CONTRACT REPORT

THE MANAGEMENT OF PHOSPHATE CONCENTRATIONS AND ALGAE IN HARTBEESPOORT DAM

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WRC Report No 289/1/92
ISBN 1 874858 32 2

THE MANAGEMENT
OF
PHOSPHATE CONCENTRATIONS AND ALGAE
IN
HARTBEESPOORT DAM

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When used as a reference, this report should be cited as:
Chutter, F M & J N Rossouw (1991). The management of phosphate concentrations and algae in Hartbeespoort Dam. WRC Report No 289/1/91. xii + 37 pp.

TABLE OF CONTENTS

ACKNOWLEDGEMENT

The research in this report emanated from a project funded by the Water Research Commission under the title

RESEARCH ON THE MANAGEMENT OF PHOSPHATE CONCENTRATIONS AND ALGAE IN HARTBEESPOORT DAM.

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

Dr M J Pieterse	Water Research Commission (Chairman)
Mr G Offringa	Water Research Commission
Mr D J M Huyser	Water Research Commission (Secretary)
Dr F M Chutter	Division of Water Technology
Mr J N Rossouw	Division of Water Technology
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Mr W van der Merwe	Department of Water Affairs & Forestry
Dr D C Grobler	Initially Department of Water Affairs & Forestry, later CSIR
Dr H van Vliet	Department of Water Affairs & Forestry

The financing of the project by the Water Research Commission and the contribution by the members of the Steering Committee are gratefully acknowledged.

TERMS OF REFERENCE

The research reported here was carried out in terms of a contract entered into by the Water Research Commission, the Department of Water Affairs & Forestry and the Division of Water Technology of the CSIR.

The intended research would be concerned with the management of phosphate concentrations and algae in Hartbeespoort Dam.

The aims of the research contract were defined in the agreement as follows:

1. Identify and quantify the mechanisms by which large quantities of phosphate have been lost in the reservoir, since it filled in 1987/88 after the drought, the rate of removal and, if possible, the permanence of the removal mechanisms.

2. Identify the mechanisms which resulted in the virtual absence of *Microcystis* in summer 1988/89, establish whether they persisted into 1989/90 and establish whether they can be artificially manipulated to manage algal species composition in reservoirs in general.

3. In the light of the findings of aims 1 and 2 advise the Department of Water Affairs & Forestry whether a full scale aeration of Hartbeespoort Dam should be used to manage *Microcystis* populations and phosphate concentrations.

The justification for the contract referred to the facts that the physical and chemical limnology of Hartbeespoort Dam had been under close observation since 1980 and that the 1 $mg\ell^{-1}$ phosphate effluent standard would probably be insufficient to achieve the Department of Water Affairs & Forestry's water quality management objectives, which were to reduce the abundance of *Microcystis* in particular and of the phytoplankton in general. The Department was therefore considering the destratification of the Dam to achieve these objectives. However, it became apparent that in summer 1988/89, for the first time since 1980, the phytoplankton of Hartbeespoort Dam was not dominated by *Microcystis* - a state of affairs desired by the Department in terms of its management objectives. The Department therefore decided to shelve its proposal to destratify the dam, until such time as the reasons for the lack of *Microcystis* dominance and the permanence of this change had been further elucidated. These considerations led the Department and the Water Research Commission to enter into the contract described here. It was hypothesized that the absence of *Microcystis* might be due to lower water temperatures leading to a lower stability of the water column; or to a decline in phosphate concentrations due to dilution of the dam; or to an increase in the loss of soluble phosphates to the sediments.

The contract addressed the material and methods to be used in the study. Field and analytical methods, sampling points and data storage and handling techniques would be the same as in the long-term studies carried out since 1980. The historical data would be used in the interpretation of the data to be gathered during the contract. Field work on the dam would be carried out at two-weekly intervals (from June 1989 to May 1990) by the Division of Water Technology. Water samples would be collected daily by the Atomic Energy Board from the Crocodile River (Weir A2M12) and by the Department of Water Affairs & Forestry from the outflows of the dam. All water samples would be delivered to the Hydrological Research Institute of the Department of Water Affairs & Forestry for chemical analysis. Biological samples would be analyzed by the Division of Water Technology and the Division would undertake the data analysis and report writing.

The project would commence on 1 June 1989 and terminate on 30 November 1990, a date which was subsequently extended to 31 July 1991.

EXECUTIVE SUMMARY

This report is an account of the major physical, chemical and biological changes which have taken place in Hartbeespoort Dam over the period 1980 to 1990. From a management point of view, two of these changes are of interest. The first is the impact of the 1 $mg\ell^{-1}$ special orthophosphate standard for effluents on the load of phosphorus on the dam. The second is the disappearance of *Microcystis* in the summers of 1988/89 and 1989/90. Arising out of this, the cause of the disappearance and future replication of the cause in order to manage *Microcystis* are of management importance.

After a general description of Hartbeespoort Dam, its catchment and the sampling points used in the study, the methods used are described. The reported analytical values for Kjeldahl nitrogen, orthophosphate and total phosphorus depended on the laboratory analysing the water samples. This resulted from the fact that the analysis of all chemical samples was transferred from the Division of Water Technology, CSIR, to the Hydrological Research Institute of the Department of Water Affairs & Forestry. The origins of the differences and the manner in which the problem was overcome are described in the methods section of the report.

The period of the study included the drought phase of the long-term hydrological cycle. Hartbeespoort Dam was full when the study commenced. Its mean volume was between 35 and 42 percent of full supply volume from 1982/83 to 1985/86. During this time its minimum volume was between 20 and 30 percent of full supply volume. Thereafter the dam filled rapidly and spilled in 1987/88 and in the years thereafter. Inflow volumes were low during the drought. The hydrological mass balance for the reservoir is good, except during the periods when the volume of water stored in the dam changed rapidly. At these times, inaccuracies in the measured components of the balance resulted in volumes of stored water estimated from the previous year's stored volume plus inputs less outputs differing from the measured year end stored volumes by up to 28 percent. These inaccuracies were taken into account in the estimation of nutrient mass balances for the dam.

The temperature and stability of the water column are presented in the form of temperature isotherms and the frequency of occurrence of diurnal mixed layers at the water surface. An analysis of the temperature and stability conditions in 1988/89 and 1989/90 showed that conditions in these years were not outside the range of conditions found in previous years.

Records of the chemical data from 1984 to the present show that since the dam filled after the

drought, the annual mean concentration of the major ions in the inflowing water, the dam and its outflow have declined. Silica concentrations have been particularly low.

In the Crocodile River the flow-weighted annual mean total phosphorus concentration peaked at nearly 3 $mg\ell^{-1}$ in 1983/84 and has since declined to between 1.4 and 1.1 $mg\ell^{-1}$ from 1985/86 to 1988/89. Simultaneously the annual mean flow-weighted total nitrogen concentration has varied between 8 and nearly 12 $mg\ell^{-1}$. In the surface waters of the dam the mean annual total phosphorus concentration peaked at about 0.7 $mg\ell^{-1}$ in 1983 and 1984, whereafter it hardly changed until 1988 when it dropped to 0.2 $mg\ell^{-1}$ in 1988 and to 0.14 $mg\ell^{-1}$ in 1989 and 1990. The total nitrogen concentration in the surface waters of the dam built up to a peak of over 5 $mg\ell^{-1}$ in 1986, but has subsequently declined to about half this concentration. The ratio between total nitrogen and total phosphorus in the surface waters has risen from below 5 from 1980 to 1985, to about 10 between 1986 and 1988, to 17 in 1989 and to 21 in 1990.

The phytoplankton species composition during the summer months was dominated between 1982 and 1988 by *Microcystis*, which virtually disappeared thereafter. It was largely replaced by Chlorophytes (green algae) and Cryptophytes (flagellated, motile unicellular algae) in the summers of 1988/89 and 1989/90 until the beginning of February. At this time there was a two month bloom of a very small celled blue-green alga, *Aphanothece*, which had previously been a rarity in the dam. This blue-green alga has never been recorded in the literature as a nuisance.

The abundance of the phytoplankton, measured as chlorophyll *a*, has shown only minor changes over the study period, given that on occasion during the times of *Microcystis* dominance scum concentrations of chlorophyll were measured. Over the past two years winter chlorophyll values have been lower and peak monthly concentrations have tended to be slightly lower.

There have been several long term trends in the abundance of the zooplankton species relative to one another. Over the study period the relative abundance of the Cyclopoid Copepoda has increased and the *Daphnia* and *Ceriodaphnia* have declined in abundance. Numbers of the other major species have fluctuated and no systematic long term trends were evident.

The only possibly meaningful change seen in the zooplankton biomass over the study period occurred during the last two months of the study, April and May 1990. In these months the highest ever biomass for this time of the year occurred.

Possible causes of the disappearance of *Microcystis* were then considered. There was no evidence that a change in the water temperature or in the stability of the water column brought about the disappearance of the species.

The disappearance was associated with the greatly altered total nitrogen to total phosphorus ratio which has occurred in the last two years. This is consistent with observations on the occurrence of *Microcystis* and total nitrogen to total phosphorus ratios made in the northern hemisphere. The lack of a decline in the chlorophyll *a* concentrations with the decline in the total phosphate concentration is also consistent with overseas work. This showed that the chlorophyll *a* yield per unit total phosphorus increases as the ratio rises.

Factors contributing to the sharp decline in the mean total phosphorus in the surface waters of Hartbeespoort Dam in 1989 and 1990 were considered from an analysis of the mass balance of total phosphorus in the dam. The major cause of the low phosphorus concentration was that the dam filled up. This resulted in a very much larger percentage of the incoming phosphorus load being sedimented, despite the fact that the actual sedimentation rate per unit area was lower. The lower flow-weighted mean annual phosphorus concentrations in the inflowing Crocodile River in recent years further contributed to the decline. Comparing the phosphorus sedimentation rate with the mean total phosphorus concentration in the dam revealed a close association between the concentration and the rate. This confirmed the conclusion reached in earlier laboratory studies that the adsorption rate of phosphorus by the sediments is governed by the ambient dissolved phosphorus concentration.

There was no evidence that changes in the zooplankton population composition or size was responsible for the change in the phytoplankton species composition.

It is recommended from the results of this study that the phytoplankton of Hartbeespoort Dam should be managed by maintaining the total nitrogen to total phosphorus ratio at least at its present levels. It is pointed out that there is an uncertainty about the validity of this recommendation, should conditions of high total phosphorus concentration arise. This is because the impact of the absolute total phosphorus concentration on the critical level of the total nitrogen to total phosphorus ratio is unknown. Should the total phosphorus concentration tend to rise relative to the total nitrogen concentration, more nitrogen could be made available by relaxing the nitrogen standards for effluents or by destratifying the dam. A previous study had shown that large amounts of nitrogen are lost from the dam by denitrification under anoxic conditions. Destratification could prevent the loss of most of this nitrogen.

The application of the special effluent phosphate standard should not be relaxed in the Hartbeespoort Dam catchment, since a further drop in the phosphorus load on the dam would only improve its algological quality.

It is recommended that the nutrients and phytoplankton in Hartbeespoort Dam should continue to be monitored, but that the frequency of monitoring might be lowered in the future.

LIST OF FIGURES

LIST OF TABLES

GLOSSARY

Epilimnion	The upper, well-oxygenated, warmer portion of the water column in a lake or reservoir during the stratified summer period.
Epilimnetic	Pertaining to the epilimnion.
Euphotic	With sufficient light for active photosynthesis.
Hypolimnion	The lower, colder, portion of the water column in a lake or reservoir, often lacking oxygen. Normally only present during summer stratification when the water becomes stagnant.
Hypolimnetic	Pertaining to the hypolimnion.
Isotherm	Line on a depth/time graph connecting depths of equal temperature.

ACKNOWLEDGEMENTS

This report would have been impossible to write without data provided by several Directorates of the Department of Water Affairs & Forestry - Pollution Control, Hydrology and the Hydrological Research Institute. In addition the Hydrological Research Institute contributed through the analysis of water samples and the addition of new data to the Hartbeespoort Dam data base. We would like to record our sincere thanks to the Department of Water Affairs & Forestry for its help, so willingly given, in these matters.

Dr W V Pitman of Stewart, Sviridov & Oliver provided estimates of the quantities of treated effluent released in the catchment of Hartbeespoort Dam.

Former members of the NIWR/WATERTEK (CSIR) listed in NIWR (1985) established the research routines and methods used in this study. The field work and laboratory analysis of samples during the period covered by this report was carried out by Cangela Bester, Peter Macmillan, Susan Combrinck, Dana Wessels, Colleen Todd and Isabeau van Vuuren. We thank them for their cheerful persistence in tasks that were often repetitive and routine.

Our thanks are also due to the Department of Water Affairs & Forestry, the Water Research Commission, the Director of the Division of Water Technology and the Water Quality Information Systems Programme Manager for their financial and scientific inputs and for creating the opportunity to make this study.

1. INTRODUCTION

Over the past decade Hartbeespoort Dam has been the focal point of much limnological research (NIWR 1985, Chutter 1989). It is a highly eutrophic reservoir, noteworthy, at least in years gone by, for the abundance of its phytoplankton, the dominance of *Microcystis* in the phytoplankton community and the size and persistence of *Microcystis* scums. The notoriety of Hartbeespoort Dam stems ultimately back to the fact that it receives all the natural run-off and effluent streams from the urbanised and industrialised northern slopes of the Witwatersrand.

The water quality objectives of the Department of Water Affairs & Forestry include reduction of the nuisance due to phytoplankton in dams, such as Hartbeespoort which is used as a drinking water supply. To this end a special effluent phosphate-P standard of 1 $mg\ell^{-1}$ was introduced in the catchment of Hartbeespoort Dam (and in other sensitive catchments) in 1985. A subsequent study (Rossouw & Grobler 1988), revealed that, while achievement of the effluent phosphate standard would result in a decline in the availability of this nutrient to algae in Hartbeespoort Dam, the standard alone would not be sufficient to reduce the phytoplankton abundance to desirable levels.

The Department of Water Affairs & Forestry therefore considered the feasibility of managing the abundance of *Microcystis*, in particular, through the destratification of Hartbeespoort Dam. However, biological events within the dam changed direction and resulted in the summer of 1988/89 in a phytoplankton population almost devoid of *Microcystis* (Chutter 1989). Management of the phytoplankton by means of destratification was obviously unnecessary, at least for the present. At the same time two things became apparent. Firstly, had destratification commenced at the beginning of summer 1988/89 it would possibly have been recorded as a good management action, when in fact the problem species, *Microcystis*, vanished for reasons other than destratification. Secondly, further surveillance of the dam might allow the identification of the unrecognised changes which brought about the disappearance of *Microcystis*. In the future these might be simulated to control the abundance of the species.

The Water Research Commission therefore sponsored the study which is reported here. The aim of this study was to keep the physical, chemical and biological conditions in the dam under surveillance for a further year and then to examine the complete limnological record for the period 1980 to 1990 for changes which might explain the disappearance of *Microcystis*. In particular, hypotheses that the change was due to lower water temperatures leading to a lower stability in the water column; or to a decline in phosphate concentrations, due either to dilution with the filling of the dam after the prolonged and severe drought of the middle 1980's; or to a change in the rate of phosphorus loss to the sediments, needed to be tested. There was also considerable speculation that after one year of absence, *Microcystis* might return in abundance.

In the sections of the report which follow, the dam and field and laboratory methods are first described. The results are presented in two parts, the first of which consists of summarised records of the physical, chemical and plankton limnology for the past ten years. In the second part of the results, the summarised data are synthesised to yield information on the phosphorus dynamics within the dam and to consider mechanisms which may have led to the disappearance of *Microcystis*. The report is completed with a discussion of the findings, followed by conclusions and recommendations.

2. GENERAL DESCRIPTION OF HARTBEESPOORT DAM

A very full description of Hartbeespoort Dam is given in NIWR (1985). The purpose of this brief description of the dam is to provide sufficient background information for appreciation of the report.

Hartbeespoort Dam was completed in 1925. It lies at the downstream end of a gorge where the Crocodile River cuts through the Magaliesberg Mountains (Figure 1). It was originally intended to be used solely for the provision of irrigation water, but with the passage of time and the growth in the population, it is now also used as a source of drinking water and for recreation.

Two perennial rivers, the Crocodile and the Magalies, drain into Hartbeespoort Dam. Urbanisation of the catchment is extensive (Figure 2), but all lies in the catchment of the Crocodile River. Agricultural development in the Magalies catchment is moderately intense. The Crocodile River is the principle source of water. Its natural flow is supplemented by a treated sewage flow which has increased steadily over the study period (Table 1).

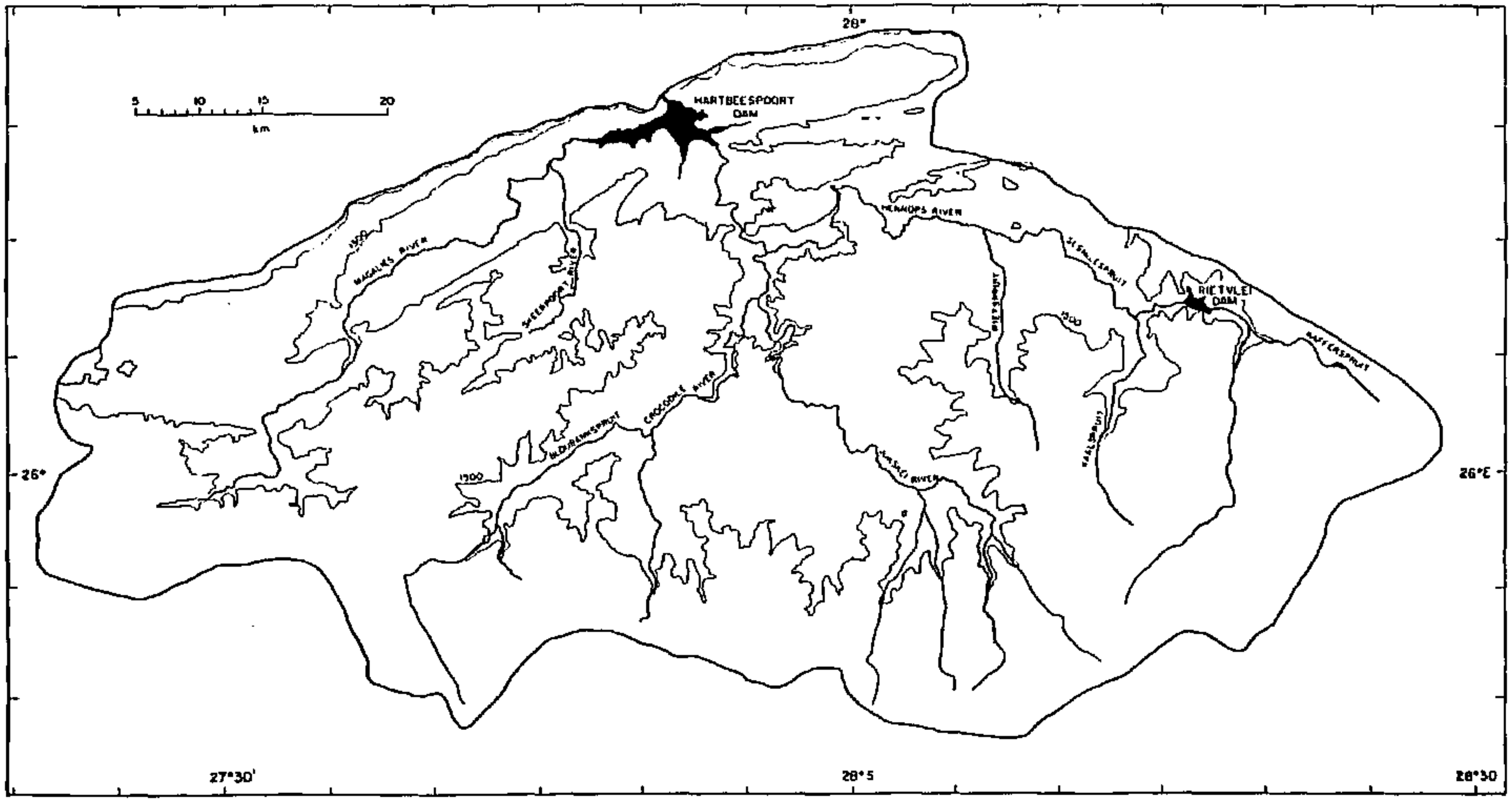

Figure 1. Hartbeespoort Dam and its catchment. Rivers, dams and topography.

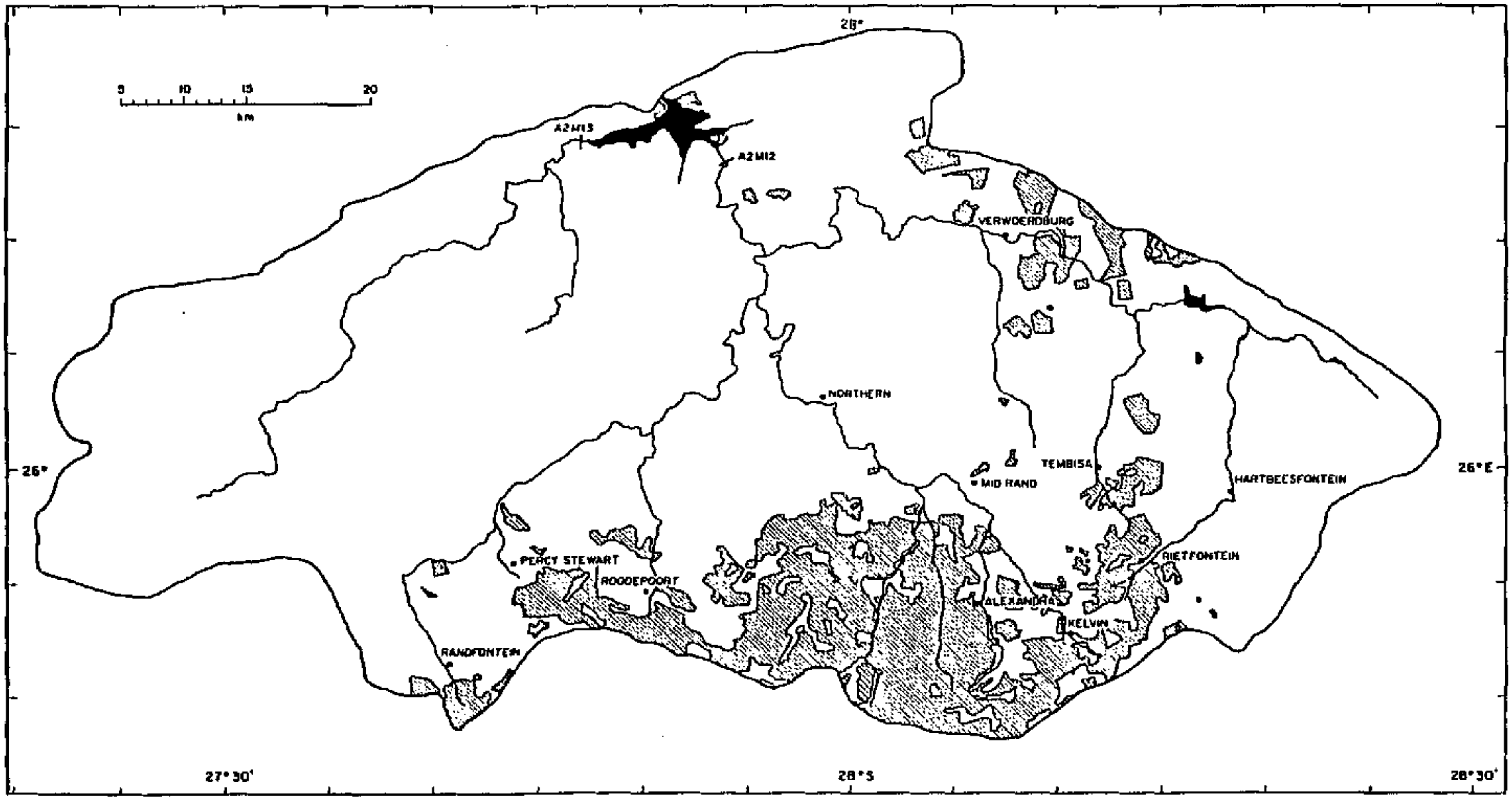

Figure 2. Hartbeespoort Dam and its catchment. Urban areas and the position of flow gauging weirs A2M12 and A2M13.

Table 1. Hartbeespoort Dam. Morphological and hydrological characteristics, from Chutter 1989, from Middleton *et al* 1981 (MAR) and from W V Pitman (pers. comm. - volumes of treated effluent in inflows).

Full supply:	Volume	195	x $10^6 m^3$
	Level	1162	m above mean sea level
	Maximum depth	32,5	m
	Mean depth	9,6	m
	Surface area	20	km^2
	Maximum breadth	12	km
	Length	5,6	km
Catchment area:		4144	km^2
Inflows:	Precipitation	9,5	x $10^6 m^3$
	Virgin MAR	154	x $10^6 m^3$
Vol. treated effluent discharged in catchment:	1981/82	69	x $10^6 m^3$
	1983/84	68	x $10^6 m^3$
	1985/86	80	x $10^6 m^3$
	1987/88	94	x $10^6 m^3$
	1989/90	105	x $10^6 m^3$

The dimensions and hydrological properties of the dam and its catchment are given in Table 1, while the surface area and volume of the dam are given in relation to depth in Table 2. The bathymetry of the basin in which the dam lies and the location of the sampling point in the main basin of the dam are shown in Figure 3. Other sampling points were located on the Magalies and Crocodile Rivers at the flow gauging weirs nearest to the Dam (A2M13 and A2M12, Figure 2), the spillway of the dam and the irrigation canal outlets.

Table 2. Hartbeespoort Dam. Depth, surface area and volume data (from tables provided by the Department of Water Affairs, 1980).

Depth		Surface Area		Volume	
m	%	ha	%	$10^6 m^3$	%
13*	40,0	245,5	7,2	10,740	5,5
14	43,1	295,7	14,5	13,450	6,9
15	46,2	334,1	16,4	16,605	8,5
16	49,2	390,0	19,2	20,208	10,4
17	52,3	444,9	21,9	24,385	12,5
18	55,4	516,6	25,4	29,176	15,2
19	58,5	591,7	29,1	34,721	17,8
20	61,5	665,3	32,7	41,007	21,1
21	64,6	736,6	36,2	48,021	24,7
22	67,7	792,6	39,0	55,679	28,6
23	70,8	851,2	41,8	63,889	32,8
24	73,9	918,9	45,2	72,725	37,3
25	76,9	1028,9	50,6	82,428	42,3
26	80,0	1149,4	56,5	93,323	47,9
27	83,1	1271,9	62,5	105,427	54,1
28	86,2	1393,3	68,5	118,757	61,0
29	89,2	1508,1	74,1	133,266	68,4
30	92,3	1633,2	80,3	148,954	76,5
31	94,5	1793,4	88,2	166,060	85,3
32	98,5	1957,1	96,2	184,823	94,9
32,5	100,0	2034,4	100,0	194,803	100,0

* The data provided does not include the dead storage (12,38 m) which is included in the volumes given above.

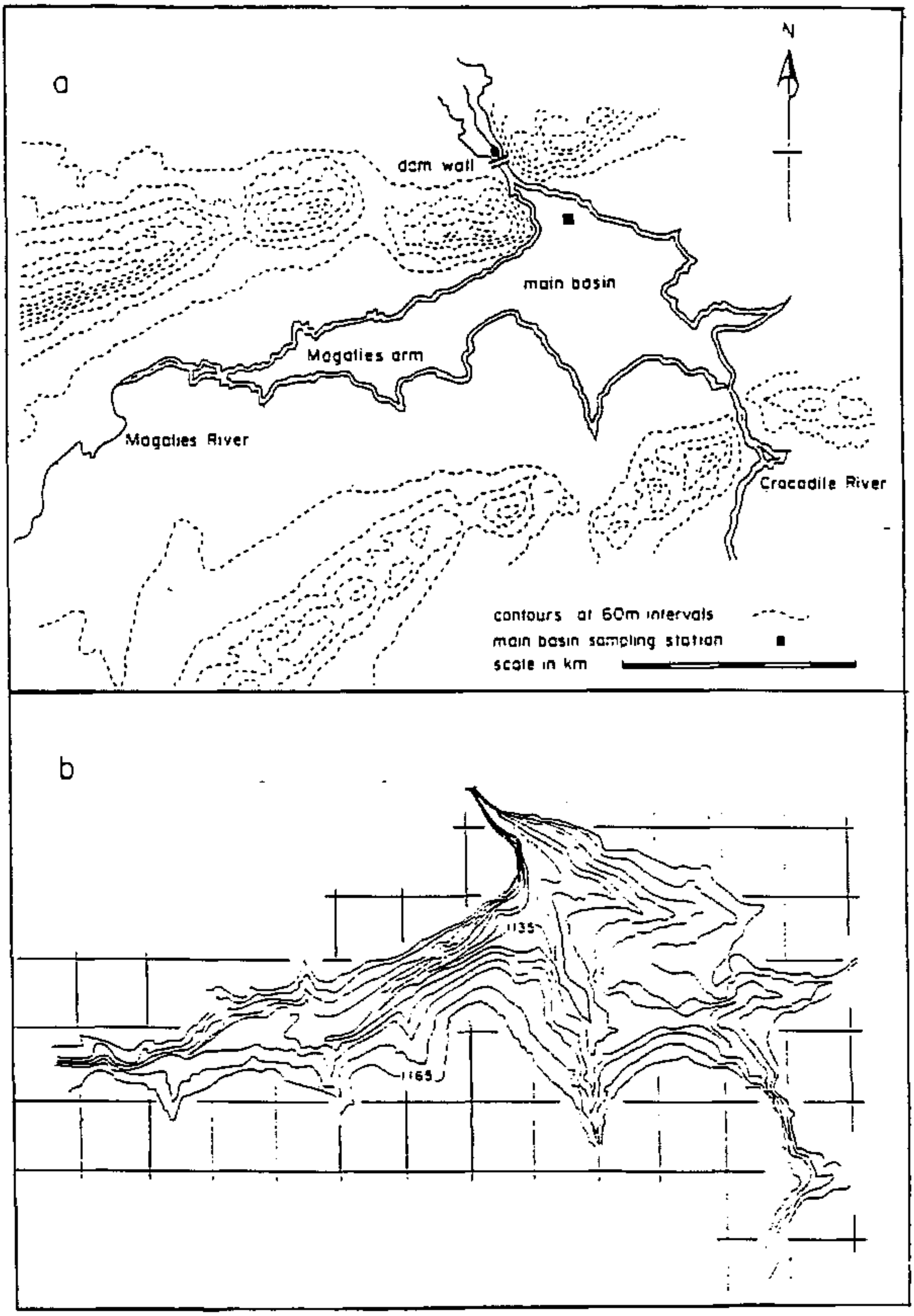

Figure 3. *Hartbeespoort Dam. a. Locality of sampling point. b. Bathymetry (contour lines at 5 m intervals, grid 1 km x 1 km).*

3. METHODS

Most field and laboratory methods used in this study have been described in NIWR (1985). However, chemical analysis of water samples from the inflows and outflows was transferred from the Division of Water Technology (WATERTEK) to the Hydrological Research Institute (HRI) in April 1988 and of water samples from the dam in May 1989. During the time that WATERTEK was responsible for the analysis of the water samples from the dam, pH and alkalinity were measured in the field. The HRI, which conducts a nation-wide water quality monitoring programme, analyses pH and alkalinity in the laboratory, some days after the samples have been collected. This means that the pH and alkalinity results from the two laboratories are not comparable. This is unfortunate for the change-over in responsibility for water analysis coincided with a major change in the composition of the phytoplankton (see below).

It also became clear that there were meaningful differences between the analytical results reported by the two laboratories regarding Orthophosphate, Total Phosphate and Kjeldahl Nitrogen. The causes of the differences between the values reported by the two analytical laboratories were investigated (Kempster *et al*, 1990).

Orthophosphate values differed because WATERTEK field staff filtered dam water samples through glass fibre filters instead of 0,45μ filters, used by the HRI, following AHPA (1989). The reason why WATERTEK used non-standard filters relates back to the very earliest days of research on Hartbeespoort Dam, when the abundance of *Microcystis* prevented the effective filtering of water through 0,45μ filters. Comparisons were made of analytical values arising from 0,45μ and glass fibre filters and it was found that, due to the clogging of the glass fibre filters by *Microcystis*, the glass fibre filters effectively acted as 0,45μ filters. This fact was over-looked some 8 years later when *Microcystis* disappeared from the dam and the practice of using glass fibre filters continued.

In the case of Total Phosphates no really satisfactory explanation for the differences in the results reported by the two laboratories was arrived at. It was concluded that 'At high Total Phosphate values there is reasonable agreement between the two groups'.

Kjeldahl Nitrogen analytical values differed because WATERTEK digested the samples to be analysed for a very much shorter period than did HRI. This reflects a problem typical of the role of the differing perceptions of field ecologists and analytical chemists. Field ecologists want a Kjeldahl

Nitrogen determination which will reflect what they conceive to be the organic nitrogen which is amenable to reasonably rapid microbial mobilisation, whereas an analytical chemist wants a precise determination of the total amount of organically bound nitrogen.

WATERTEK collected the water samples from Hartbeespoort Dam that were used in the 'First round comparison' reported in Tables 1 to 3 of Kempster *et al* (1990). The samples were drawn from successively greater depths at the sampling point on the dam and numbered from 1 to 15. A hidden control was inserted in the series in that the sample number 15 was drawn at the second depth from the surface, that is at 2,5 m. As expected the values of the determinands reported by both analytical laboratories increased with depth, with the striking exception of the value for Kjeldahl Nitrogen in sample 15 reported by the WATERTEK analytical laboratory. Following normal practice in WATERTEK, this analytical value would have been identified as being an outlier and the sample would have returned for re-analysis. In this case the analytical value was not confirmed. In the regression analysis of the paired analytical values presented below, Kjeldahl Nitrogen data from sample 15 has been omitted as an outlier.

Since the vast majority of Orthophosphate, Total Phosphate and Kjeldahl Nitrogen values in the Hartbeespoort Dam data base are due to the WATERTEK analytical laboratory, it was decided that where necessary, the HRI values should be adjusted to eliminate the inconsistency in the data. This was done by using the regression constants from regressions calculated between the sets of determinations, with the HRI values as the independent values. The regression formulae were:

PO_4-P	$Y = 1,3\ X + 68$;	$r^2 = 0,80$;	$n = 15$
TP	$Y = 1,1\ X + 21$;	$r^2 = 0,94$;	$n = 15$
Kjeldahl N	$Y = 1,1\ X - 990$;	$r^2 = 0,95$;	$n = 14$,

where X is the concentration measured by the HRI and Y the adjusted value, consistent with the WATERTEK values of the previous record.

Graphical plots of the paired concentration measurements from the two laboratories showed that there were straight line relationships for TP and Kjeldahl N. In the PO_4-P relationship there was a marked inflection, splitting it into two straight lines of differing slopes. Data points were insufficient to analyse the relationship further, but this finding does mean that adjusted PO_4-P values should be treated with great caution.

Missing values occurred in both the flow and concentration data used to calculate annual loads of nutrients into and out of the dam. Annual loads were calculated by summing monthly loads, which were calculated from daily values of both flow and concentration. Where there were missing values, the monthly loads were adjusted by dividing the preliminary load estimates by the number of days on which they were based and multiplying by the number of days in the month to which the data referred.

Annual nutrient loads into and out of the dam were calculated from the measured inflow and outflow volumes. As will be demonstrated later, there are short-comings in the hydrological data base, which resulted in a lack of agreement in measured and predicted dam volumes. The consequences of this lack of agreement between the measured and predicted dam volumes for the nutrient mass balances of the dam were investigated by examining two scenarios. In the first of these scenarios, it was assumed that the hydrological imbalance was due to incorrect measurement of the inflows and in the second, it was assumed that the imbalance was due to incorrect measurement of the outflows. The estimated nutrient loads were adjusted in direct proportion to the inflow and outflow volume adjustments required to bring the annual hydrology into balance.

4. RESULTS - SUMMARISED DATA

4.1 Hydrology of Hartbeespoort Dam

Summarised hydrological conditions in Hartbeespoort Dam are recorded in Table 3 where it may be seen that both the inflow volumes and the direct rainfall were low after 1980/81 through to 1986/87, due to the drought experienced during this period. From hydrological year 1982/83 through to hydrological year 1985/86 the year-end volume of the reservoir lay between 46 and 56 10^6m^3, that is about a quarter of the full supply volume (Table 2). 1981/82 and 1982/83 were years in which the volume of the dam declined considerably, while 1986/87 and 1987/88 were years in which the volume of the dam increased considerably.

The accuracy of the data recorded in Table 3 is reflected in the right hand column of the table. In the four hydrological years shown in which there was considerable change in the volume of the dam (1981/82, 1982/83, 1986/87 and 1987/88) there were considerable discrepancies between the measured year-end volumes and the year-end volumes arrived at from the sum of the previous year's year-end volumes plus annual inflows and direct rainfall and less annual evaporation and outflows

(Table 3). The agreement between measured and calculated year-end volumes was reasonable for the other years. The extent of the imbalances was up to 28% (1986/87) of the measured volume of the dam. They cannot therefore be ignored in calculating nutrient balances for the dam.

It is unlikely that the measured year-end dam volumes are incorrect through misreading, for dam volumes are measured at monthly intervals and the data records for dam volumes are internally consistent. There may well be errors in the hypsographic data for Hartbeespoort Dam, though the likelihood of these being large is remote. This is because the hydrological balances were reasonable for five of the nine years shown on Table 3. The measured direct rainfall and evaporation values are not large enough to account for the large hydrological imbalances. It is therefore concluded that the inaccuracies in the hydrological measurements most probably lie in the inflow volumes or in the outflow volumes.

Table 3. Hartbeespoort Dam. Hydrology from reservoir records provided by the Department of Water Affairs (1991).

Hydrological Year	Previous Year end Volume 10^6m^3 A	River Inflow Volume 10^6m^3 B	Direct Rainfall (gain) 10^6m^3 C	Direct Evaporation (loss) 10^6m^3 D	Outflow Volume 10^6m^3 E	Year end Volume Measured 10^6m^3 F	Year end Volume Calc.* 10^6m^3 G	Difference 10^6m^3 F - G
1980/81	168	222	32	26	219	174	177	- 3
1981/82	174	157	20	25	207	134	119	+15
1982/83	134	96	10	15	166	46	59	- 13
1983/84	46	117	8	14	99	56	58	- 2
1984/85	56	114	8	14	110	56	54	+ 2
1985/86	56	123	7	14	124	50	48	+ 2
1986/87	50	223	24	18	142	109	137	- 28
1987/88	109	180	19	24	145	161	139	+22
1988/89	161	170	26	26	167	172	164	+ 8

* $G = A + B + C - D - E$

New sets of inflow volumes and outflow volumes have therefore been calculated (Table 4). Each of these sets of volumes would alone bring the measured and calculated year-end volumes of the dam into balance. They will later be used to calculate alternative mass balances of nutrients (see below section 5.1).

Table 4. Hartbeespoort Dam. Measured annual total inflows and outflows, together with values calculated to bring the observed and estimated year-end volumes into agreement. Calculations from data in Table 3.

Hydrological Year	Measured Inflow Volume 10^6m^3	Corrected Inflow Volume 10^6m^3	Measured Outflow Volume 10^6m^3	Corrected Outflow Volume 10^6m^3
1980/81	222	219	219	222
1981/82	157	172	207	192
1982/83	96	83	166	179
1983/84	117	115	99	101
1984/85	114	116	110	108
1985/86	123	125	124	122
1986/87	223	195	142	170
1987/88	180	202	145	123
1988/89	170	178	167	159

The mean volumes, surface areas and depths of the dam for the study period (Table 5) also reflect the effects of the drought of the mid-1980's. During the drought period water was retained in the dam for about 0,6 of a year, whereas at other times the residence time was approximately one year. On the other hand, the hydraulic load, which depends on the discharge volume and the surface area of the dam, was greatest when the dam was being drawn down in 1982/83. The hydraulic load was lowest towards the end of the study period.

Table 5. Hartbeespoort Dam. Mean and derived hydrological properties for the study period, based on measured values shown in Table 3.

Hydrological Year	Mean Volume 10^6m^3	Mean Surface Area km^2	Mean Depth m	Water Residence Time y	Hydraulic Load m
1980/81	185	19,55	9,44	0,83	11,17
1981/82	169	18,22	9,28	1,08	11,36
1982/83	82	10,20	8,00	0,85	16,26
1983/84	69	8,92	7,79	0,59	11,84
1984/85	76	9,53	7,98	0,67	11,49
1985/86	74	9,26	7,94	0,60	13,39
1986/87	116	13,67	8,46	0,52	10,39
1987/88	174	18,65	9,33	0,97	7,75
1988/89	178	18,98	9,36	1,02	8,81

Water residence time and hydraulic loads calculated from the estimated inflows and outflows (Table 3) are shown in Table 6. They differ little from the values calculated from the measured inflows and outflows. It may be concluded that the inaccuracies in the hydrological data base do not materially effect the estimates of annual water residence time or of the hydraulic load.

Table 6. Hartbeespoort Dam. Annual water residence time and hydraulic loads following the calculated inflows and outflows shown in Table 4.

Hydrological Year	Water Residence Time y	Hydraulic Load m
1980/81	0,84	11,36
1981/82	0,98	10,54
1982/83	1,00	17,55
1983/84	0,60	11,32
1984/85	0,66	11,33
1985/86	0,59	13,17
1986/87	0,59	12,44
1987/88	0,86	6,60
1988/89	1,00	8,38

4.2 General Physical Conditions in Hartbeespoort Dam

The information contained in Figure 4 reveals the variation of the temperature and water column stability in the dam from year to year. Table 7 summarises the information contained in Figure 4. Surface temperature variation from year to year is readily read from the isotherms, but the assessment of water column stability reflected in Table 7 requires some elaboration. In comparing the annual isotherm diagrams, the behaviour of the 26°C isotherm was interpreted as follows. The penetration of this isotherm to considerable depths early in the summer (1980/81 and 1981/82) indicated strong wind mixing and therefore low water column stability. A shallow 26°C isotherm (1984/85) indicated little mixing and therefore high water column stability. A 26°C isotherm moving rapidly up and down indicated periods of strong mixing interspersed with calm periods, while periods of low mixing (high water column stability) were apparent from prolonged periods with a shallow layer of water warmer than 28°C (1986/87). On the other hand, the existence of a 28°C isotherm down to 2 m (1988/89) suggests a hot period with wind mixing.

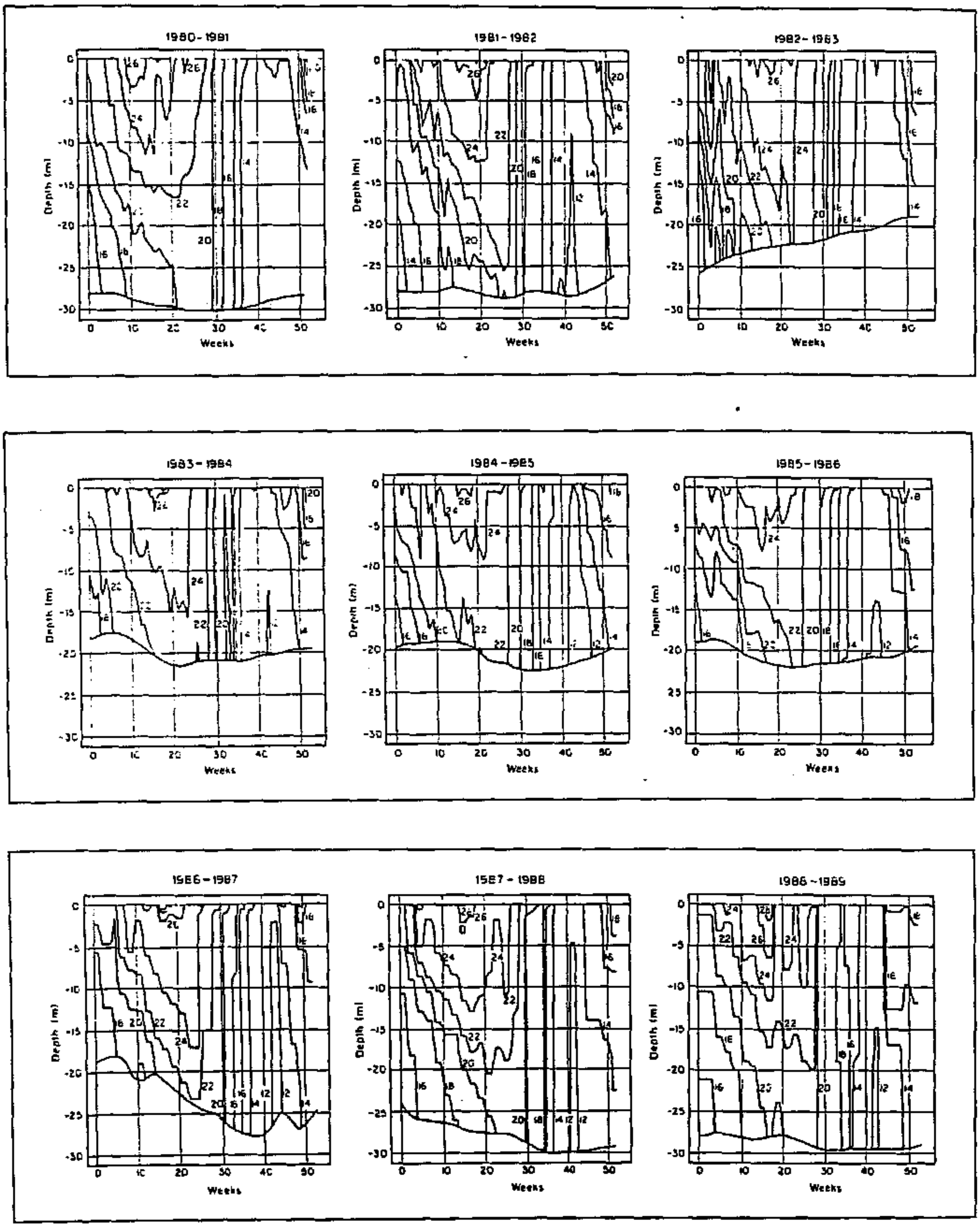

Figure 4. Hartbeespoort Dam. Isotherms for the hydrological years 1980/81 to 1988/89. Continued over.

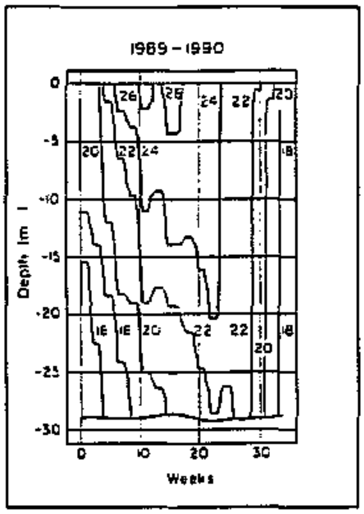

Figure 4 continued

Table 7 shows that 1984/85 and 1985/86 had cool summers of relatively low stability. In the period 1980/81 to 1988/89, these would have been years when the temperature and stability conditions would have been least favourable for *Microcystis* dominance of the phytoplankton, since this species prefers warm stable conditions allowing it to remain in the euphotic zone. In these two years *Microcystis* was as abundant (Table 7) as it was in 1983/84 and 1987/88, years which in terms of stability and temperature, would appear to have been very favourable for *Microcystis* growth and dominance.

A second way to consider the stability of the surface waters of the dam is to calculate the proportion of time that the density gradient of the surface waters exceeds certain values. This method was employed by Zohary and Robarts (1989), who set the density gradient values at 20 g m^{-4} and 100 g m^{-4} for their consideration of the environment of *Microcystis* in Hartbeespoort Dam. Table 8 shows the variation in density gradients in the surface waters of the dam for the period of the study, with the years in which there were no *Microcystis* blooms shaded. During the stratified period, which is the time of *Microcystis* growth, the occurrence of the two levels of density gradient was similar in the years with and without *Microcystis* blooms. The low frequency of occurrence (45%) of 100 g m^{-4} density gradients in 1989/90 is not significant, since it is based on only eleven observations of which five had density gradients > 100 g m^{-4}. Had there been six occurrences of density gradients > 100 g m^{-4} in the eleven occurrences, the percentage would have been 54 which is within the range of percentages recorded in other years.

Table 7. Hartbeespoort Dam. A summary of the year to year variation in the temperature and stability of the surface waters of the dam and of the abundance of *Microcystis* from information contained in Figures 4 and 5.

	Hydrological Year									
	1980-1981	1981-1982	1982-1983	1983-1984	1984-1985	1985-1986	1986-1987	1987-1988	1988-1989	1989-1990
Spring temp.*	Moderate	Cool	Warm	Cool	Moderate	Moderate	Cool	Warm	Moderate	Cool
Early Summer Temp.	Hot	Cool	Hot	Hot	Cool	Cool	Cool	Intermediate	Cool	Hot
Mid Summer Temp.	Cool	Hot	Hot	Hot	Cool	Cool	Hot	Hot	Hot	Hot
Winter Temp.	Warm	Moderate	Warm	Moderate	Cold	Moderate	Cold	Cold	Moderate	-
Early Summer Stability	High	Low	High	High	Low	Low	Low	High	High	Low
Mid Summer Stability	Low	High	Low	High	Low	Low	High	High	High	Low
Microcystis abundance	High	High	Very High	High	High	Very High	Very High	Very high	Very Low	Very Low

* October temperature. In October, Cool = 20°C < maximum temperature < 22°C
Warm = maximum temperature > 24°C

4.3 The mean inflow, outflow and surface water quality of Hartbeespoort Dam

Annual mean values for water quality determinands are shown in Table 9, where it may be seen that the conductivity and concentrations of all the major ions in the river inflows and in the dam were lower in 1988/89 and 1989/90 than they had been in the previous drought years. The same is true of the pH, but in this case the decline was due to the manner in which the pH was measured. Prior to hydrological year 1988-89, pH was measured in the field. In 1988-89 and 1989-90 pH was measured in the laboratory on water samples after a lapse of time sufficient for the effect of photosynthesis on pH to have been eliminated.

Table 8. Hartbeespoort Dam. The proportion (as a percentage) of the time during the stratified (str.) and the non-stratified (n-str.) periods that a shallow (<2m depth) diurnal mixed layer, identified by a density gradient ($d\rho/dz$) >20 g m^{-4} or >100 g m^{-4}, was recorded in the main basin of Hartbeespoort Dam.

Year	$d\rho/dz$ >20 g m^{-4} (%)		$d\rho/dz$ >100 g m^{-4} (%)	
	str.	n-str.	str.	n-str.
1982/83[1]	79[3]	75[3]	54[3]	30[3]
1983/84[1]	85[3]	56[3]	56[3]	12[3]
1984/85[1]	83[3]	68[3]	60[3]	36[3]
1985/86[1]	82	67[3]	72	43[3]
1986/87[2]	93	72	87	45
1987/88[2]	87	90	56	30
1988/89[2]	80	50	53	38
1989/90[2]	82	no data	45	no data

1. Temperatures measured at weekly intervals.
2. Temperatures measured at fortnightly intervals.
3. Data taken from Zohary & Robarts (1989).

Both original and corrected values of Kjeldahl nitrogen, total phosphate and orthophosphate phosphorus are shown in Table 9. Mean Kjeldahl nitrogen concentrations in the Crocodile River have fluctuated over the period covered by Table 9. Nitrate + Nitrite concentrations in the Crocodile River rose by about 20% between 1984/85 and 1985/86, remained at about the same levels over the next three years and then declined to their former levels in 1988/89 and 1989/90.

Mean total phosphorus concentrations in the Crocodile River have declined by less than 15% since 1985/86, though they were a lot higher in 1984/85. For orthophosphate in the Crocodile River the greatest decline in mean annual concentration took place between 1984/85 and 1985/86. Since then mean concentrations have fluctuated between only 1264 and 1013 $\mu g \ell^{-1}$.

Mean annual concentrations of nutrients in the Magalies River were variable, but are not considered in detail here, as the flow of the river and the nutrient concentrations are so low in relation to those of the Crocodile River (NIWR 1985), that the Magalies River contributes little (<5%) to the nutrient content of the dam.

Table 9. Summarised water quality data for Hartbeespoort Dam, the inflowing Crocodile and Magalies Rivers and the water flowing out of the dam. The Hartbeespoort Dam data from integrated (hose-pipe) sampling from surface to 4 m below the surface.

Property and Units	Hydro-logical Year	Crocodile A2M12		Magalies A2M13		Hartbeespoort Dam			
						Raft		Outflow	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
pH	1980-81	7,5	0,3	7,7	0,4	8,5	0,6		
	1981-82	7,8	0,3	8,5	0,0	8,9	0,6		
	1982-83	7,7	0,4	8,2	0,3	9,2	0,3		
	1983-84			8,1	0,2				
	1984-85	7,5	0,3	8,1	0,1	9,1	0,4	8,0	0,4
	1985-86	7,3	0,3	8,1	0,2	9,2	0,4	7,5	0,3
	1986-87	7,1	0,2	8,0	0,2	9,0	0,5	7,8	0,3
	1987-88	7,4	0,3	7,9	0,3	9,3	0,5	7,6	0,3
	1988-89	7,7	0,5	8,1	0,3	7,9	0,6	8,1	0,4
	1989-90	7,9	0,4	8,2	0,4	8,1	0,3	8,0	0,2
Conductivity mSm^{-1}	1980-81	74,8	14,6	35,4	4,9	55,4	2,5		
	1981-82	76,4	7,4	37,8	1,6	58,1	2,9	60,8	1,8
	1982-83	62,2	10,7	40,6	5,1	57,9	3,1	59,6	4,6
	1983-84	70,6	10,9	44,2	6,8	62,8	5,5	65,5	5,3
	1984-85	74,4	11,6	44,8	4,8	64,5	6,8	64,8	7,1
	1985-86	77,4	6,4	50,5	4,0	65,6	3,9	68,1	6,8
	1986-87	70,8	10,4	42,8	3,9	60,8	4,7	60,9	4,5
	1987-88	70,1	9,8	43,7	5,2	59,8	3,9	60,4	6,0
	1988-89	66,0	11,3	45,1	5,8	58,0	5,1	56,4	6,5
	1989-90	60,6	11,3	40,6	4,4	53,5	2,6	55,7	2,9
Sodium mgℓ^{-1}	1984-85	66	16	12	3	55	6	54	7
	1985-86	62	12	12	4	53	8	52	8
	1986-87	58	10	9	2	54	9	44	8
	1987-88	55	14	11	4	49	3	46	8
	1988-89	52	14	15	11	48	4	46	5
	1989-90	51	15	11	2	48	2	48	2
Potassium mgℓ^{-1}	1984-85	11	2	2	2	10	1	10	1
	1985-86	12	1	1	2	11	1	11	1
	1986-87	9	2	2	2	11	1	9	2
	1987-88	9	2	2	1	9	1	9	2
	1988-89	9	2	1	1	9	1	9	1
	1989-90	10	2	1	1	9	>1	9	>1
Calcium mgℓ^{-1}	1980-81	51	9	30	4	41	2		
	1981-82	56	4	33	2	42	3	46	2
	1982-83	47	6	39	5	47	2	48	4
	1983-84	54	13	42	9			50	10
	1984-85	50	6	39	5	45	4	44	5
	1985-86	54	6	43	5	49	6	48	7
	1986-87	50	10	39	6	46	3	45	5
	1987-88	50	10	37	5	45	4	42	2
	1988-89	48	8	37	5	40	3	40	4
	1989-90	44	7	35	5	32	3	36	3
Magnesium mgℓ^{-1}	1980-81	24	5	23	3	22	1		
	1981-82	26	2	26	3	23	1	23	1
	1982-83	20	3	27	4	21	2	22	2
	1983-84	21	3	28	5			22	5
	1984-85	19	3	28	4	18	2	18	2
	1985-86	17	2	31	3	16	2	16	2
	1986-87	17	4	26	3	16	1	15	1
	1987-88	18	3	27	5	16	1	18	1
	1988-89	18	4	29	4	18	1	17	2
	1989-90	17	4	27	4	18	1	18	1

Table 9 (continued)

Property and Units	Hydro-logical Year	Crocodile A2M12		Magalies A2M13		Hartbeespoort Dam Raft		Hartbeespoort Dam Outflow	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Kjeldahl - N $\mu g \ell^{-1}$	1980-81					748	254		
	1981-82	1439	455	216	69	1073	599	817	310
	1982-83	826	407	246	213	949	314	1049	586
	1983-84	935	414	279	144	982	314	947	396
	1984-85	1449	746	167	137	890	135	1045	274
	1985-86	1633	768	288	80	954	253	1087	264
	1986-87	1040	321	290	143	816	148	1252	364
	1987-88	1363	854	443	278	532	139	1274	624
	1988-89	1920	1010	470	290	1084	334	1400	640
	1989-90	1970	940	550	480	1229	301	1490	720
	1988-89*	1122*		202*		202*		550*	
	1989-90*	1177*		362*		362*		649*	
Nitrite + Nitrate - N $\mu g \ell^{-1}$	1980-81	8090	3740	650	320	1037	578		
	1981-82	10635	1979	708	183	1205	483	1810	543
	1982-83	7542	2208	837	1126	1163	698	1081	1366
	1983-84	8021	3263	707	567	1773	882	1891	765
	1984-85	9071	2972	516	247	1381	641	1519	637
	1985-86	11285	2038	184	113	3509	513	3690	630
	1986-87	11441	3361	945	700	3467	1401	3752	1173
	1987-88	11661	4342	795	332	2037	801	2556	1494
	1988-89	9340	3080	780	960	1739	629	2000	710
	1989-90	8540	2390	730	250	1333	525	1440	1080
Silica $mg \ell^{-1}$	1980-81	7	1	10	1	5	<1		
	1981-82	5	1	11	1	5	1	5	<1
	1982-83	6	1	15	19	5	<1	5	1
	1983-84	6	2	12	2	4	1	4	1
	1984-85	6	1	13	1	4	1	4	1
	1985-86	9	5	18	6	7	4	7	5
	1986-87	7	1	12	2	5	1	6	1
	1987-88								
	1988-89	6	1	11	1	2	1	2	1
	1989-90	6	1	9	1	1	1	2	1
Sulphate $mg \ell^{-1}$	1984-85	123	25	19	4	108	16	105	16
	1985-86	110	30	17	5	109	14	106	17
	1986-87	110	18	18	3	98	14	95	13
	1987-88	104	22	16	6	92	6	81	15
	1988-89	92	22	17	12	87	9	82	8
	1989-90	90	22	14	4	85	4	82	5
Total P $\mu g \ell^{-1}$	1980-81					443	76		
	1981-82	2856	512	119	50	593	277	630	195
	1982-83	2155	732	237	329	711	213	792	440
	1983-84	2375	932	234	250	831	528	801	150
	1984-85	2117	607	166	30	624	93	612	164
	1985-86	1659	440	161	39	369	93	478	77
	1986-87	1508	439	199	101	364	41	510	141
	1987-88	1550	676	57	78	236	74	414	178
	1988-89	1239	640	109	355	98	65	233	266
	1989-90	1302	537	85	153	106	44	274	377
	1988-89*	1383*		141*		129*		277*	
	1989-90*	1453*		114*		138*		322*	

Table 9 (continued)

Property and Units	Hydro-logical Year	Crocodile A2M12		Magalies A2M13		Hartbeespoort Dam			
						Raft		Outflow	
		Mean	SD	Mean	SD	Mean	SD	Mean	SD
Orthophosphate - P $\mu g\ell^{-1}$	1980-81	1690	480	20	20	304	63		
	1981-82	2621	479	38	27	373	74	552	157
	1982-83	1873	665	163	281	442	175	646	366
	1983-84	2073	795	123	238	501	147	676	130
	1984-85	1831	647	48	19	476	101	495	167
	1985-86	1264	395	38	11	303	51	345	118
	1986-87	1164	350	59	51	291	54	387	97
	1987-88	1195	557	16	12	134	77	377	284
	1988-89	727	548	57	268	11	6	88	165
	1989-90	788	466	32	71	13	11	72	237
	1988-89*	1013*		142*		82*		184*	
	1989-90*	1092*		110*		85*		162*	
Chloride $mg\ell^{-1}$	1980-81	59	14	8	2	42	3		
	1981-82	69	7	6	1	44	4	41	3
	1982-83	66	15	11	10	64	2	52	10
	1983-84	76	16	13	8			57	8
	1984-85	64	16	10	2	50	6	54	4
	1985-86	66	15	13	6	50	6	54	6
	1986-87	51	13	9	1	51	7	48	7
	1987-88	60	12	12	2	52	4	48	8
	1988-89	54	13	15	15	52	5	49	5
	1989-90	55	15	11	3	50	2	52	3
Alkalinity mg $CaCO_3\ell^{-1}$	1980-81	95	16	152	21	142	7		
	1981-82	83	18	193	12	141	64		
	1982-83	116	9	203	25	159	12		
	1983-84			206	32	182	19		
	1984-85	108	16	209	23	137	9	131	14
	1985-86	82	21	216	24	109	13	103	16
	1986-87	77	16	184	28	107	8	104	11
	1987-88	91	22	181	28	126	13	116	21
	1988-89	114	24	197	27	108	6	119	10
	1989-90	104	19	190	27	108	6	119	9

*Values adjusted to expected had the samples been analysed in the WATERTEK analytical laboratory (see Methods)

The integrated 0 - 4 m nutrient concentrations in the dam shown in Table 9 are presented for readers who might at some time wish to consider data arrived at in this way. Variation in the nutrient concentrations in the dam will be described from Table 10.

During the eleven year period covered by Table 10, nitrogen and phosphorus concentrations reached their highest values in the middle 1980's and have declined since then. Total nitrogen rose from about 2 $mg\ell^{-1}$ (1980) to 5 $mg\ell^{-1}$ in 1986 and 1987 and has since fallen to under 3 $mg\ell^{-1}$. Total phosphorus concentration peaked at 738 $\mu g\ell^{-1}$ in 1984, having risen from 405 $\mu g\ell^{-1}$ in 1980. Thereafter it declined slowly until 1987 and then by more than half to 1988. There was another sharp concentration drop from 1988 to 1989, resulting in the low mean concentration of 140 $\mu g\ell^{-1}$ which has not changed significantly in 1990.

Table 10. Hartbeespoort Dam. Mean annual (calendar year) nutrient concentrations and nutrient ratios based on mean concentrations from discrete samples drawn at weekly or fortnightly intervals at 0; 0,5; 1; 2; 3; 4; and 5 m below the water surface. Values shown in parenthesis are mean values determined partly from WATERTEK analyses and partly from HRI analyses (1989) or entirely from HRI analyses (1990). Adjusted values for these years are listed without brackets.

Year	Kjeldahl nitrogen ** $\mu g \ell^{-1}$	Nitrate + nitrite $\mu g \ell^{-1}$	Total nitrogen ** $\mu g \ell^{-1}$	Total phos-phorus** $\mu g \ell^{-1}$	Ortho-phos-phate $\mu g \ell^{-1}$	TN:TP * ratio
1980	850	1135	1984	456	311	4,3
1981	731	1133	1864	431	303	4,3
1982	1056	1004	2060	586	401	3,5
1983	979	1429	2408	693	455	3,5
1984	783	1689	2471	738	534	3,4
1985	1170	1958	3128	606	402	5,2
1986	1130	4015	5145	466	307	11,0
1987	1425	3393	4817	582	232	8,3
1988	706	1812	2487	235	125	10,6
1989	799	1638	2437	140	69	17,4
	(1213)		(2850)	(124)	(35)	(22,9)
1990	321	2434	2755	134	92	20,6
	(1192)		(3626)	(97)	(19)	(35,2)

* Total nitrogen : Total phosphorus

** Value for unfiltered water sample

Total nitrogen to total phosphorus ratios were lowest in 1984 but thereafter rose sharply between 1985 and 1986 and again from 1988 to 1989. The change in ratio between 1980 and 1990 has been approximately five-fold, from 4,3 in 1980 to 20,6 in 1990. Other ratios such as those between total nitrogen and orthophosphate and between nitrite plus nitrate and orthophosphate. have followed the same trend over time.

As would be expected from the factors used to convert HRI analytical values to WATERTEK values (see above - Methods), HRI total phosphorus and orthophosphate values were lower than their equivalent WATERTEK values, while HRI Kjeldahl nitrogen values were higher than WATERTEK values. Despite these differences, the general trends of change reflected in the two data sets were similar, though the combination of differences in TN:TP ratios resulted in very high ratios for the last two years recorded in Table 10.

4.4 Species composition and abundance of the phytoplankton

The composition (by biomass) of the phytoplankton of Hartbeespoort Dam from January 1983 through to May 1990 is shown in Figure 5. The most noteworthy feature in Figure 5 is the virtual disappearance of *Microcystis* after August 1988. The other blue-green algae, which dominated the phytoplankton population from January to April 1990, were predominately *Aphanothece*. In May 1990 the *Aphanothece* population crashed to less than 1 percent of the total phytoplankton. *Aphanothece* is a minute species (cell diameter about 1 μ) which is frequently mistaken for bacteria in phytoplankton analyses (W E Scott, personal communication). Consequently, little is known about the ecology and environmental requirements of this species. It would appear that it is not a bloom or scum-forming species.

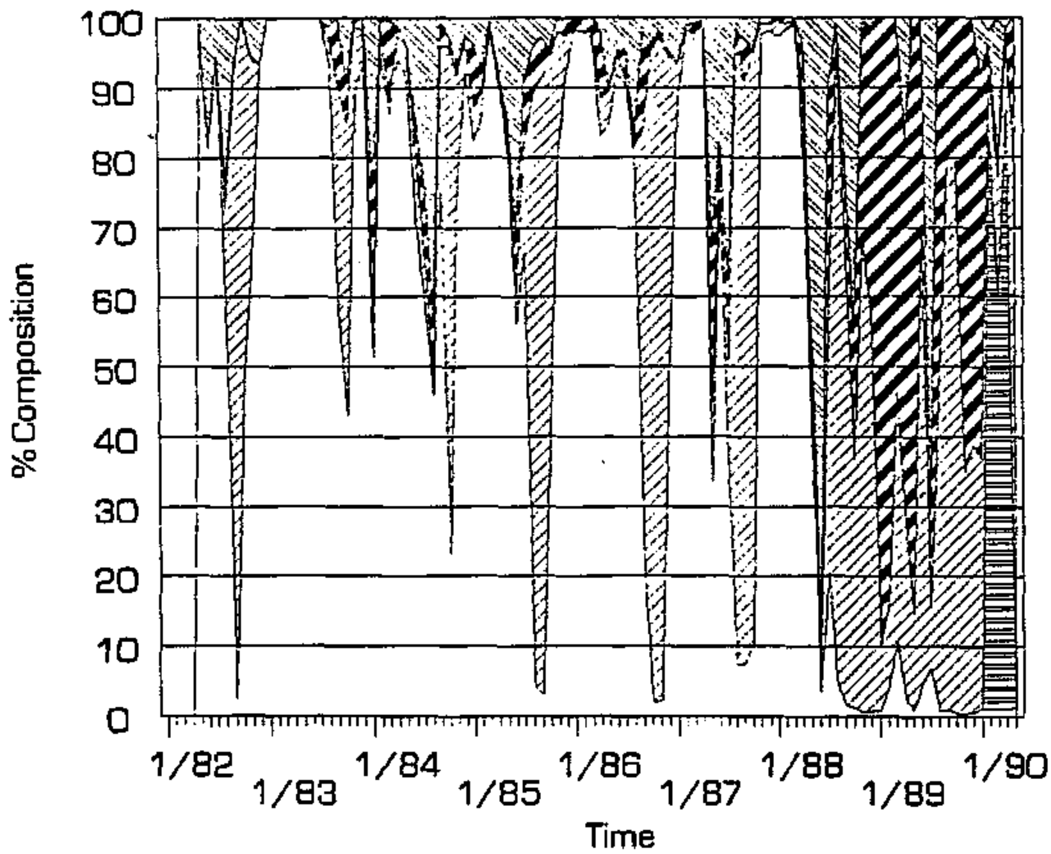

Figure 5. *Hartbeespoort Dam. The composition of the phytoplankton. January 1983 to May 1990.* Total Green Algae ; Other Blue-green Algae ; Microcystis ; Chrysophyta ; Cryptophyta .

It is evident from Figure 5 that the duration of the *Microcystis* domination of the phytoplankton was lower in 1987 and 1988 than it had been in previous years. The major disappearance of *Microcystis* was due to the dam being full in April and May 1988, to the accumulation of very large *Microcystis* scums at the sluice gates of the dam and to the repeated deliberate flushing of the scums out of the dam until there was insufficient *Microcystis* remaining to form further scums. The disappearance of *Microcystis* may therefore be accounted for. Its failure to return is the reason for this study.

Among the major groups of phytoplankton other than the blue-green algae, the groups which immediately replaced *Microcystis* were the Chlorophyta or green algae and the flagellated unicellular algae or Cryptophyta. The relative abundance of the Chrysophyta, which includes the diatoms, hardly changed when *Microcystis* disappeared.

Variation in the abundance of the phytoplankton, measured as the chlorophyll *a* concentration, is shown in Figures 6 (euphotic zone chlorophyll) and 7 (integrated 0 to 4 m chlorophyll). Both figures

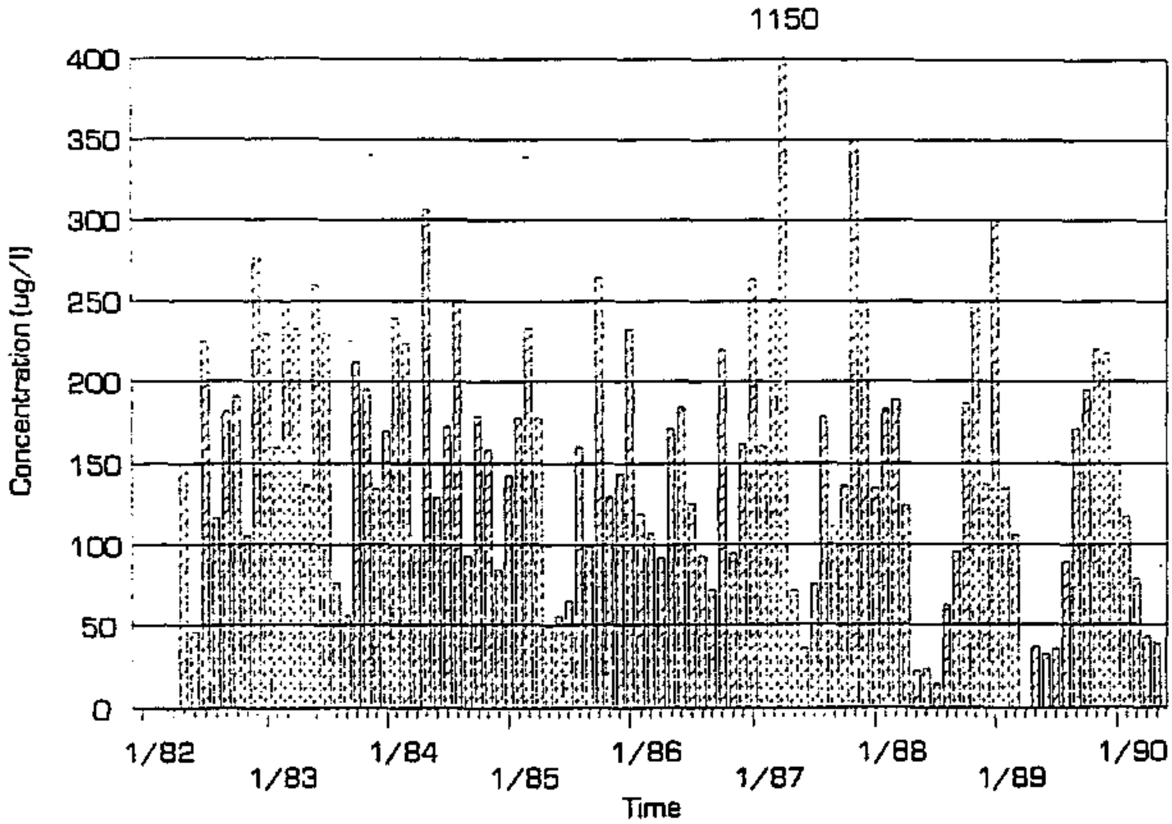

Figure 6. *Hartbeespoort Dam. Monthly mean euphotic zone chlorophyll* a *concentrations. June 1982 to May 1990. In April 1987 a scum at the sampling point resulted in an outlying value of 1150 μg ℓ⁻¹, which is off the scale of this bar-chart.*

reflect similar patterns of change both seasonally (low winter abundance) and from year to year. The euphotic zone chlorophyll values, in particular, show that the abundance of phytoplankton is now a little lower than it was prior to 1988. Summer values above 200$\mu g \ell^{-1}$ have become less frequent and winter values are lower than they were from 1983 to 1987. In 1984, 1985 and 1986 the chlorophyll concentration never fell below 50$\mu \ell^{-1}$, in 1987 there was one month in which it did so, in 1988 three months and in 1989 probably 4 months (there is a missing value which was probably $< 50\ \mu g \ell^{-1}$).

Since most phytoplankton live in the euphotic zone and the euphotic zone seldom extends down as far as 4 m in Hartbeespoort Dam, the 0 to 4 m chlorophyll *a* concentrations were considerably lower than euphotic zone concentrations (see Figures 6 and 7). 0 to 4 m chlorophyll *a* is frequently reported and it is mainly for this reason that Figure 7 is presented here.

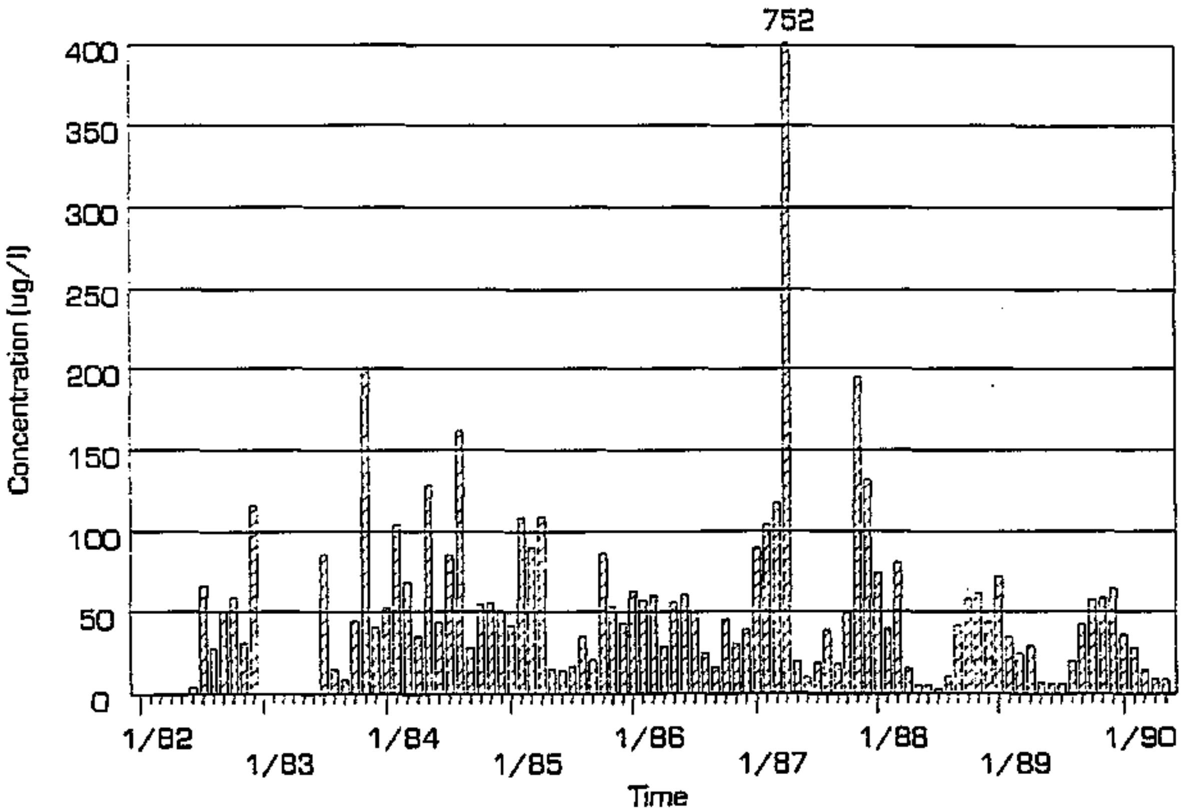

Figure 7. Hartbeespoort Dam. Monthly mean integrated (hose-pipe) surface (0 to 4 m) chlorophyll a *concentrations. June 1982 to May 1990.*

4.5 Species composition and abundance of the zooplankton

The monthly mean biomass of the zooplankton (Figure 8) reveals that in broad outline the zooplankton was most abundant in 1983, 1984 and 1987. There would appear, superficially, to be little difference between the periods before and after the disappearance of *Microcystis*. However, scrutiny of Figure 8 shows that the zooplankton biomass in April and May 1990 was higher than in any other previous April and May. Since there are always time lags between events as one moves up the food chain from the primary producers to the consumers, it may be that this difference represents the beginning of a longer term response of the zooplankton to changes which have been evident in the phytoplankton composition for the past two years.

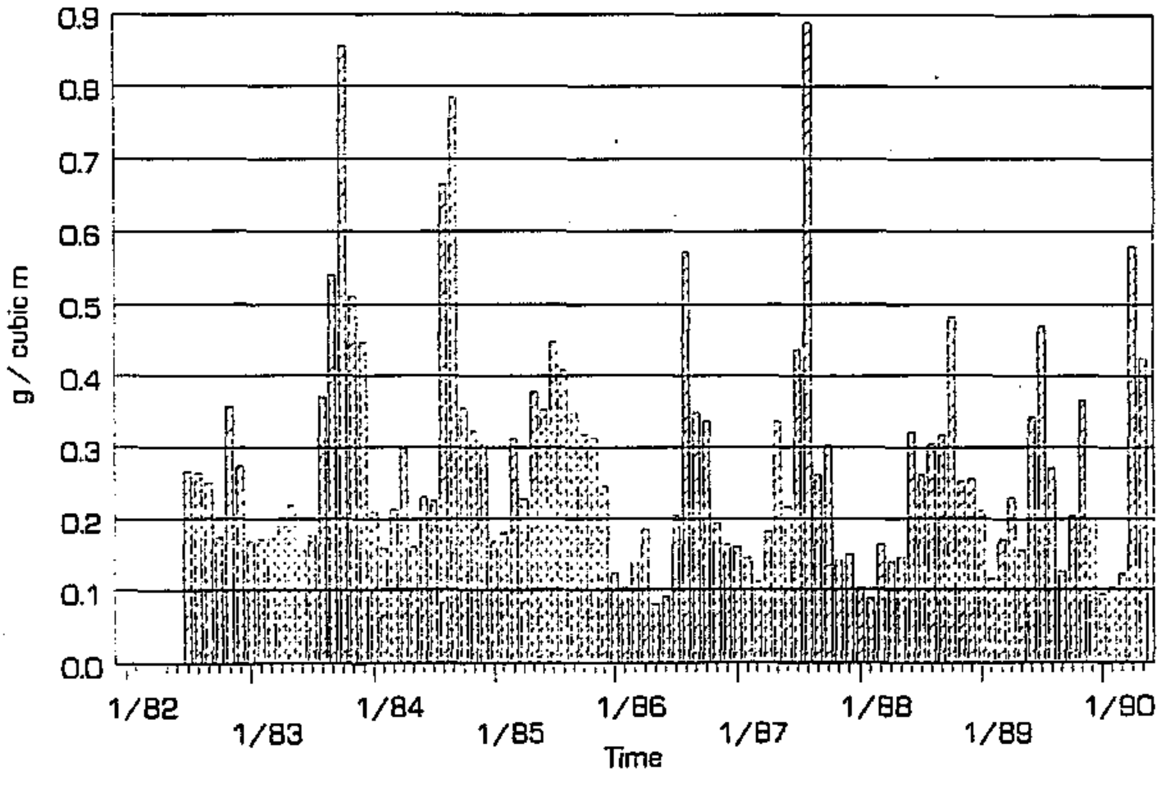

Figure 8. Hartbeespoort Dam. The biomass of the zooplankton. July 1982 to May 1990.

Long term trends of change in the zooplankton species composition in Hartbeespoort Dam are evident in Figure 9. The abundance of *Ceriodaphnia* declined between 1983 and 1988 so that by 1989 and 1990 it made up a small part of the zooplankton. Although *Daphnia* was never a numerically dominant species, it is so much larger than the other species that it is important. Its numbers have also declined over the study period. The Cyclopoid Copepoda (*Cyclops*) are the group whose relative abundance has increased over the study period. There is no evident systematic change in the abundance of *Bosmina*, or of the *Moina* + *Diaphanosoma* group.

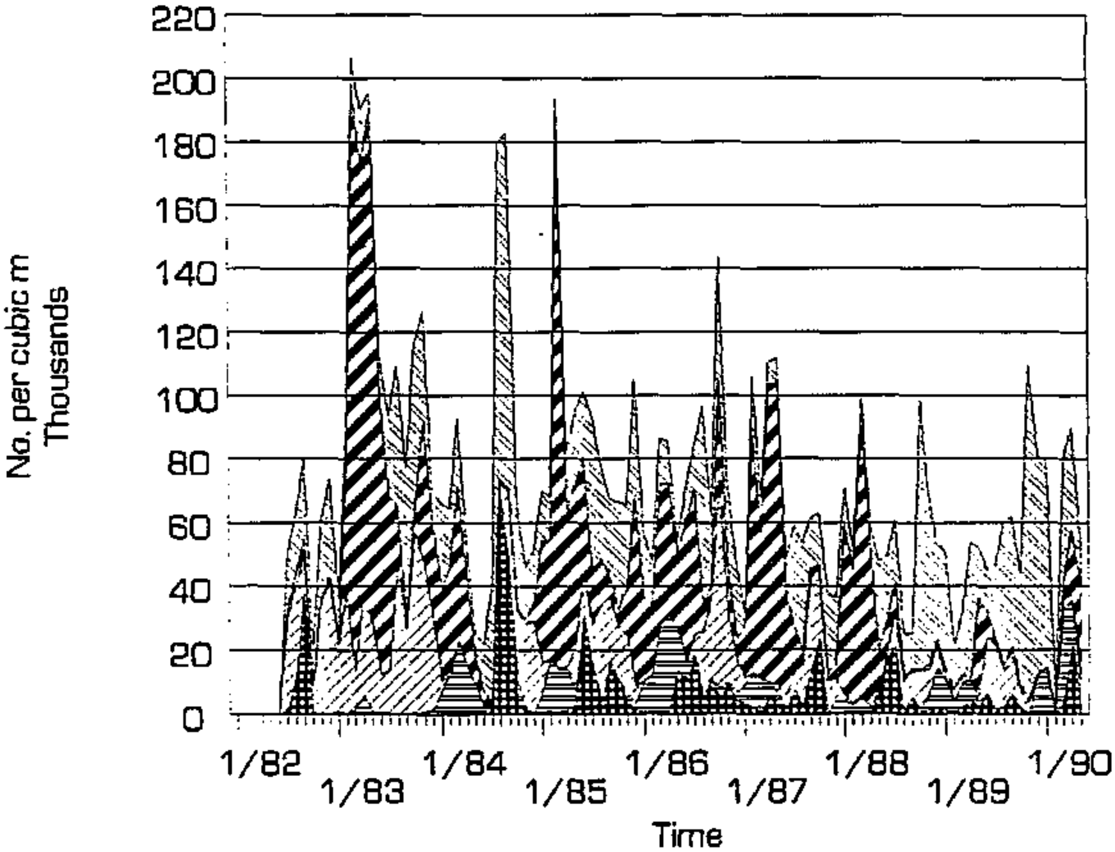

Figure 9. *Hartbeespoort Dam. The composition of the zooplankton. July 1982 to May 1990.* Bosmina ; Daphnia ; Ceriodaphnia ; Moina & Diaphanosoma ; Cyclops .

5. RESULTS - INFORMATION FROM DATA

5.1 Phosphorus dynamics of Hartbeespoort Dam

The mean concentrations (adjusted to WATERTEK analytical values) of total phosphorus and of orthophosphate in water samples from the Crocodile River (Table 9) have changed little since 1985/86, though there has been a pronounced decline in mean annual concentrations of both these determinands in the dam itself since the end of 1987 (Table 10). The root of this anomaly appears to lie in the fact that the mean river concentration is a misleading number. The flow weighted mean annual concentrations of total phosphorus in the river (Table 11) and particularly the annual total

Table 11. Crocodile River. Mean flow-weighted concentrations in $\mu g \ell^{-1}$ of Total Phosphorus and of Total Nitrogen of the river water at weir A2M12.

	Hydrological year						
	1982 /83	1983 /84	1984 /85	1985 /86	1986 /87	1987 /88	1988 /89
Total Phosphorus	2,1	2,9	1,7	1,4	1,1	1,3	1,1
Total Nitrogen	8,1	7,7	8,2	11,3	10,2	11,7	9,9

Table 12. Hartbeespoort Dam. Annual Total Phosphorus and Total Nitrogen loads expressed as g m^{-2} a^{-1}.

	Hydrological year						
	1982 /83	1983 /84	1984 /85	1985 /86	1986 /87	1987 /88	1988 /89
Total Phosphorus load	20	37	20	18	17	12	9
Total Nitrogen load	76	101	98	151	165	113	88

phosphorus loads on the dam expressed in g m^{-2} a^{-1} (Table 12) reveal a decline in both measures of incoming total phosphorus since 1983/84. It may be concluded that part of the reason for the recent decline in the quantities of total phosphorus and orthophosphate in the epilimnion of Hartbeespoort Dam is a lower concentration of these substances in the Crocodile River at a time when the dam has filled, resulting in a large decline in the phosphorus input load per unit area.

Further major potential contributors to the reduction in the total phosphorus and orthophosphate concentrations in the dam are discharges from the dam and the "sedimentation" of phosphorus on the bottom of the dam. Sedimentation in this sense includes sedimentation of particulate phosphorus, chemical precipitation and adsorption. The annual sedimentation rate (Table 13) is calculated from the annual mass balance of total phosphorus. Estimates of the sedimentation rates which would have been measured had the imbalance in the hydrological balance been due to errors in either the recorded inflow volumes or the recorded outflow volumes (Table 4) are also shown in the Table. It is apparent, from the sedimentation rates calculated for these corrections to the hydrological imbalance, that the errors in the hydrological balance make minor differences to the sedimentation rate and that they may therefore be ignored.

Table 13 shows that the sedimentation rate per unit area has declined by about 70 percent from its peak of 27,9 g m^{-2} a^{-1} in 1983/84, to 7,7 g m^{-2} a^{-1} in 1988/89. At the same time the percentage of the incoming load which has sedimented has risen from between 60 and 74 percent in 1982/83 to 1986/87 to over 80 percent in 1987/88 and 1988/89. Thus, although the sedimentation rate per unit

Table 13. Hartbeespoort Dam. Annual mass balances of phosphorus from hydrological year 1982/83 to 1988/89.

	Hydrological year						
	1982 /83	1983 /84	1984 /85	1985 /86	1986 /87	1987 /88	1988/ 89
FROM RECORDED HYDROLOGY							
Mass (t) in dam 1 October	86	43	53	32	24	55	35
Inflow mass (t)	206	336	190	169	240	226	180
Outflow mass (t)	123	77	76	68	64	54	50
Predicted mass (t) in dam 30 Sept	169	302	167	133	200	227	165
Measured mass (t) in dam 30 Sept	43	53	32	24	55	35	19
"Sedimented" (t)	126	249	135	109	145	192	146
Sedimented/inflow mass (percent)	61	74	71	64	60	85	81
Mean area of dam (km^2)	10,2	8,9	9,5	9,3	13,7	18,7	19,0
Sedimentation rate (g m^{-2} a^{-1})	12,4	27,9	14,2	11,8	10,6	10,3	7,7
FROM HYDROLOGY BALANCED BY ADJUSTING INFLOW VOLUME							
Sedimentation rate (g m^{-2} a^{-1})	9,6	27,2	14,5	12,1	8,4	11,8	8,1
FROM HYDROLOGY BALANCED BY ADJUSTING OUTFLOW VOLUME							
Sedimentation rate (g m^{-2} a^{-1})	11,4	27,7	14,3	11,9	9,7	10,7	7,8

area has dropped in the past two years, the fraction of the incoming mass which is sedimented has increased. Sedimentation has therefore also removed a larger part of the incoming load from the water and has in this way contributed to the decline in the phosphate concentration in the dam.

The sedimentation rate (Table 13) and the phosphorus loading rate per unit area were strongly correlated (r^2 = 0,95). This observation is in agreement with the experimental studies reported in NIWR (1985), which showed that the adsorption of orthophosphate by sediments was directly related to the orthophosphate concentration in the overlying water. It should not, however, be overlooked that the area of the dam (Table 13) increased considerably at a time when an increased proportion of the incoming phosphorus load was sedimented out of the water column. A low sedimentation rate per unit area was therefore compensated for by a large area over which sedimentation could take place.

5.2 Processes responsible for the disappearance of *Microcystis*

5.2.1 Physical conditions

Microcystis is an algal species equipped with a buoyancy mechanism which allows it to maintain itself in the upper portion of the euphotic zone of the water column. Strong mixing or low stability of the water column carries the species out of the euphotic zone, which disadvantages it. It thrives under the temperature conditions usually encountered at Hartbeespoort Dam.

Examination of Table 7 (which is itself based on Figure 4) shows that 1984/85 and 1985/86 were years in which surface water temperatures were cool and in which the stability of the water column as a whole was low. In other words they were among the years in which gross physical conditions were least favourable for *Microcystis*. Nevertheless, these were years in which *Microcystis* dominated the phytoplankton (Figure 5) which was, if anything, more abundant than it has been in the past two years (Figure 6). Table 7 shows that the period in which *Microcystis* has disappeared from the phytoplankton (1988/89 and 1989/90) has been more favourable, in terms of temperature and gross water column stability, for the species than were 1984/85 and 1985/86.

As is evident from Table 8, the microstratification in the surface waters of the dam in years without *Microcystis* dominance of the phytoplankton was not abnormal. It does not account for the disappearance of *Microcystis*.

The available temperature and stratification data do not suggest that the disappearance of *Microcystis* in summers 1988/89 and 1989/90 were due to changes in the water temperature or in the water column stability.

5.2.2 Chemical conditions - nitrogen and phosphorus

It has been reported that the total nitrogen : total phosphorus (TN:TP) ratio is important in the dominance of the phytoplankton community of lakes by bloom-forming nuisance blue-green (BFNBG) algae (Smith 1983, 1986, Harris 1986), which conventionally include the genera *Microcystis, Anabaena, Aphanizomenon* and *Oscillatoria.* Smith (1986) has suggested that the availability of light has an impact on the critical level of the ratio, which rises in turbid waters. Nevertheless, Smith concluded that under any light conditions the proportion of BFNGB algae biomass in the phytoplankton biomass is always < 10 percent at TN:TP > 29. Harris (1986) suggested that the intensity of mixing of the water column, due to the raising of phosphorus-rich hypolimnetic water to the surface, plays a role in determining the critical TN:TP ratio.

Smith (1986) suggested that managing of the availability of phosphorus to the phytoplankton should be accompanied by management of the availability of nitrogen. He referred to studies by Barica *et al* (1980) and by Leonardson & Ripl (1980) in which the TN:TP ratio had been adjusted by increasing the bound nitrogen load on lakes, successfully resulting in a reduction of the abundance of the BFNBG algae. (Leonardson & Ripl even go so far as to suggest in their discussion that effluent treatment should be taken as far as the nitrification stage in sewage works and that the nitrified water should be allowed to flow to the eutrophied lake, where the denitrification stage would take place).

However, in an earlier paper (Smith & Shapiro 1980), it was pointed out that in lake restoration by the reduction of the external phosphorus load, the TN:TP ratio increase can be expected to result in an increase in the chlorophyll yield per unit TP. This modifies the extent of the expected benefits of the phosphorus removal. It should be pointed out that when the management objective is to eliminate BFNBG algal dominance of the phytoplankton, this change in yield is not necessarily important.

Examination of Table 10 reveals that in 1989 and 1990 the total phosphorus and orthophosphate concentrations in Hartbeespoort Dam had declined to levels that were low relative to their previous levels. The decline in total nitrogen concentration was less pronounced, with the result that the

TN:TP ratio rose sharply, continuing a trend which started as long ago as 1985. While the TN:TP ratios for 1989 and 1990 are not as great as Smith's (1983, 1986) studies suggested to be necessary for the disappearance of *Microcystis*, the principle that TN:TP ratios are important in governing the dominance of the phytoplankton by BFNBG algae would appear to be confirmed by the changes in the phytoplankton composition which took place in Hartbeespoort Dam in 1989 and 1990 (Figure 5).

In relation to the fivefold reduction in the mean annual total phosphate concentration from 1984 to 1989, the change in the mean annual chlorophyll concentration has been limited (Table 10). This confirms Smith and Shapiro's expectation that, with a reduction in the external total phosphorus load on a dam with a low TN:TP ratio, the chlorophyll yield per unit total phosphorus will increase.

5.2.3. Chemical conditions - other determinands

Of the chemical determinands other than nitrogen and phosphorus shown in Table 9, none have changed in concentration concurrently with the disappearance of *Microcystis* to levels where they might be expected to bring about the *Microcystis* disappearance. However, the recent (1988/89 and 1989/90) very low mean annual silica concentrations in the Dam might limit the size of the diatom populations.

5.2.4. The zooplankton

Symptoms of a zooplankton population change sufficient to impact the phytoplankton species composition and abundance would be a large change in the abundance of the zooplankton. There were no such changes (Figure 8 and 9) immediately before *Microcystis* disappeared. The subsequent changes in the zooplankton, such as the increasing dominance of the Cyclopoid Copepoda and the unusually high biomass in April and May 1990 are probably due to the change in the species compositon of the phytoplankton subsequent to the disappearance of *Microcystis*.

6. DISCUSSION

There are several ways in which nitrogen to phosphorus ratios have been calculated. In this study the Total Nitrogen to Total Phosphorus ratio has been used. It is evident from Table 10, that the ratios for 1989 and 1990 differ considerably depending on which analytical laboratory's nitrogen and phosphorus values are used. Nevertheless, it is clearly evident that N:P ratios have increased since 1984.

It is important to bear in mind that although the immediate reason for the recent disappearance of *Microcystis* seems most likely to be the decline in the phosphorus content of the water resulting in the change in the TN:TP ratio, the ultimate reason lies in the origins of the considerable reduction in the total phosphorus concentration. This has taken place at a time when the dam has filled and at the same time the flow-weighted mean annual phosphorus concentration of the Crocodile River inflow has declined. These events must be taken into account in any prognoses of the future changes in the nutrient conditions and of the phytoplankton composition of the dam.

Prognoses for the future involve either changes in the nutrient loads and nutrient ratios or changes in the volumes of inflowing water or stored water. These scenarios are discussed below, together with possible steps to increase the availability of bound nitrogen, which would appear to be frequently required to mitigate undesirable nutrient conditions.

The important unknown in all the scenarios to be portrayed here is whether or not the actual total phosphate concentration has an impact on the critical level of the TN:TP ratio for the disappearance of *Microcystis*. At high total phosphorus concentrations it may be that it is the actual total phosphorus concentration which provides a competitive advantage to the BFNBG algae. This uncertainty is of concern in scenarios where the total phosphorus concentration is expected to rise and the management recommendation is to ensure that the TN:TP ratio does not fall. It is of no concern where the total phosphorus concentration is expected to fall below current levels.

In the first scenario it will be assumed that the flow of the river will decrease due to drought, but that the nutrients discharged into Hartbeespoort Dam catchment will remain at present levels. When the next series of successive low rainfall years occurs, the volume of stored water in Hartbeespoort Dam will again decrease, probably by the amount it decreased in the middle 1980's, that is to about 33 percent of full supply volume. Provided that the TN:TP ratio in the dam is maintained at its present high level, there would be no reason to expect a return of *Microcystis* (but note caveat in previous paragraph).

In the second scenario it is assumed that phosphorus loads will increase due to the impact of increased urbanisation and improved standards of living on the quantity of effluent discharged. In this case care should once again be taken to maintain the TN:TP ratio at present levels, if necessary increasing the availability of nitrogen. It is again desirable to bear the content of the paragraph above the previous paragraph in mind.

In the third scenario the phosphate load on Hartbeespoort Dam continues to decline, due to the wider and more effective application of the special orthophosphate effluent standard of 1 $mg\ell^{-1}$. Should the mean total phosphorus concentrations drop to 85 $\mu g\ell^{-1}$, following criteria suggested by the OECD study (OECD 1982) Hartbeespoort Dam would be classified as eutrophic with an expected mean annual chlorophyll concentration of 14 $\mu g\ell^{-1}$ and an annual mean chlorophyll peak value of 43 $\mu g\ell^{-1}$. It needs to be pointed out here that as the external phosphate load on the dam decreases, the internal load (released from the sediments) will become apparent. The rate of recovery of the dam due to lower available phosphorus concentrations will decrease until such time as the mobile phosphorus in the sediment has declined to levels in equilibrium with the phosphorus content of the water.

There are three ways in which the nitrogen availability in Hartbeespoort Dam can be modified to increase the TN:TP ratio. Firstly, factories could be encouraged to allow the bound nitrogen content of their effluents to increase. This option is obviously appropriate to Hartbeespoort Dam in whose catchment there are nitrogen-rich waste waters. Secondly, restrictions on the nitrogen content of sewage and other effluents could be relaxed. Thirdly, the dam could be mixed during summer stratification to ensure that the hypolimnetic waters were permanently aerobic. Ashton (1985) found that between 35 and 49 percent of the total annual nitrogen load on Hartbeespoort Dam is lost by denitrification. Since denitrification takes place under anoxic conditions, it could be reduced by intensities of destratification necessary to eliminate the anoxic conditions, which currently occur in the hypolimnion in summer.

The future role of destratification in the management of the phytoplankton in Hartbeespoort Dam is therefore perceived to be the reduction of nitrogen loss through denitrification, to ensure that TN:TP ratios are maintained at present or higher levels. In the past destratification has also been seen to reduce the competitive advantage of the BFNBG algae, through mixing them down into conditions of darkness, which they tolerate less well than other phytoplankton species. The competitive advantage of other species, such as the heavy diatoms, would be increased by the fact that the mixing would reduce the rate at which they dropped out of the euphotic zone.

The mean annual flow-weighted total phosphorus concentrations reported in Table 11 have hardly changed since 1985/86. There are, however, effluent treatment works, notably the Johannesburg Northern Works, which had temporary exemption from the application of the special phosphorus standard. When the standard is successfully met by all effluent treatment plants in the Hartbeespoort Dam catchment, it is to be expected that the flow-weighted mean annual total phosphorus load will decline further and that there will be a further improvement in the algological conditions in the dam.

7. CONCLUSIONS

7.1 The temperature conditions and stability of the water column in Hartbeespoort Dam have not been outside the range of normal conditions over the past two summers.

7.2 The external load of total phosphate per unit area of Hartbeespoort Dam has decreased in the past two years.

7.3 The flow-weighted mean annual concentration of total phosphorus in the Crocodile River has also declined.

7.4 The external load and flow-weighted mean annual concentration of total nitrogen have also declined over the same period, but to a lesser extent than the total phosphorus load and concentration.

7.5 While the phosphorus sedimentation rate per unit area in Hartbeespoort Dam has declined over the past two years, the proportion of the annual inflow load that has been sedimented has increased.

7.6 The reduction in the annual mean total phosphate concentration in the dam is due to the reduced incoming load and to the greater proportion of this reduced load which has been sedimented.

7.7 The modified external total phosphorus loads and the increased sedimentation of phosphorus in relation to the load have resulted in marked decreases in total phosphorus and particularly orthophosphate concentrations in the dam and an increase in the TN:TP ratio.

7.8 The disappearance of *Microcystis* from the phytoplankton in the last two summer seasons is almost certainly due to the increased TN:TP ratio. However, the exact mechanisms involved are not known.

7.9 The yield of chlorophyll per unit phosphate has increased since the increase in the TN:TP ratio, as evidenced by the small decline in the chlorophyll content of the water with the decline in the total phosphorus concentration. This is due to the fact that green algae produce more chlorophyll per unit phosphorus than do blue-green algae (P J Ashton, personnal communication).

7.10 Findings 7.8 and 7.9 are in agreement with findings on the impact of nutrient ratios on the occurrence of bloom-forming nuisance blue-green algae reported in the international scientific literature.

7.11 There is no evidence that the zooplankton has caused the change in the presence of *Microcystis* seen in the past two years.

7.12 Management of Hartbeespoort Dam to prevent the return of *Microcystis* should be through the maintenance of high TN:TP ratios.

7.13 Information on the effect of total phosphorus concentration on the occurrence of *Microcystis* at high (> 20) TN:TP ratios is unknown. It is therefore possible that, should total phosphorus concentrations rise to the levels recorded in the middle 1980's, the TN:TP ratio will no longer govern the occurrence of *Microcystis* in the manner in which it does at current low total phosphorus concentrations.

7.14 The condition of Hartbeespoort Dam may be expected to further improve when the special phosphate standard is met by all effluent dischargers in the catchment of the dam.

8. RECOMMENDATIONS

8.1 It is essential to the management of the phytoplankton of Hartbeespoort Dam that the 1 $mg\ell^{-1}$ effluent phosphate standard be enforced in the catchment of the dam. The desirability of lowering the concentration of the standard should never be overlooked.

8.2 The Department of Water Affairs & Forestry should maintain surveillance (which includes regular monitoring and review of the monitoring data) of nutrient ratios in Hartbeespoort Dam and of the composition of the phytoplankton community.

8.3 It would not be necessary to monitor Hartbeespoort Dam at less than monthly intervals when the dam is full, but it would be desirable to maintain a closer watch on the dam during drought summers in which the dam is considerably drawn down.

8.4 Should nutrient ratios appear to be declining, steps should be taken to increase the availability of nitrogen to the phytoplankton.

8.5. Increased availability of nitrogen to phytoplankton could be achieved by destratifying the dam to limit denitrification under anoxic conditions. Should this prove to be inadequate, consideration should be given to relaxing standards for nitrogen in effluents (including those from factories with nitrogen rich waste water) in the Hartbeespoort Dam catchment and to lowering the concentration of the phosphate standard (see 8.1 above).

8.6 The Directorate of Pollution Control, Department of Water Affairs & Forestry, should be advised of the findings of this report and of the strategy for the management of *Microcystis* through nutrient ratio regulation.

8.7 When more than one analytical laboratory becomes involved in the analysis of water samples for any particular study, it is imperative that the pre-treatment of samples for analysis receive close attention. Satisfactory results from inter-laboratory comparison studies on duplicated prepared water samples are only the starting point for satisfactorily comparable results from field water samples.

8.8 Laboratory studies of the impact of N:P ratios at various phosphate concentrations on the composition of phytoplankton populations should be undertaken.

9. POSTSCRIPT

Subsequent to the approval of the draft of this report by the Steering Committee, an important review of the factors governing the dominance of the phytoplankton by the blue-green algae appeared (Shapiro, J 1990 Current beliefs regarding dominance by blue-greens: the case for the importance of CO_2 and pH. *Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 24: 38 - 54.*). In this review it was concluded that the environmental conditions associated with blue-green algal dominance are a high pH and a low availability of carbon dioxide. The author of the review points out that the arguments in favour of this pH/CO_2 hypothesis can be regarded as circuitous, since blue-green algae usually occur in very high densities and their active photosynthesis raises the pH and lowers the ambient CO_2 concentration. Unfortunately, the Hartbeespoort Dam chemical data are, due to the change in water quality analysis practises (see Methods, above) which fortuitously coincided with the decline in the blue-green algae populations, unsuitable to test Shapiro's hypothesis. Shapiro found the evidence for the regulation of blue-green algal dominance by high N:P ratios to be inconclusive and contradictory.

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