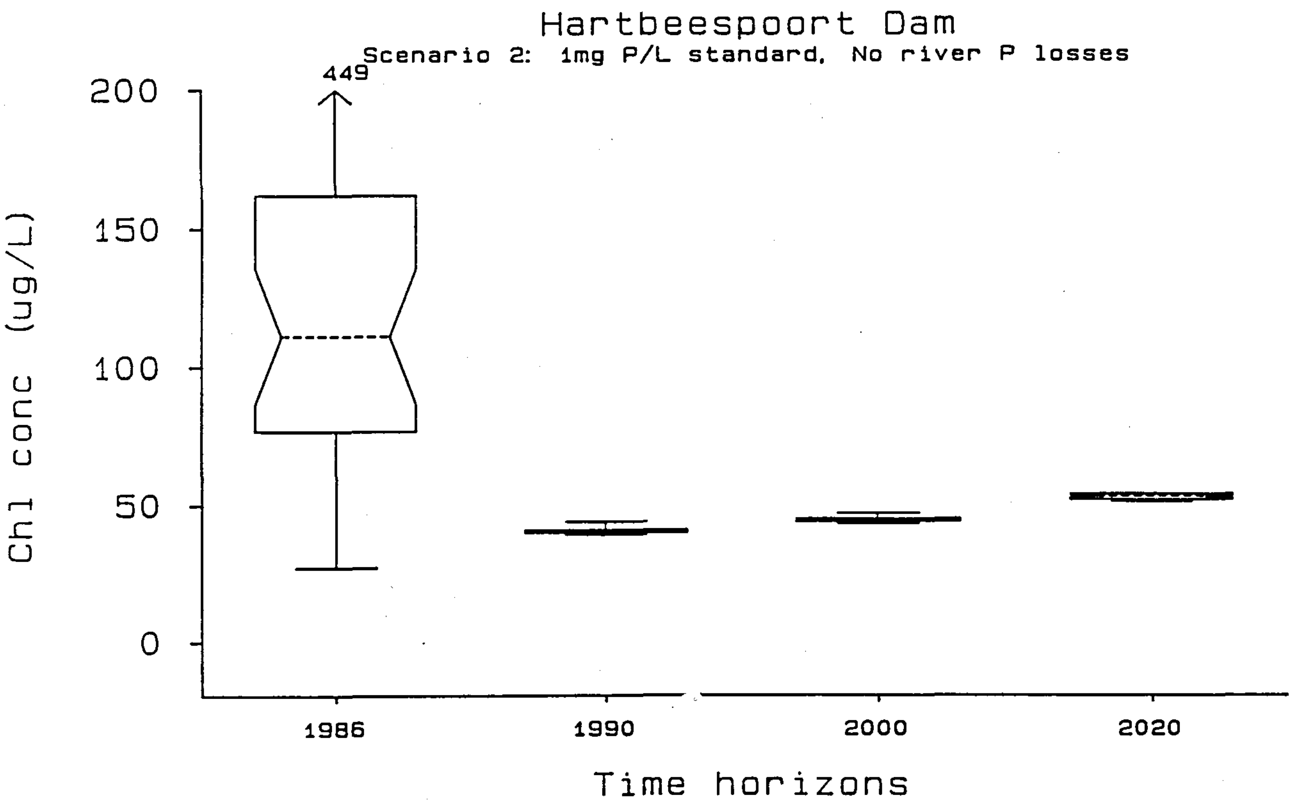


Figure 7b Boxplot of predicted Chlorophyll concentrations in Hartbeespoort Dam for the different time horizons if the 1 mg P/L standard is enforced on point sources in the catchment.

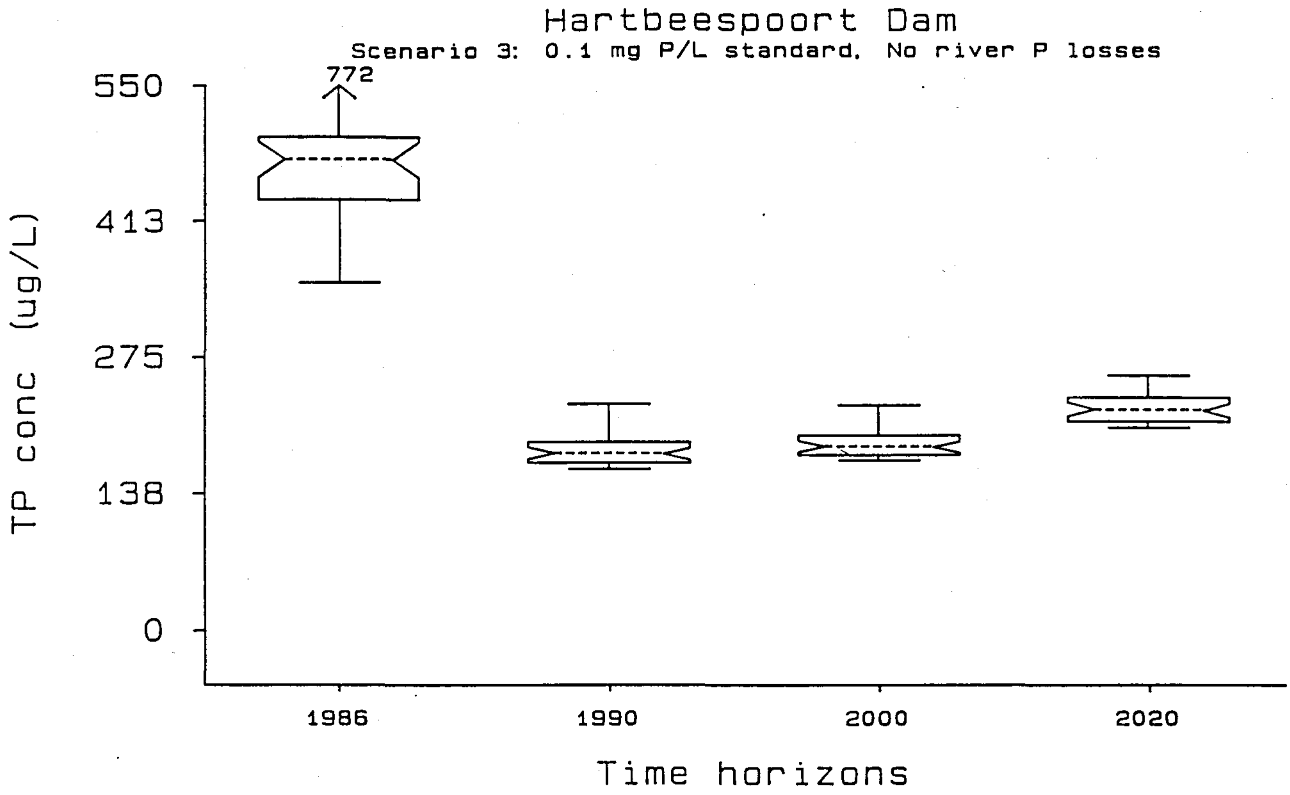


**Figure 8a** Boxplot of predicted TP concentrations in Hartbeespoort Dam for the different time horizons if a 0.1 mg P/L standard is introduced in the catchment.(1986 is observed concentration)

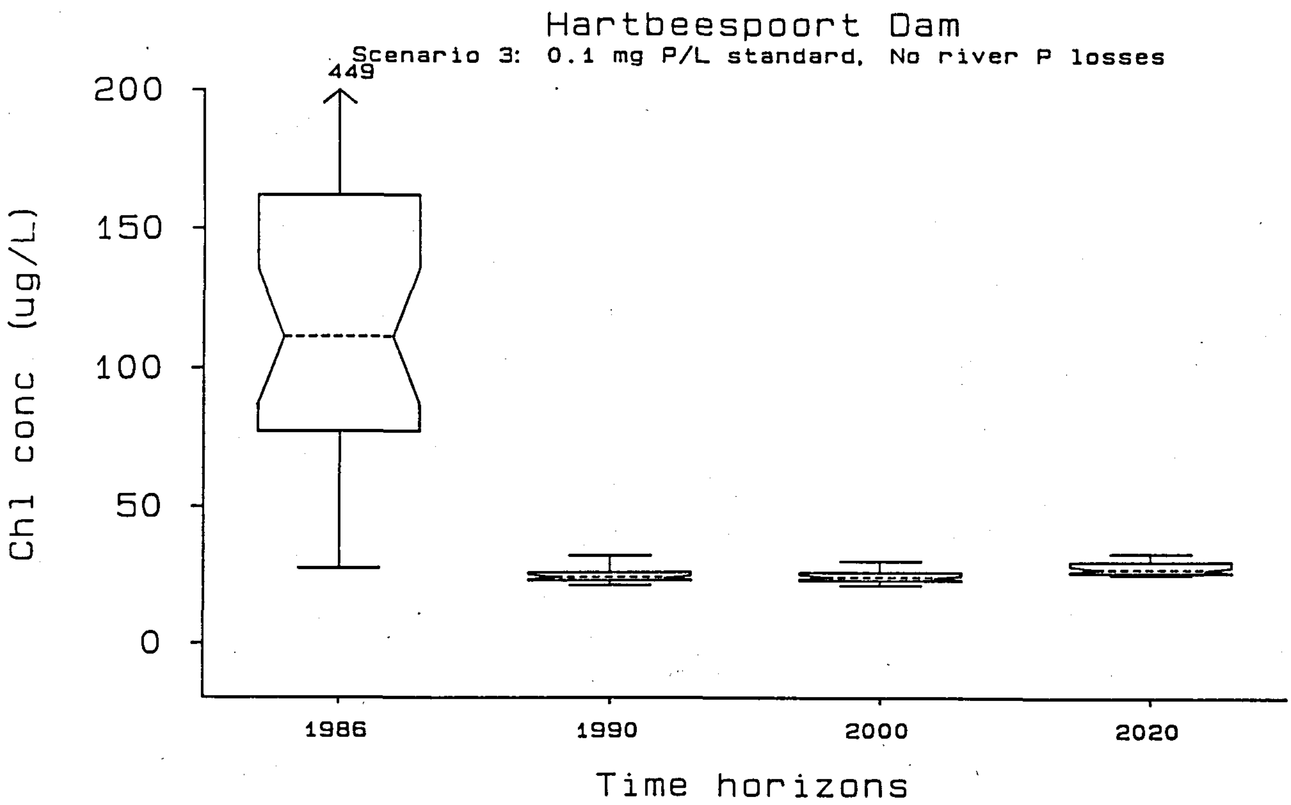


**Figure 8b** Boxplot of predicted chlorophyll concentrations in Hartbeespoort Dam for the different time horizons if a 0.1 mg P/L standard is introduced in the catchment.(1986 is observed concentration)

If the mean seasonal TP concentrations are converted to chlorophyll, the mean summer concentrations would vary between about 23 µg/L for 1990 and 25 µg/L for 2020 conditions (Figure 8b) which means that nuisance conditions are likely to occur for 22% of the time in 1990 and for 24% of the time for 2020 conditions. The predicted average chlorophyll concentration is much lower than the observed (1986) average chlorophyll concentrations of 135 µg/L.

### 6.2.3 Scenario 4 25% and 50% River loss scenario

The aim of simulating a loss scenario was to evaluate the sensitivity of predictions if point sources in the Hartbeespoort Dam catchment comply to the 1 mg P/L standard and 25% or 50% of the P are lost between the point sources and the reservoir.

If all the point sources in the Hartbeespoort Dam catchment conform to the 1 mg P/L effluent standard and 25% of the P is lost between the point sources and the reservoir, the load would be reduced from 141 to 105 ton/a for 1990 and from 518 to 388 tons/a for the 2020 conditions (Appendix D). This load reduction would result in the average reservoir TP concentrations ranging from 263 µg/L for 1990 to 365 µg/L for 2020 conditions (Figure 9a). These concentrations are lower than the observed (1986) average concentrations in Hartbeespoort Dam (≈ 470 µg/L). If the mean seasonal TP concentrations are converted to chlorophyll, the average chlorophyll concentrations would vary from 37 to 48 µg/L (Figure 9b). Nuisance conditions are likely to occur for 39% of the time for 1990 and 52% of the time for the 2020 conditions.

If a 50% loss of P occur, the load would be reduced from 141 to 70 tons/a for 1990 and from 518 to 259 tons/a for the 2020 conditions (Appendix D). This would result in average reservoir TP concentrations ranging from 226 µg/L for 1990 to 301 µg/L for the 2020 conditions (Figure 9a). If the mean seasonal TP concentrations are converted to chlorophyll, the average chlorophyll concentrations would vary from 33 µg/L for 1990, to 41 µg/L for the 2020 conditions (Figure 9b). Nuisance conditions are likely to occur for 35% of the time in 1990 and 45% of the time for the 2020 conditions.

## 6.3 Conclusions and recommendations

### Control vs. No control options

Hartbeespoort is a point source dominated system i.e. the point source P load is much larger than the nonpoint source load and the changes in P concentrations in Hartbeespoort Dam can be directly ascribed to the point source load entering the reservoir. As such, any P control measures in the catchment are going to reduce the TP concentrations in Hartbeespoort Dam (Figure 10a,b). If the 1 mg P/L effluent standard is enforced in the Hartbeespoort Dam catchment, average reservoir TP concentrations, and chlorophyll concentrations, would be reduced by 48%, 50% and 52% for the 1990, 2000 and 2020 conditions. The predicted chlorophyll concentrations would still result in nuisance conditions occurring for about 50% of the time in Hartbeespoort Dam which will not be a visual improvement of the water quality in Hartbeespoort Dam.

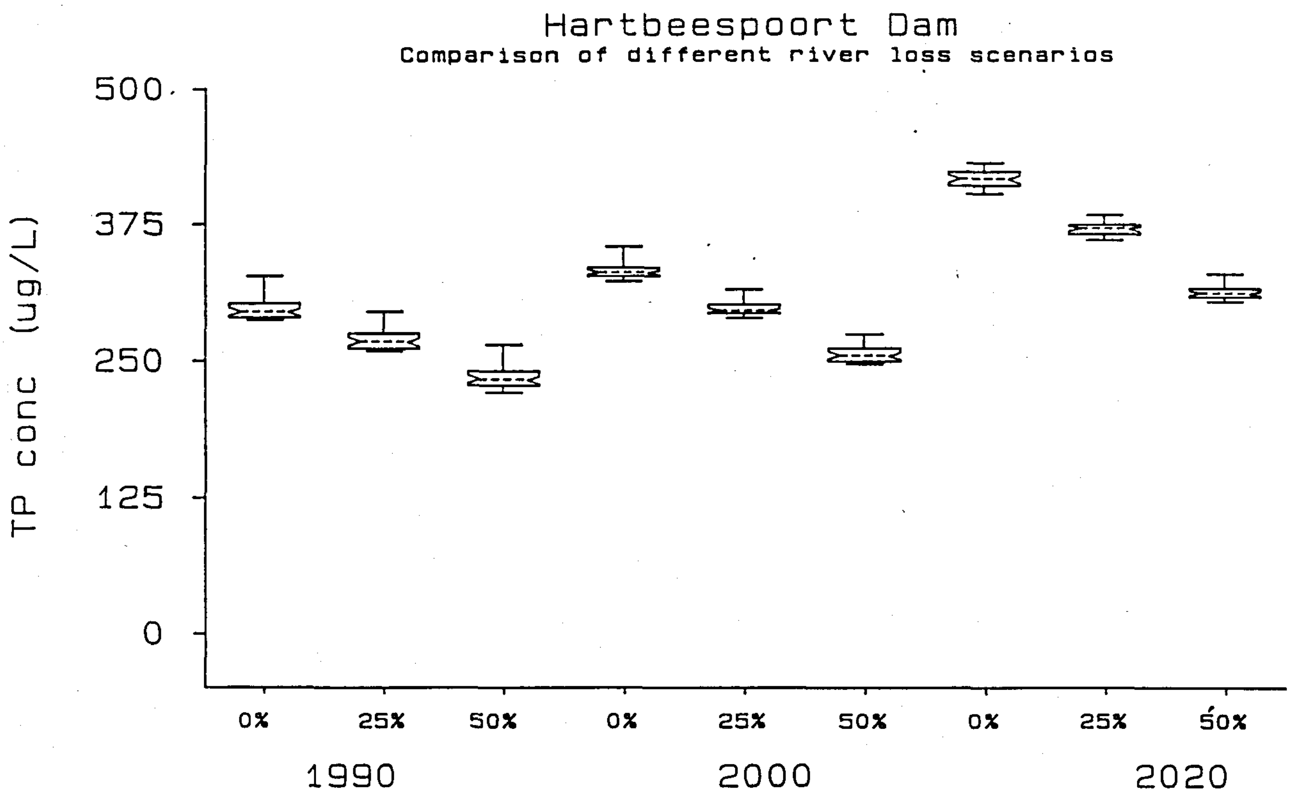


Figure 9a Boxplot of predicted TP concentrations in Hartbeespoort Dam for the different time horizons if the 1 mg P/L standard is enforced on point sources in the catchment and 25% and 50% P losses occur in the river.

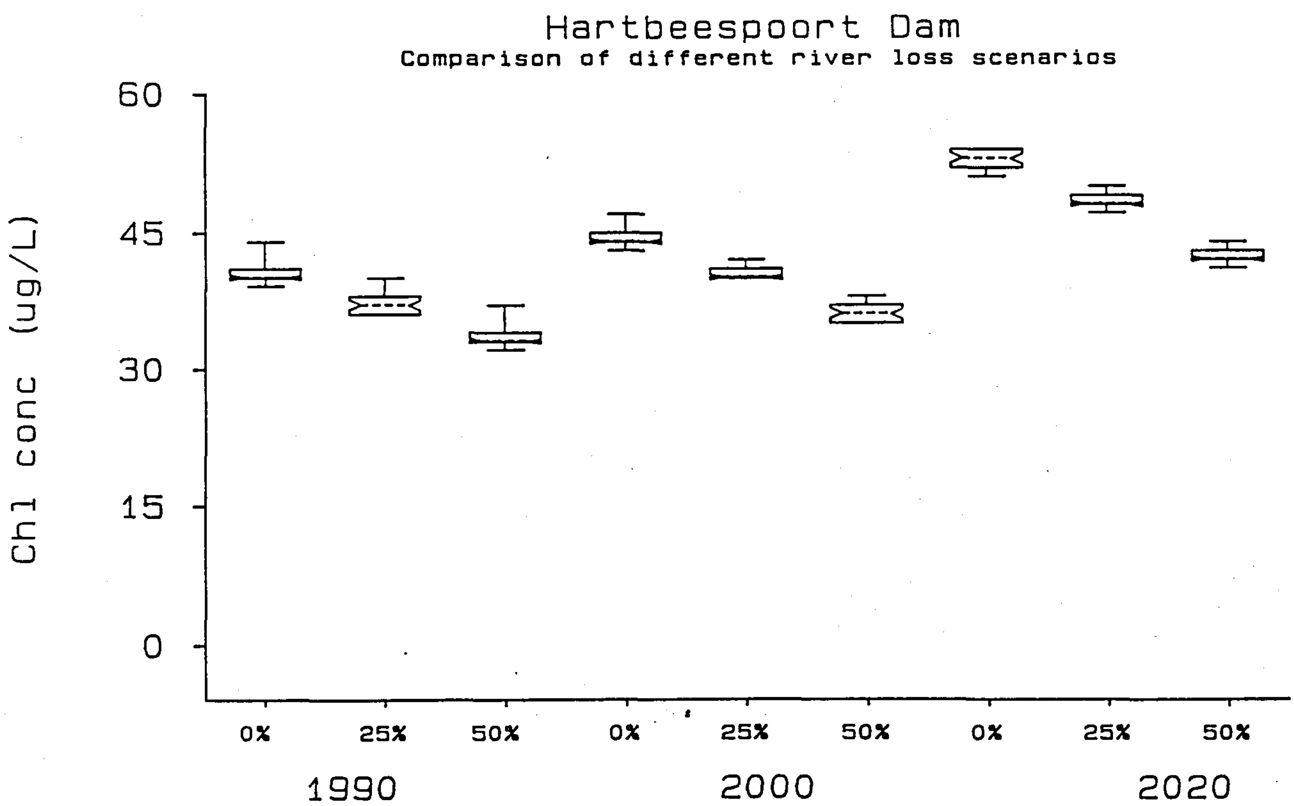


Figure 9b Boxplot of predicted Chlorophyll concentrations in Hartbeespoort Dam for the different time horizons if the 1mg P/L standard is enforced on point sources in the catchment and 25% and 50% P losses occur in the river.

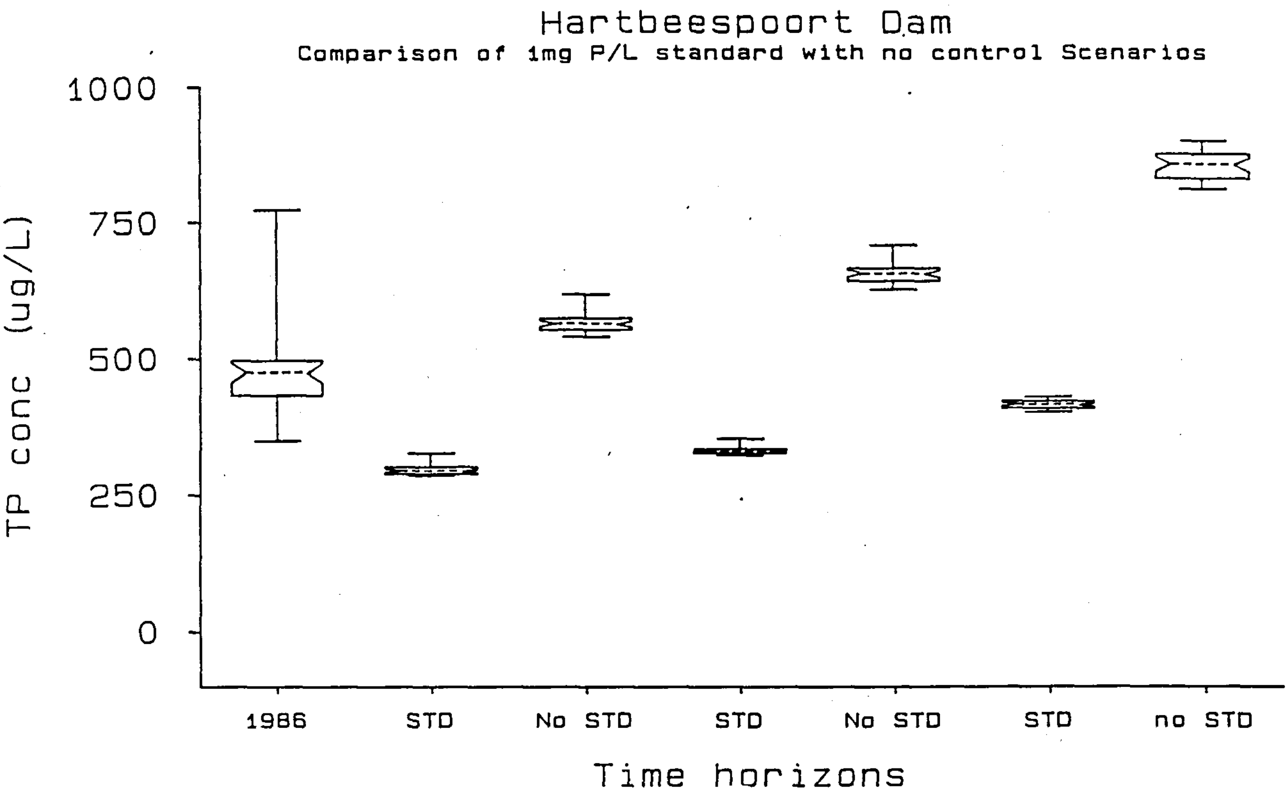


Figure 10a Comparison of predicted TP concentrations in Hartbeespoort Dam if a 1 mg P/L standard is implemented and if no control is exercised.(1986 is observed concentration)

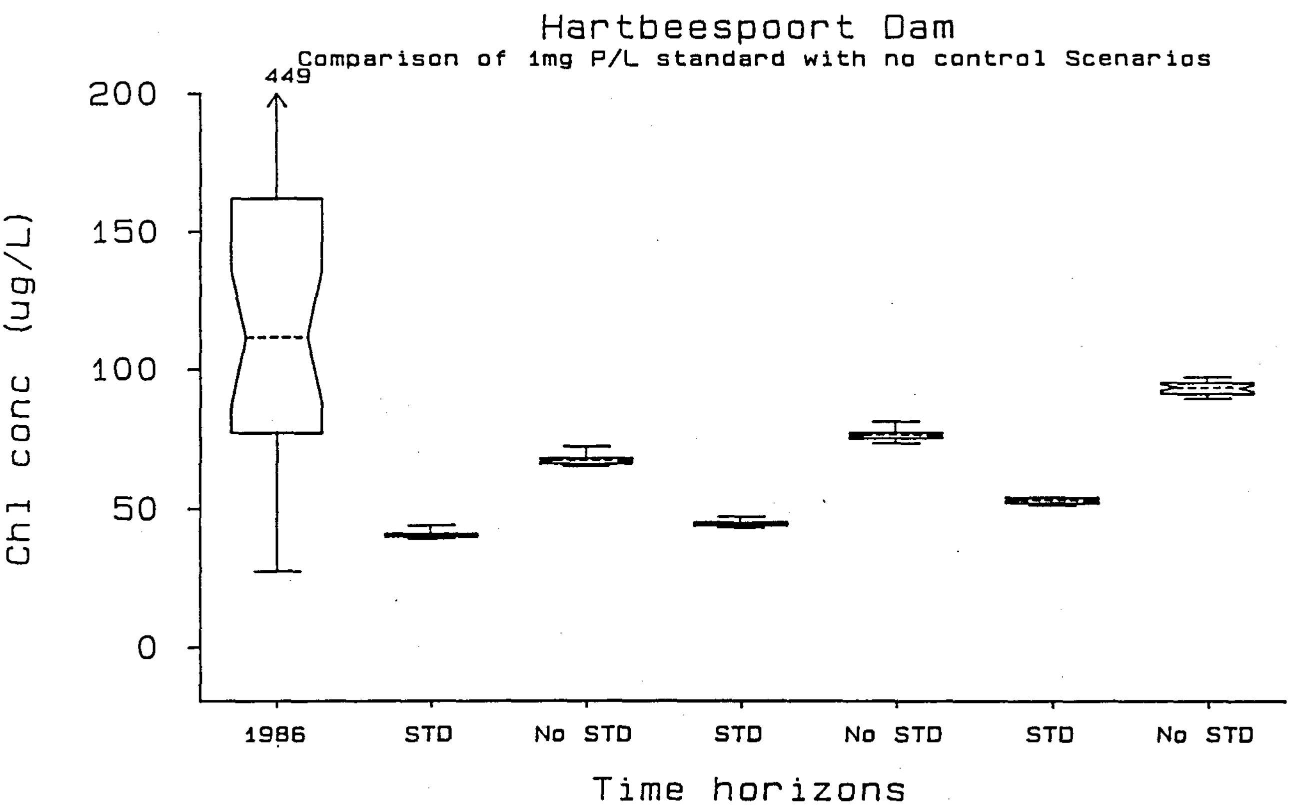


Figure 10b Comparison of predicted chlorophyll concentrations in Hartbeespoort Dam if a 1 mg P/L standard is implemented and if no control is exercised.(1986 is observed concentration)

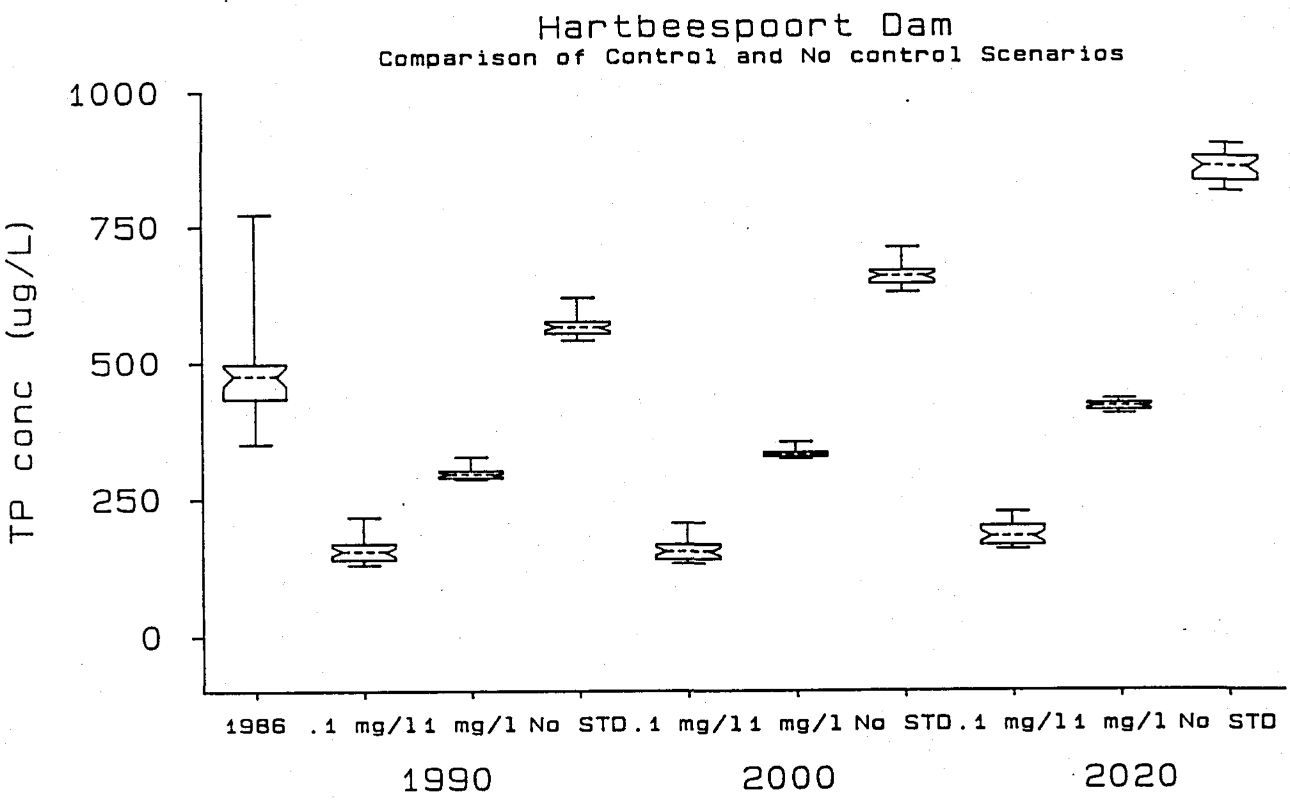


**Figure 11a** Comparison of the predicted TP concentrations in Hartbeespoort Dam if a standard of 0.1 mg P/L (.1 mg/l), a standard of 1 mg P/L (1 mg/l) and no P control (No STD) is implemented in the catchment.(1986 is observed concentration)

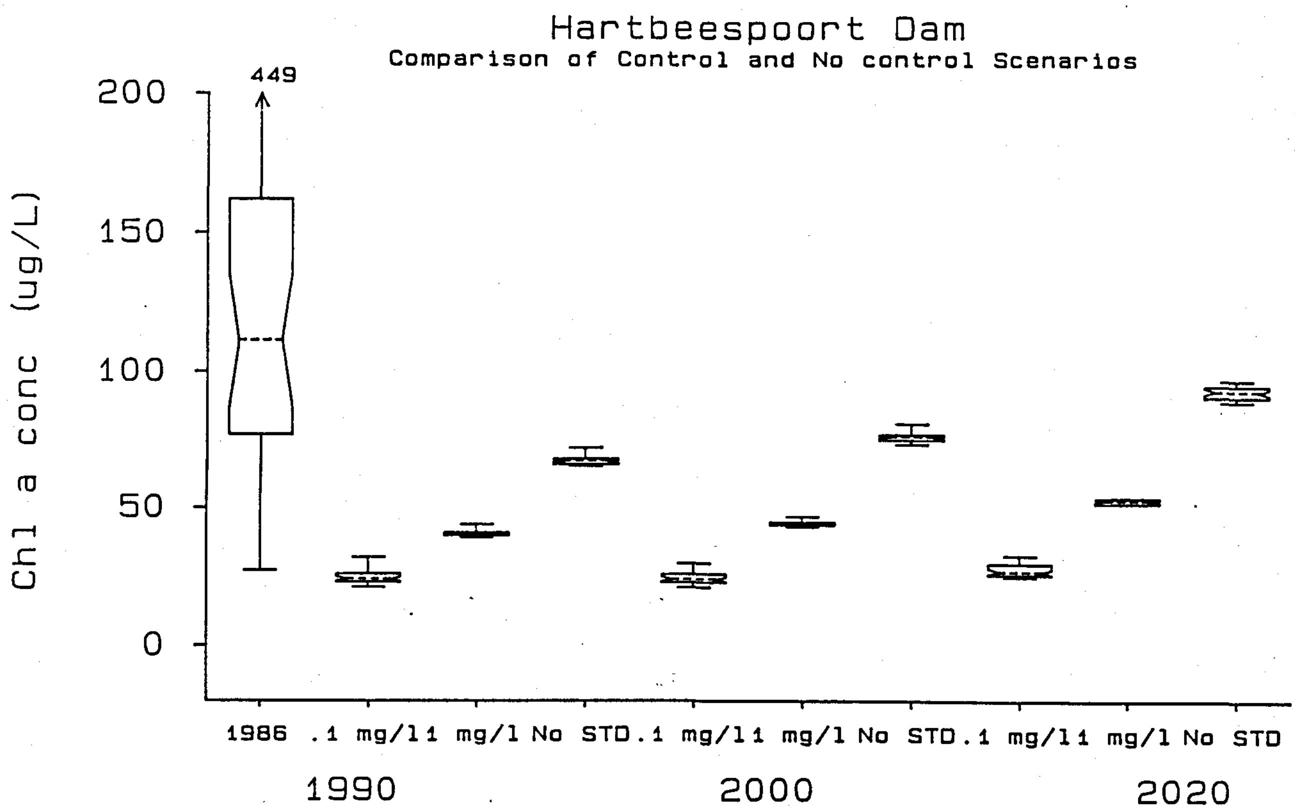


**Figure 11b** Comparison of the predicted chlorophyll concentrations in Hartbeespoort Dam if a standard of 0.1 mg P/L (.1 mg/l), a standard of 1 mg P/L (1 mg/l) and no P control (No STD) is implemented in the catchment.(1986 is observed concentration)

It is therefore recommended that, as a starting point, the existing 1 mg P/L effluent standard be enforced on point sources in the Hartbeespoort Dam catchment.

### Degree of P control measures

It is clear that to rehabilitate Hartbeespoort Dam and maintain it as an important source of acceptable quality potable water in the region, P control measures have to be enforced in the catchment. It was concluded in the previous section that the existing 1 mg/L special effluent standard would not reduce the nuisance conditions to acceptable levels. A stricter standard than the existing 1 mg P/L standard will have to be considered in the Hartbeespoort Dam catchment. Therefore, the question is how strict a standard should be introduced.

It is technologically possible to treat sewage effluent to a final P concentration of 0.1 mg/L. It was predicted that a 0.1 mg/L effluent would result in TP concentrations of about 160-180 µg/L and chlorophyll concentrations of about 24-28 µg/L (Figure 11 a,b). These concentrations borders on nuisance conditions.

The single most important polluter is the Johannesburg Northern Works which contributes about 46% of the total P load to Hartbeespoort Dam. AECI and the Alexandra sewage treatment plant contribute about 15% and 11% each, while the remaining 6 point sources contribute the remaining 28% of the total TP load. It may be cheaper to treat all the effluents of the regions, to lower than the present standard, at a single plant that can be operated more effectively than to treat it at a number of effluent treatment plants. Other P control measures may have to be introduced in addition to an effluent P standard such as in-lake management techniques.

It is recommended that an effluent standard stricter than the 1 mg P/L standard be considered for introduction in the Hartbeespoort Dam catchment.

### N:P ratio and nutrient limitation

The present N:P ratio (1985) of 5:1 indicates that Hartbeespoort Dam is marginally N limited if a ratio of 7:1 is assumed to represent the onset of a changeover from N to P limitation. If P control measures are enforced in the catchment, the N:P ratio will increase because the process by which P is reduced in the sewage effluents does not influence the N in the effluent. The N load are expected to increase proportionally to the effluent volume which means that Hartbeespoort Dam would become a P limited reservoir with the consequence that a reduction in P concentrations would result in a reduction of chlorophyll concentrations.

### Effect of water residence time

Hartbeespoort Dam would be operated at maximum yield which means that the increased runoff and increased demand would reduce the water residence time (Table 8).

The median water residence time in Hartbeespoort Dam would be reduced from

9 months to 3 months for the 1990 and 2020 conditions. This would influence the growth of phytoplankton as well as thermal stratification in the reservoir.

The reduced retention time is not short enough to reduce the Microcystis standing crop during the summer as Microcystis has a doubling time of about 10-12 days. However, during the winter when the growth rate is very low due to low water temperatures, some of the standing crop may be flushed out.

Table 8 The effect of hydrology on the water residence time in Hartbeespoort Dam for the different time horizons

| Time horizon | | 1990 | 2000 | 2020 |
|---|---|---|---|---|
| Inflows into Hartbeespoort Dam | | | | |
| Natural inflow ($m^3x10^6$/annum) | Average | 151.05 | 174.56 | 288.67 |
| | Median (50%) | 81.54 | 103.08 | 200.88 |
| | 25 % | 24.90 | 28.98 | 48.54 |
| | 75 % | 192.90 | 234.48 | 439.68 |
| Rietvlei outflows ($m^3x10^6$/annum) | Average | 22.74 | 38.74 | 94.42 |
| | Median (50%) | 15.34 | 31.44 | 87.59 |
| | 25 % | 9.10 | 23.92 | 73.30 |
| | 75 % | 27.62 | 45.12 | 110.03 |
| Total Point source outflow ($m^3x10^6$/annum) | | 140.28 | 227.52 | 518.04 |
| Total inflow ($m^3x10^6$/annum) | Average | 314.07 | 440.82 | 901.43 |
| | Median (50%) | 237.16 | 362.04 | 806.51 |
| | 25 % | 174.28 | 280.42 | 639.88 |
| | 75 % | 360.80 | 507.12 | 1067.75 |
| Reservoir volume ($m^3x10^6$) FSL = 192.7 | Average | 171.63 | 173.86 | 172.99 |
| | Median (50%) | 180.50 | 182.78 | 185.50 |
| | 25 % | 155.60 | 158.18 | 157.88 |
| | 75 % | 192.70 | 192.70 | 192.70 |
| Residence time (Months) | Average | 6.6 | 4.7 | 2.3 |
| | Median (50%) | 9.1 | 6.1 | 2.8 |
| | 25 % | 10.7 | 6.8 | 3.0 |
| | 75 % | 6.4 | 4.5 | 2.2 |

**River losses**

The predictions are sensitive to river losses. It is difficult to quantify the losses of P in the river between the point source and the reservoir and there is uncertainty whether the loss is a temporary loss (it may be resuspended during storm runoff) or whether it is a permanent loss. However, the predictions which were made with the assumption of no river loss, were conservative and simulated the worst conditions. We are fairly sure that losses greater than 50% would not occur and the 50% loss therefore represents the best possible case if P losses occur in the river.

River losses can be viewed as an ecological safety margin which is highly dependent on the ecological status of the river. It is therefore recommended that river losses should not be used as a reason for not enforcing an effluent P standard in the Hartbeespoort Dam catchment.


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Directorate of Planning for planning reports on Hartbeespoort Dam

Dr. W.V. Pitman, Stewart, Sviridov and Oliver, for hydrological simulations

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## Appendix A

**Scenario 1 No P standard applied to point sources**

| | 1990 | 2000 | 2020 |
|---|---|---|---|
| | | Time horizons | |
| Nonpoint source TP load (Tons/annum) | | | |
| Median load | 15.92 | 21.54 | 50.92 |
| Rietvlei Dam TP load (Tons/annum) | | | |
| Median load | 6.67 | 15.31 | 51.90 |
| Point source TP loads (Tons/annum) | | | |
| Tembisa | 71.00 | 115.00 | 261.00 |
| Verwoerdburg | 70.00 | 113.00 | 258.00 |
| Alexandra | 95.40 | 153.60 | 349.80 |
| AECI | 21.30 | 34.30 | 78.20 |
| JHB Northern Works | 390.60 | 629.40 | 1433.40 |
| Roodepoort | 29.00 | 47.00 | 108.00 |
| Krugersdorp | 97.60 | 156.80 | 356.80 |
| Randfontein | 81.00 | 131.00 | 298.00 |
| Midrand | 2.11 | 8.00 | 17.60 |
| Total point load | 857.61 | 1388.10 | 3160.80 |
| Predicted TP concentration (µg/L) | | | |
| Average | 568 | 659 | 856 |
| Percentiles | | | |
| 5% | 537 | 627 | 811 |
| 25% | 553 | 644 | 832 |
| 50% | 563 | 657 | 857 |
| 75% | 573 | 668 | 877 |
| 95% | 617 | 710 | 901 |
| Predicted Chlorophyll concentration (µg/L) | | | |
| Average | 67 | 76 | 93 |
| Percentiles | | | |
| 5% | 65 | 73 | 89 |
| 25% | 66 | 75 | 91 |
| 50% | 67 | 76 | 93 |
| 75% | 68 | 77 | 95 |
| 95% | 72 | 81 | 97 |
| Hydrology ($10^6$ $m^3$/annum) | | | |
| Median nett runoff | 81.60 | 103.08 | 200.88 |
| Median Rietvlei outflow | 15.36 | 31.44 | 87.60 |
| Total effluent volume | 140.26 | 227.50 | 518.00 |

* The percentiles is the values below which a certain percentage of observations fall.

## Appendix B

**Scenario 2 1 mg P/L standard applied to point sources**

| | Time horizons 1990 | 2000 | 2020 |
|---|---|---|---|
| Nonpoint source TP load (Tons/annum) | | | |
| Median load | 15.92 | 21.54 | 50.92 |
| Rietvlei Dam TP load (Tons/annum) | | | |
| Median load | 6.67 | 15.31 | 51.90 |
| Point source TP loads (Tons/annum) | | | |
| Tembisa | 7.10 | 11.50 | 26.10 |
| Verwoerdburg | 7.00 | 11.30 | 25.80 |
| Alexandra | 15.90 | 25.60 | 58.30 |
| AECI | 21.30 | 34.30 | 78.20 |
| JHB Northern Works | 65.10 | 104.90 | 238.90 |
| Roodepoort | 2.90 | 4.70 | 10.80 |
| Krugersdorp | 12.90 | 19.60 | 44.60 |
| Randfontein | 8.10 | 13.10 | 29.80 |
| Midrand | 0.66 | 2.50 | 5.50 |
| Total point load | 140.96 | 227.50 | 518.00 |
| Predicted TP concentration (µg/L) | | | |
| Average | 297 | 334 | 418 |
| Percentiles | | | |
| 5% | 282 | 323 | 403 |
| 25% | 286 | 328 | 411 |
| 50% | 290 | 331 | 417 |
| 75% | 298 | 336 | 424 |
| 95% | 321 | 355 | 432 |
| Predicted Chlorophyll concentration (µg/L) | | | |
| Average | 41 | 44 | 53 |
| Percentiles | | | |
| 5% | 39 | 43 | 51 |
| 25% | 39 | 44 | 52 |
| 50% | 40 | 44 | 53 |
| 75% | 41 | 45 | 54 |
| 95% | 43 | 47 | 54 |
| Hydrology ($10^6$ $m^3$/annum) | | | |
| Median nett runoff | 81.60 | 103.08 | 200.88 |
| Median Rietvlei outflow | 15.36 | 31.44 | 87.60 |
| Total effluent volume | 140.26 | 227.50 | 518.00 |

* The percentiles is the values below which a certain percentage of observations fall.

## Appendix C

**Scenario 3 0.1 mg P/L standard applied to point sources**

| | Time horizons 1990 | 2000 | 2020 |
|---|---|---|---|
| Nonpoint source TP load (Tons/annum) | | | |
| Median load | 15.92 | 21.54 | 50.92 |
| Rietvlei Dam TP load (Tons/annum) | | | |
| Median load | 2.89 | 6.04 | 17.61 |
| Point source TP loads (Tons/annum) | | | |
| Tembisa | 0.71 | 1.15 | 2.61 |
| Verwoerdburg | 0.70 | 1.13 | 2.58 |
| Alexandra | 1.59 | 2.56 | 5.83 |
| AECI | 2.13 | 3.43 | 7.82 |
| JHB Northern Works | 6.51 | 10.49 | 23.89 |
| Roodepoort | 0.29 | 0.47 | 1.08 |
| Krugersdorp | 1.22 | 1.96 | 4.46 |
| Randfontein | 0.81 | 1.31 | 2.98 |
| Midrand | 0.07 | 0.25 | 0.55 |
| Total point load | 14.03 | 22.75 | 51.80 |
| Predicted TP concentration (µg/L) | | | |
| Average | 144 | 146 | 158 |
| Percentiles | | | |
| 5% | 111 | 116 | 125 |
| 25% | 125 | 127 | 138 |
| 50% | 137 | 141 | 154 |
| 75% | 153 | 155 | 174 |
| 95% | 202 | 197 | 201 |
| Predicted Chlorophyll concentration (µg/L) | | | |
| Average | 23 | 23 | 25 |
| Percentiles | | | |
| 5% | 19 | 19 | 20 |
| 25% | 21 | 21 | 22 |
| 50% | 23 | 22 | 24 |
| 75% | 25 | 24 | 27 |
| 95% | 30 | 29 | 30 |
| Hydrology ($10^6$ $m^3$/annum) | | | |
| Median nett runoff | 81.60 | 103.08 | 200.88 |
| Median Rietvlei outflow | 15.36 | 31.44 | 87.60 |
| Total effluent volume | 140.26 | 227.50 | 518.00 |

* The percentiles is the values below which a certain percentage of observations fall.

## Appendix D

**Scenario 4 25% and 50% P losses in the river when 1 mg P/L standard is applied**

| | 1990 | | 2000 | | 2020 | |
|---|---|---|---|---|---|---|
| Loss | 25% | 50% | 25% | 50% | 25% | 50% |
| Nonpoint source TP load (Tons/annum) | | | | | | |
| Median load | 15.92 | 15.92 | 21.54 | 21.54 | 50.92 | 50.92 |
| Rietvlei Dam TP load (Tons/annum) | | | | | | |
| Median load | 5.00 | 3.34 | 11.49 | 7.66 | 38.92 | 25.95 |
| Point source TP loads (Tons/annum) | | | | | | |
| Tembisa | 5.32 | 3.55 | 8.63 | 5.75 | 19.58 | 13.05 |
| Verwoerdburg | 5.25 | 3.50 | 8.48 | 5.65 | 19.35 | 12.90 |
| Alexandra | 11.93 | 7.95 | 19.20 | 12.80 | 43.72 | 29.15 |
| AECI | 15.98 | 10.65 | 25.72 | 17.15 | 58.65 | 39.10 |
| JHB Northern Works | 48.82 | 32.55 | 78.68 | 52.45 | 179.18 | 119.45 |
| Roodepoort | 2.17 | 1.45 | 3.53 | 2.35 | 8.10 | 5.40 |
| Krugersdorp | 9.15 | 6.10 | 14.70 | 9.80 | 33.45 | 22.30 |
| Randfontein | 6.07 | 4.05 | 9.82 | 6.55 | 22.35 | 14.90 |
| Midrand | 0.49 | 0.33 | 1.88 | 1.25 | 4.13 | 2.75 |
| Total point load | 105.18 | 70.13 | 170.64 | 113.75 | 388.51 | 259.00 |
| Predicted TP concentration (µg/L) | | | | | | |
| Average | 263 | 226 | 296 | 250 | 365 | 301 |
| Percentiles | | | | | | |
| 5% | 252 | 213 | 287 | 240 | 355 | 292 |
| 25% | 256 | 218 | 291 | 243 | 361 | 296 |
| 50% | 260 | 223 | 293 | 248 | 365 | 299 |
| 75% | 270 | 230 | 300 | 254 | 369 | 303 |
| 95% | 290 | 251 | 313 | 267 | 379 | 316 |
| Predicted Chlorophyll concentration (µg/L) | | | | | | |
| Average | 37 | 33 | 40 | 35 | 48 | 41 |
| Percentiles | | | | | | |
| 5% | 35 | 31 | 39 | 34 | 47 | 40 |
| 25% | 36 | 32 | 40 | 35 | 47 | 40 |
| 50% | 36 | 32 | 40 | 35 | 48 | 41 |
| 75% | 37 | 33 | 41 | 36 | 48 | 41 |
| 95% | 40 | 35 | 42 | 37 | 49 | 42 |
| Hydrology ($10^6$ m$^3$/annum) | | | | | | |
| Median nett runoff | 81.60 | 81.60 | 103.08 | 103.08 | 200.88 | 200.88 |
| Median Rietvlei outflow | 15.36 | 15.36 | 31.44 | 31.44 | 87.60 | 87.60 |
| Total effluent volume | 140.26 | 140.26 | 227.50 | 227.50 | 518.00 | 518.00 |

* The percentiles is the values below which a certain percentage of observations fall.