Evaluation of the Impact of the 1 mg l^{-1} Phosphate-P Standard on the Water Quality and Trophic State of Hartbeespoort Dam

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CONTRACT REPORT

Evaluation of the impact of the 1 mg l^{-1} phosphate-P

standard on the water quality and trophic state of

Hartbeespoort Dam

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

Dr W H J Hattingh	Water Research Commission (Chairman)
Dr H N S Wiechers	Water Research Commission (Former Chairman)
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TERMS OF REFERENCE

This Report arises out of a contract agreement entered into between the CSIR, through its Division of Water Technology (DWT), and the Water Research Commission (WRC). The research commenced in April 1986 and terminated in March 1989. The terms of the contract were amended by mutual agreement in May 1988.

The original contract agreement pre-supposed that the 1 mg l^{-1} orthophosphate-phosphorus effluent standard would be implemented during the course of the contract. The objectives of the project were therefore to:

1. Evaluate changes in point source phosphate loads.

2. Evaluate changes in water quality flowing into the dam.

3. Evaluate the chemical and biological response of the dam to changed input water quality.

4. Evaluate and further refine predictive models of water quality and trophic status, including models predicting impoundment response time.

5. Evaluate changes in suitability of water abstracted from the dam as raw water, either for direct use in agriculture or for treatment for domestic or industrial use.

6. Maintain and update the existing computerised data base on Hartbeespoort Dam.

The contract agreement recognised that these objectives could only be achieved with the financial support of the DWT and of the CSIR Foundation for Research Development. However the following tasks were clearly associated in the contract agreement with the Water Research Commission funding:-

1. **Assess changes in point source phosphate loads.**
   The assessment was to be based on data made available, by agreement, by the Pollution Control Division of the Department of Water Affairs. The purpose of this task was to quantify the effect of the progressive implementation of the 1 mg l^{-1} orthophosphate-phosphorus effluent standard.

2. **Measure the chemical quality and nutrient load (nitrogen and phosphorus compounds) of the water flowing into Hartbeespoort Dam.**
   Flow proportional sampling was proposed at Weir A2M12 on the Crocodile River for nutrient load determination. Weekly sampling for general water quality determinands, such as the dominant anions and cations, pH, conductivity, hardness and iron and manganese, would be undertaken. In addition dissolved organic carbon and chlorinated hydrocarbon precursors would be measured at weekly intervals and heavy metals quarterly. At Weir A2M13 on the Magalies River sampling would be at weekly intervals.

3. **Measure chemical quality of lake water.**
   This was to be done at weekly intervals from a raft moored in Hartbeespoort Dam. Samples were to be collected from the surface waters and then at 5m intervals to the bottom. Variables to be analysed were the same as in the inflowing water, except that chlorinated hydrocarbon precursors would be measured less frequently.

4. **Measure chemical quality and load of the outflowing water.**
   Samples of the outlet water would be analysed for the same variables as the inflow and in-lake waters.

The following additional tasks were to be undertaken and reported to the Water Research Commission, recognizing that they were not funded by the Commission.

5. **Integrated interpretations of lake response to the 1 mg l^{-1} effluent phosphate-P standard.**

   These were to include:
   - the partitioning and fate of phosphorus and nitrogen species using a mass balance approach,
   - the role of allochthonous and autochthonous sources of trihalomethane precursors,
   - the abundance, distribution and species composition of the phytoplankton, zooplankton and fish.

6. **Evaluation and refinement of productive water quality and trophic status models.**
   The main purpose of this task was to establish the validity of various simulation and static (e.g. Vollenweiler, OECD) models of phosphate load/phytoplankton response under conditions of a falling nutrient load and lake rehabilitation.

7. **Evaluation of outflow water quality.**
   Established water quality requirements for domestic, industrial and agricultural use of water would be compared with the quality of water released from the dam.

8. **Data base.**
   The information arising from the study would be used to update an existing data base, which might be used in the future for activities such as cost benefit evaluation of the 1 mg l^{-1} phosphate standard or the evaluation of new water quality models.

By early 1988 it had become obvious that the expected application of the 1 mg l^{-1} orthophosphate-P effluent standard had not yet been achieved. Prospects for its complete application in the Hartbeespoort Dam catchment were not good but the Department of Water Affairs was considering destratifying the dam from September 1989 onwards. Furthermore the Foundation for Research Development terminated its support for research on Hartbeespoort Dam in March 1988.

In the light of these developments the contract objectives were re-defined jointly by the Water Research Commission and the Division of Water Technology in March 1988. The revised objectives were as follows:

1. Evaluate changes in point source phosphate loads.

2. Evaluate changes in the quality of water flowing into the dam.

3. Evaluate the chemical and biological response of the dam to changing input water quality and to any other management actions which may take place during the remaining course of the contract.

4. Compare the chemistry and biology of the dam in years when it spills with years when it does not spill.

The original tasks were replaced by the following:

i) **Assess changes in point source loads.**
This task remaining the same as in the original contract.

ii) **Measure the chemical quality and load in the inflowing water.**
This task was modified from the original contract in that flow-proportional sampling (when had proved to be unattainable), heavy metal analysis, dissolved organic carbon analysis and chlorinated hydrocarbon precursor analysis were discontinued. Daily samples from the Crocodile River would be analysed for nitrogen and phosphorus species, but the major anions and cations would be analysed at weekly intervals.

iii) **Measure chemical quality of lake water.**

The sampling frequency was reduced to fortnightly and in winter only surface and bottom water samples were to be analysed. Only nitrogen and phosphorus species were to be analysed.

iv) **Measure chemical quality of outflow water.**

Samples to be drawn from the outflows at weekly intervals and analysed for the properties measured in the inflow water.

The Hydrological Research Institute of the Department of Water Affairs undertook to execute the water analyses involved in tasks 2 and 4 and to collaborate in writing up the results.

v) **Evaluation of chlorophyll a concentration and the phytoplankton species composition and abundance.**

vi) **Evaluation of zooplankton species composition and abundance.**

These two tasks were to be undertaken as previously, but with the sampling frequency reduced to fortnightly. In the analyses of results responses to scum removal, changed nutrient loads and the fullness of the dam would be assessed.

EXECUTIVE SUMMARY

This report deals with the phosphates in effluents released in the catchment of Hartbeespoort Dam and the quality of water entering, within and leaving Hartbeespoort Dam from 1985 to 1989 (March). It also describes the phytoplankton and zooplankton populations of the dam and how they have responded to changing conditions in the dam. Data on Hartbeespoort Dam dating back to 1980 have been used in the interpretation of results, which to a considerable degree, is concerned with the impact of the effluent phosphate standard on the dam.

In 1985 a 1 mg l^{-1} effluent orthophosphate-P standard came into effect in the catchment of Hartbeespoort Dam, although the largest effluent treatment plant was granted an exemption from the standard for three years. Effluent data are available only from the latter half of 1986, since when there has been insignificant change in the total mass of phosphates released in the catchment of Hartbeespoort Dam. The mean concentration of phosphate measured in the Crocodile River, where it enters Hartbeespoort Dam, declined by about 20% from hydrological year 1984/85 to 1985/86. Since then there has been no concentration decline in the river. There is, nevertheless, evidence that without the standard the phosphate load would have been greater after 1984/85 than that measured.

Due to an increasing rainfall, the mean stored volume of Hartbeespoort Dam increased from $73 \times 10^6 m^3$ (38% full) in 1985/86 to $174 \times 10^6 m^3$ (90% full) in 1987/88. The dam spilled in 1987/88 and 1988/89 for the first time since 1981/82. With the filling of the reservoir the in-lake annual mean orthophosphate-P concentration steadily declined from 476 $\mu g\ l^{-1}$ in 1984/85 to 134 $\mu g\ l^{-1}$ in 1987/88 and the trend of declining concentration has continued into 1988/89. This change in phosphate concentration was brought about within the impoundment rather than by a decline in the phosphate concentration in the inflowing water. Ultimately, it would appear to be the increase in the stored volume of water which was responsible for the decline in the phosphate concentration in the dam. Due to the increase in the surface area of the bottom, the mass of

phosphorus sedimented or otherwise retained in the dam increased from 118 t a^{-1} in 1985/86 to 190 t a^{-1} in 1987/88. Furthermore, due to the increasing volume of the dam the aerial and volumetric phosphorus loading rates declined.

Unlike phosphates, the loads of nitrogen species arriving in the dam were lowest in 1984/85 and increased sharply from 1395 t a^{-1} in 1985/86 to 2266 2266 t a^{-1} in 1986/87 and 2109 t a^{-1} in 1987/88. Nitrogen losses within the impoundment have increased from 769 t a^{-1} in 1985/86 to 1734 t a^{-1} in 1987/88 as the stored volume has increased. A feature of water quality in summer 1988/89 is that phosphate-P concentrations in the surface (0- 5 m) water have been as low as 5 µg l^{-1} and that N:P ratios have risen to over 25:1.

With regard to the non-nutrient major anions and cations, the water stored in Hartbeespoort Dam has, for the most part, remained remarkably constant in quality as the dam filled from 1985/86 to 1988/89. Far and away the largest concentration change was a decline in sulphate concentration from 1985/86 (109 mg l^{-1}) to 1987/88 (92 mg l^{-1}). In general water quality in the dam was intermediate between the low quality water of the Crocodile River and the high quality of the Magalies River. Outflow water was very similar to impounded water.

Heavy metal concentrations and total organohalogen potential (TOHp) were measured in the inflowing rivers, in the impoundment and in the outflowing water at quarterly intervals in 1985/86 and 1986/87. Although concentrations of most heavy metals were higher in the Crocodile River than in the dam, at no sites were heavy metal concentrations at levels to be of concern. There was no indication that heavy metal concentration varied systematically with depth in the impoundment.

TOHp was of the same order (260 to 349 µg l^{-1}) in the dam, its outflow, the Magalies River and the Crocodile River in 1986/87. It was higher (556 µg l^{-1}) in the Crocodile River in 1985/86. There was no evidence that potential increased or decreased with depth in the dam or that the presence of large quantities of phytoplankton in the water increased the TOHp.

The chemical quality of water in Hartbeespoort Dam was classified following German Technical Standards (G.D.R., 1982) and was found to be moderately impaired, requiring comprehensive treatment for domestic and industrial use but usable for irrigation. A similar classification was arrived at from comparing Hartbeespoort Dam data to a set of internationally accepted water quality standards. (Kempster, et al 1980).

The species composition of the plankton of Hartbeespoort Dam remained similar to that of previous years through to the end of 1987/88. In summer 1988/89 profound changes occurred in both the zooplankton and the phytoplankton. Microcystis aeruginosa, in previous years the dominant species (>80% biomass) for ten months of the year, was almost entirely absent. The zooplankton came to be dominated by a predatory species, while filter-feeding species had previously been dominant. These biological changes are ascribed to the reduced phosphate and nitrogen species concentrations in the water and to the increased N:P ratio. Changes in wind speed and temperature, which might have resulted in phytoplankton change, were well within the previously recorded range of variation. The change in the phytoplankton could therefore not be associated with these physical factors. It could also not have been brought about by the observed change in the zooplankton to dominance by a predator.

Spilling of the reservoir, when scums formed at the end of summer was shown to result in low winter Microcystis populations. This greatly improved the aesthetic quality of the water and made it less variable for water treatment works. However, removal of the scums had a negligible impact on the nutrient content of the dam. The impact of scums flushed from the dam on the Crocodile River is unknown.

The full data base from 1980/81 through to 1988/89 was used to test simple predictive models of the phosphorus and chlorophyll concentrations in the dam. Several of the models used had been developed in the northern hemisphere for steady state lakes. The eight year data base on Hartbeespoort Dam shows that it is not in a steady state as regards volumes, inflow, outflow, the inflow-outflow relationship, water retention time, combined nitrogen and phosphorus load and the inorganic nitrogen to phosphorus ratio. Despite the dynamic nature of the impoundment, the total phosphorus concentration in the dam was adequately predicted by the O.E.C.D. (1982) model and some of its derivatives. The best and, indeed, very good model was due to Grobler and Silberbauer (1984).

No models were found that predicted chlorophyll satisfactorily. In no case was there a statistically significant relationship between observed and predicted values.

Examination of simpler relationships such as that between mean annual volume weighted inflow concentration of phosphorus, annual and volumetric phosphorus loading rates on the one hand and in-lake mean annual volume weighted phosphorus concentration and mean in-lake chlorophyll concentration on the other, showed few but important significant relationships. Areal phosphorus loading rate ($r = 0.94$) and volumetric phosphorus loading rates ($r = 0.92$) were very good predictors of mean in-lake phosphorus concentrations. Predictions of chlorophyll were again not significant.

Important conclusions arising from this study were that the enforcement of the 1 mg l^{-1} orthophosphate-P standard is not complete. The recent reduction in in-lake phosphate concentrations and disappearance of Microcystis is not due to the effluent phosphate standard and is not likely to be permanent. Nevertheless it has become clear that Microcystis occurrence is governed by phosphate availability and that strict enforcement of the effluent standard should be attempted. The prevention of stratification through aeration would also tend to drive nutrient availability and the N:P ratio in a direction unfavourable to Microcystis.

The present study clearly reveals that understanding of the quantitative functioning of South African hypertrophic lakes cannot be complete unless it includes the filling phase of the hydrological cycle. The changes in the composition of the plankton following the disappearance of *Microcystis* were not those predicted from earlier studies.

Microcystis scums should be removed, where this is easily done, for scum removal greatly improved the aesthetic quality of the dam. Effects of flushed scum material on the receiving river should be taken into account.

Comprehensive treatment of Hartbeespoort Dam water is necessary prior to its use for domestic and industrial purposes. Dissolved heavy metal concentrations in Hartbeespoort Dam are acceptable and TOHp concentration is not increased by the storage of water in Hartbeespoort Dam. Prediction of mean annual in-lake phosphorus concentration is satisfactory but mean annual chlorophyll concentration cannot yet be adequately predicted.

It is recommended that the 1 mg l^{-1} effluent orthophosphate-P standard should be enforced, that studies of the dam should continue to establish the permanence of the present desired chemical and biological status, that the prevention of stratification should be tested as a *Microcystis* control method, that an expert system approach should be followed for the prediction of chlorophyll concentration and phytoplankton species composition and that no further studies of chlorophyll models, heavy metals and TOHp concentrations are warranted at present.

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ACKNOWLEDGEMENTS

This report would have been impossible to write without data provided by several Directorates of the Department of Water Affairs - Pollution Control, Hydrology and the Hydrological Research Institute. Former members of the NIWR/DWT (CSIR) listed in NIWR (1985) established research routines and methods used in this study. In the most recent past, field sampling and data analysis have fallen on the shoulders of Peter McMillan, Susan Combrink, Cangela Pais Madeira and Lynne Sephton. Typing a document such as this is an onerous task undertaken by Dottie Visser Christine Coetser and Olga Webb. I record my sincere thanks to these organisations and people for their very great direct inputs. Thanks are also due to the Director of the Division of Water Technology, the Water Quality Information Systems Programme Manager, the Foundation of Research Development, the Department of Water Affairs and the Water Research Commission for their financial and scientific inputs and for creating the opportunity to make this study.

1. INTRODUCTION

This report describes aspects of chemical and biological conditions in Hartbeespoort Dam, its catchment and its inflow. The study arose out of the facts that the dam is hypertrophic and previously well-studied. During the present study the external load of orthophosphate on the dam was expected to substantially decrease. This would be due to the implementation of the new 1 mg l^{-1} orthophosphate-P effluent standard.

The hypertrophy of Hartbeespoort Dam is characterised by massive phytoplankton blooms and floating scums of algae. The most obvious impact of these blooms and scums is aesthetic. The scums are unsightly and stink as they decay. Less immediately obvious is the fact that the major scum-forming alga, Microcystis aeruginosa, is usually toxic, if ingested in very large quantities. The production of safe potable water with an acceptable taste from sources such as Hartbeespoort Dam is expensive.

The 1 mg l^{-1} orthophosphate-P effluent standard has been promulgated as a first step towards alleviating these undesirable properties of hypertrophic impoundments, through reducing the quantity of orthophosphates available for phytoplankton growth. However, achievement of the 1 mg l^{-1} orthophosphate-P standard is expensive. It was therefore desirable to record the impact of the standard on effluent orthophosphate concentrations, on effluent receiving waters and on Hartbeespoort Dam. This report is primarily concerned with these impacts, though the researchers were also asked to simultaneously address other issues. These included the origin and levels of trihalomethane precursors, the refinement of methods to measure river loads of nutrients and the refinement and assessment of eutrophication models, particularly as they applied to impoundments in which the nutrient load was declining.

The dam, its catchment and the field and laboratory methods used are first described in the sections which follow. Results deal first of all with the chemical properties and nutrient loads of the inflows, the dam and its outflows. Mass balances of phosphates and combined nitrogen are presented as are data on heavy metals and chlorinated hydrocarbon precursors in the inflows and the dam. The suitability of the impounded water for domestic and industrial use is evaluated. Attention is then given to changes in the plankton and the evaluation of simple eutrophication models using the Hartbeespoort Dam data base. The report is concluded by a discussion of the findings, conclusions and recommendations.

2. GENERAL DESCRIPTION OF HARTBEESPOORT DAM AND ITS CATCHMENT

Hartbeespoort Dam and its catchment have been described in an earlier comprehensive report (NIWR, 1985). Here salient features of the area and dam are repeated and new information, the sites of the effluent treatment works, is presented.

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). The Crocodile River drains the extensively urbanized northern slopes of the Witwatersrand (Figures 1 and 2). There are eleven effluent treatment plants in the catchment (Figure 2), all of them draining into the Crocodile River. The only other major and perennial inflow to the dam is the Magalies River which enters the dam from the west, having drained a catchment used for a diverse agriculture.

The dimensions and hydrological properties of the dam and its catchment are given in Table 1. The difference between the 'virgin MAR' and the 1964-78 MAR in Table 1 is due in part to treated effluents released into the Crocodile River system. Figure 3 is a bathymetric map of the dam. The relationships between depth, surface area and volume of the dam are shown in Table 2.

3. METHODS

Most field and laboratory methods used in this study have been described in NIWR (1985). Total organohalogen potential (TOHp) was measured coulometrically after chlorination of the water to 60 $mg l^{-1}$ Cl_2 with sodium hypochlorite.

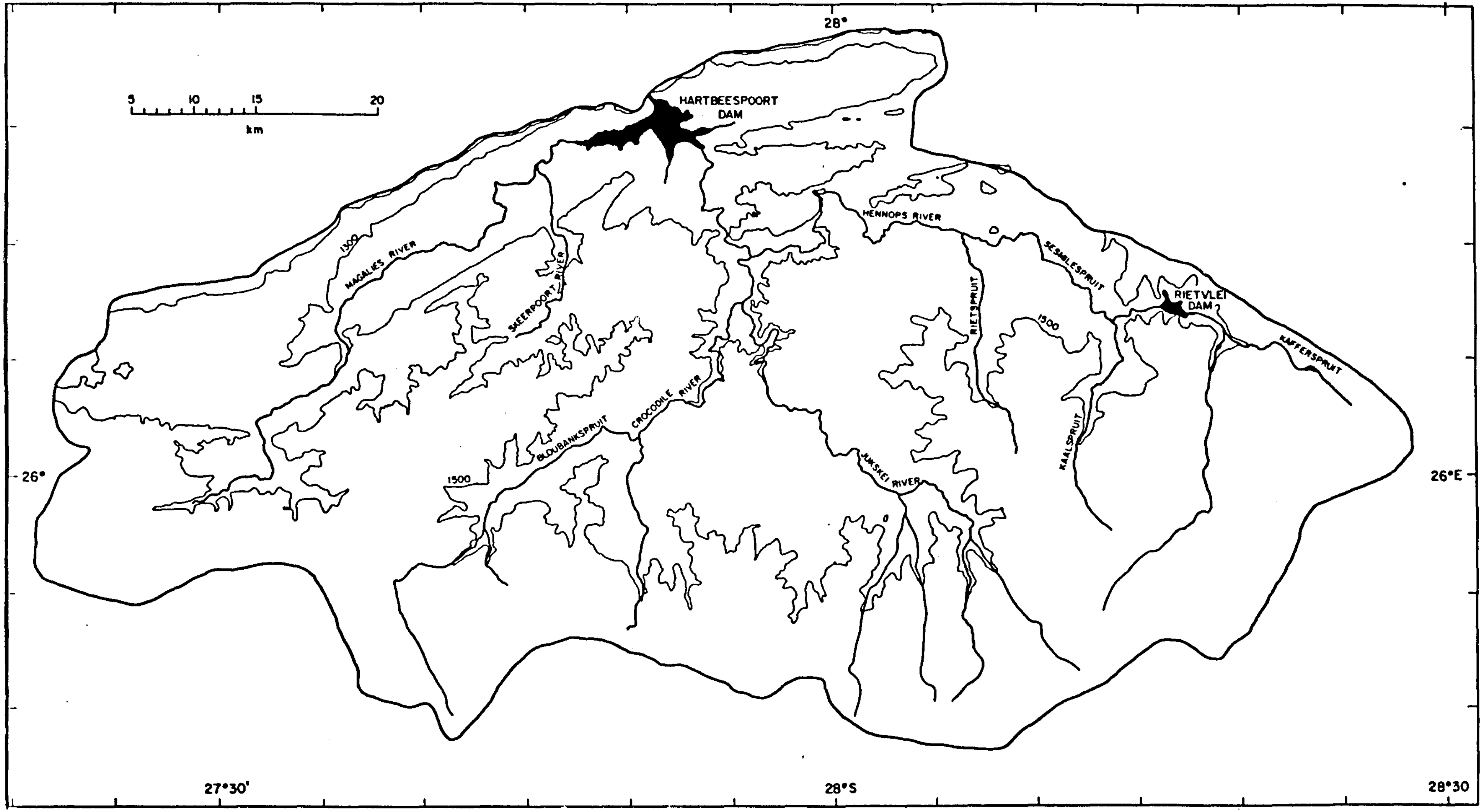

Figure 1: Hartbeespoort Dam and its catchment. Rivers, dams and topography.

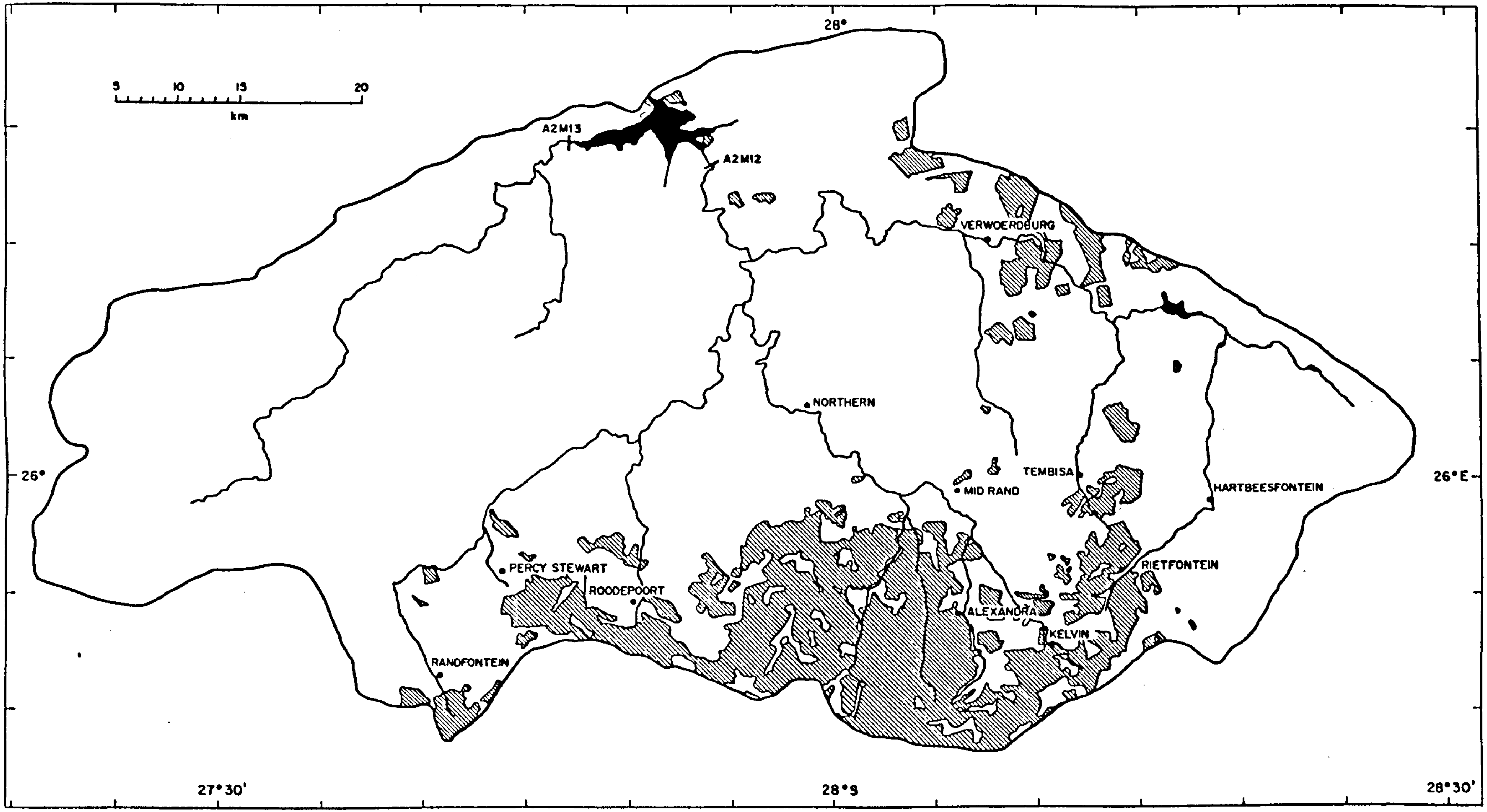

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Figure 2: Hartbeespoort Dam and its catchment. Urban areas (shaded) effluent treatment works and the position of flow guaging weirs A2M12 and A2M13.

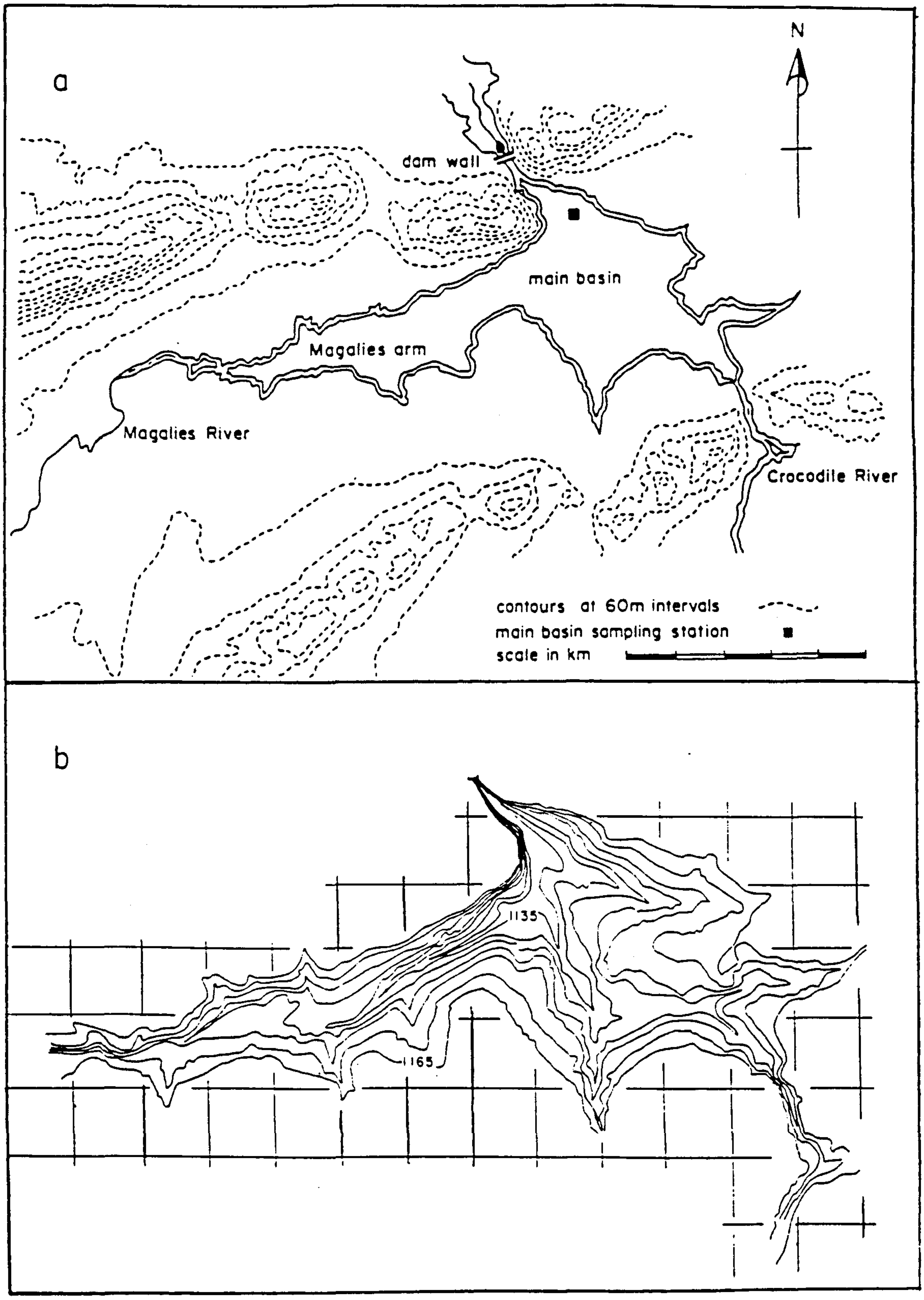

Figure 3: Hartbeespoort Dam. a. Locality of Sampling point.
b. Bathymetry (contour lines at 5m intervals, grid 1 km x 1 km).

Table 1: Hartbeespoort Dam. Morphological and hydrological characteristics. Data from Tables 3.1 and 3.2 of NIWR, 1985 and from Middleton <u>et al</u>, 1981.

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* (a)	154 x $10^6 m^3$
	1964-1978 MAR (b)	224 x $10^6 m^3$
	Effluent flow (b-a)	70 x $10^6 m^3$

* From Middleton <u>et al</u>, 1981

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	95.4	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 which is the bottom 12.38 m of the water column. The dead storage volume is included in the volumes given above.

4. RESULTS

4.1 Point Source Phosphorus Loads

The eleven effluent treatment plants, whose phosphorus loads (as orthophosphate) are described here, are shown on Figure 2. Monthly values of flow, mean orthophosphate-phosphorus concentration and orthophosphate phosphorus load are given in Appendix Tables A1 and A2. This data has been consolidated into monthly means for successive six-monthly periods covering the latter half of 1986, 1987 and 1988 (Tables 3, 4 and 5).

The largest volume of effluent is released by the Northern MP5 treatment plant, which releases about 40% of the total catchment effluent flow (Table 3). Northern Kelvin, Rietfontein and Olifantsfontein each contribute about 10% of the total flow, and the only remaining substantial contributor of effluent volume is the Alexandra treatment works.

Table 3: Effluent treatment plants in the catchment of Hartbeespoort Dam. Mean monthly flows ($10^6 m^3$) over half yearly periods. Calculated from data provided by the Pollution Control Directorate, Department of Water Affairs.

	Jul-Dec 1986	Jan-Jun 1987	Jul-Dec 1987	Jan-June 1988	Jul-Dec 1988
Driefontein	0.23	0.20	0.21	(0.23)*	?(0.22)
Alexandra	0.52	0.54	0.56	0.61*	0.53
Midrand	0.05	0.07	0.07	?(0.07)	?(0.07)
Northern Kelvin	0.99	0.89	0.91	0.92	0.98
Northern MP5	2.82	3.52	3.31	3.00	2.55
Percy Stewart	0.46	0.44	0.39	0.37	?(0.37)
Verwoerdburg	0.41	0.44	0.43	0.44	0.47
Rietfontein**	0.94	(1.10)	(0.95)	1.00	0.89
Hartbeesfontein**	0.43	(0.38)	0.43	0.42	0.43
Randfontein	0.39	0.41	0.39	0.35	0.42
Olifantsfontein	0.62	0.64	0.65	0.86	(1.03)
Total flow/month	7.86	8.63	8.30	8.27	7.96

* ( ) based on 2 months' data; ?( ) no data or only 1 month's data available, value assumed from previous record.
** Kempton Park

Estimated total monthly effluent flows (Table 3) ranged between 7.86 and 8.63 x $10^6 m^3$, there being no clear evidence for an increase in effluent flows during the period under consideration. The mean monthly total flow was 8.2 x $10^6 m^3$, giving a mean annual effluent flow of 98.4 x $10^6 m^3$. This is a considerable increase over 70 x $10^6 m^3$ effluent arrived at in Table 1. A crude estimate of the contribution of the total effluent flow in Hartbeespoort Dam is that it is 60% of the virgin MAR + direct precipitation or 38% of the estimated total inflow (virgin MAR + direct precipitation + total effluent flow).

Table 4: Effluent treatment plants in the catchment of Hartbeespoort Dam. Mean monthly concentration (mg l^{-1}) of orthophosphate phosphorus over half yearly periods. Calculated from data provided by the Pollution Control Directorate, Department of Water Affairs.

Period	Jul-Dec 1986	Jan-Jun 1987	Jul-Dec 1987	Jan-Jun 1988	Jul-Dec 1988
Driefontein	0.94	1.27	3.16	(4.94)*	?(4.5)
Alexandra	0.76	0.56	1.37	1.05	0.88
Midrand	3.39	2.74	3.18	?(3.18)	?(3.18)
North Kevin	7.60	2.60	3.95	5.78	9.52
North MP5	3.99	4.95	3.97	4.06	4.32
Percy Stewart	0.66	0.57	0.64	0.60	?(0.60)
Verwoerdburg	0.94	1.95	2.71	1.11	4.04
Rietfontein**	8.16	(6.13)	(6.14)	6.22	7.95
Hartbeesfontein**	9.01	(5.38)	8.28	2.33	1.55
Randfontein	3.89	2.10	1.00	3.01	3.05
Olifantsfontein	8.91	7.72	5.78	2.40	(1.06)
Mean concentration	4.38	3.27	3.65	3.15	3.69

* ( ) based on two months' data; ?( ) no data or only 1 month's value assessed from previous record.
** Kempton Park

From the orthophosphate-phosphorus concentrations (Table 4), it is clear that only the small (Table 3) Percy Stewart treatment works has consistently achieved the 1 mg l^{-1} effluent orthophosphate-phosphorus standard. The second best performer in these terms is the Alexandra works. Orthophosphate concentrations exceeded 6 mg $l^{-1}P$ at times in Northern Kelvin, Rietfontein, Hartbeesfontein and Olifantsfontein effluents. The largest effluent (Northern, MP5) maintained a concentration of 4 to 5 mg $l^{-1}P$ orthophosphate. Over the period covered by the survey, concentrations decreased in the Hartbeesfontein and Olifantsfontein effluents, but increased in the Driefontein effluent. The mean orthophosphate-phosphorus concentration (Table 4) was highest in 1986, but thereafter fluctuated between 3.2 and 3.7 mg l^{-1} (but see below for flow weighted mean concentrations).

The effluent from Northern MP5 contributed between 29 and 49% of the total mass of orthophosphate-phosphorus (Table 5) in effluents in the Hartbeespoort Dam catchment. Other major contributors to the mass are Northern Kelvin and Rietfontein. In the second half of 1988, these three works were the source of 80% of the mass of orthophosphate-phosphorus arising from effluents

Table 5: Effluent treatment plants in the catchment of Hartbeespoort Dam. Mean monthly loads (tonnes) of orthophosphate phosphorus over half yearly periods. Calculated from data provided by the Pollution Control Directorate, Department of Water Affairs.

Period	Jul-Dec 1986	Jan-Jun 1987	Jul-Dec 1987	Jan-Jun 1988	Jul-Dec 1988
Driefontein	0.21	0.26	0.70	(1.17)*	?(1.20)
Alexandra	0.39	0.30	0.83	0.59	0.51
Midrand	0.18	0.22	0.24	?(0.24)	?(0.24)
North Kelvin	7.53	2.30	3.59	5.34	9.36
North MP5	11.31	17.53	13.04	12.21	11.01
Percy Stewart	0.30	0.25	0.25	0.22	?(0.22)
Verwoerdburg	0.38	0.85	1.17	0.49	1.89
Rietfontein**	7.53	(6.74)	(5.82)	6.16	7.09
Hartbeesfontein**	3.87	(1.91)	3.55	0.99	0.67
Randfontein	1.52	0.85	0.40	1.16	1.33
Olifantsfontein	5.55	4.85	3.63	2.12	(1.00)
Total load/month	38.77	36.06	33.22	30.69	34.52

* ( ) based on 2 months' data; ?( ) no data or only 1 month's data available, value assumed from previous record.
** Kempton Park. These effluents flow into Rietvlei Dam (Fig 2), which retains between 30 and 67% of the incoming phosphorus load (Ashton 1981).

in the Hartbeespoort Dam catchment. The total orthophosphate phosphorus load has tended to decline slightly (Table 5).

Unfortunately, this trend is in part due to variation in effluent flows. The flow weighted mean effluent concentrations (Table 6) cannot be said to have changed between 1987 and 1988. Over the past two years the 1 mg l^{-1} orthophosphate-phosphorus standard has not resulted in a decline in the annual phosphorus load on Hartbeespoort Dam.

Table 6: Effluent orthophosphate phosphorus concentrations (mg l^{-1}) in Hartbeespoort Dam catchment. Flow weighted half-yearly mean values, derived from mean monthly total loads (Table 4) and mean monthly total flows (Table 3).

Period	Jul-Dec 1986	Jan-Jun 1987	Jul-Dec 1987	Jan-Jun 1988	Jul-Dec 1988
Mean monthly concentration	4.93	4.18	4.00	3.71	4.34

4.2 Measurement of water quality in inflows, outflows and in the dam

4.2.1 Phosphate concentration and loads derived from daily and 6-hourly sampling of the Crocodile River at Weir A2M12

The electronic devices required to control sample taking by an automatic sampler at Weir A2M12 (Fig 2) proved to be incapable of effecting flow proportional sampling. Much time was lost in testing and modifying the system with the manufacturer. When the control was taken away for modification the automatic sampler was set to fixed interval sampling.

The manufacturer finally conceded that his apparatus would not work and 6 hourly (summer) or 12 hourly winter sampling was followed. This continuous fixed interval sampling commenced in January 1987 and continued to February 1988, with the occasional breaks due to mechanical or power failures.

The data were used, by arrangement, in another contract between the Water Research Commission and the CSIR, Centre for Advanced Computing and Decision Support (Gilfillan & Swart, 1989).

4.2.2 Comparison of inflow, outflow and surface water quality in Hartbeespoort Dam

Monthly concentrations of the water quality properties which have been regularly measured, are shown in Appendix Tables A3 - A6. These data are summarized in Table 7, from which it is possible to compare values not only from site to site, but also from year to year over the past four hydrological years.

Table 7 shows differences in the quality of the Crocodile and Magalies Rivers, with markedly higher concentrations of nearly all constituents in the Crocodile River. The alkalinity, magnesium, silica and pH values were, however, greater in the Magalies River than in the Crocodile River. Mean iron concentrations in the Magalies River in 1984/85 and 1986/87 were distorted by atypically high concentrations in January of each hydrological year. At other times the majority of the recorded iron concentrations were similar in the three hydrological years in which iron concentrations were measured (Table A5).

Table 7: Summarised water quality data for Hartbeespoort Dam, the inflowing Crocodile and Magalies Rivers and the water flowing out of the dam. Hartbeespoort Dam data from integrated sampling from surface to 5m below surface. Based on daily (n = 340 to 365) samples from the Crocodile River and the outflow and on weekly (n = 50 to 52) samples in 1984/85 and 1985/86 and fortnightly (n = 24 to 26) samples in 1986/87 and 1987/88 from the Magalies River and from the dam.

Property and Units	Year	Crocodile A2M12 Mean	Crocodile A2M12 SD	Magalies A2M13 Mean	Magalies A2M13 SD	Hartbeespoort Dam Raft Mean	Hartbeespoort Dam Raft SD	Hartbeespoort Dam Outflow Mean	Hartbeespoort Dam Outflow SD
pH	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
Conductivity mSm^{-1}	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
Sodium mgl^{-1}	1984-85	66	15.8	12	3	54.6	5.5	54	7
	1985-86	62	11,5	12	4	53.2	7.8	52	8
	1986-87	58	10.3	9	2	53.7	8.8	44	8
	1987-88	55	14.4	11	4	48.9	3.0	46	8
Potassium mgl^{-1}	1984-85	11	2	2	0.6	10	1.2	10	1.3
	1985-86	12	1	2	0.3	11	1.2	11	1.4
	1986-87	9	2	2	-	11	1.2	9	1.8
	1987-88	9	2	1	0.5	9	0.6	9	1.8
Calcium mgl^{-1}	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
Magnesium mgl^{-1}	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	2
	1987-88	18	3	27	5	16	1	18	3

Table 7: (Continued)

Property and Units	Year	Crocodile A2M12 Mean	Crocodile A2M12 SD	Magalies A2M13 Mean	Magalies A2M13 SD	Hartbeespoort Dam Raft Mean	Raft SD	Outflow Mean	Outflow SD
Kjeldahl-N $\mu g l^{-1}$	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
Ammonium-N $\mu g l^{-1}$	1984-85	378	380	72	35	148	80	390	246
	1985-86	511	729	96	26	190	76	353	180
	1986-87	417	288	126	121	198	152	688	450
Nitrate+Nitrite -N $\mu g l^{-1}$	1984-85	9070	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
Nitrite-N $\mu g l^{-1}$	1984-85	191	156	14	13	104	28	137	50
	1985-86	284	138	12	6	226	117	264	149
	1986-87	316	197	22	35	186	116	268	162
Silica $mg l^{-1}$	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
Sulphate $mg l^{-1}$	1984/85	123	25	19	4	108	16	105	15
	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
Total P $\mu g l^{-1}$	1984-85	2117	607	166	30	624	93	612	164
	1985-86	1659	440	161	39	369	63	478	77
	1986-87	1508	439	199	101	364	41	510	141
	1987-88	1550	676	57	78	236	74	414	178
Orthophosphate -P $\mu g l^{-1}$	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
Chloride $mg l^{-1}$	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
Alkalinity mg $CaCO_3 l^{-1}$	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

Continued /.....

Table 7: (Continued)

Property and Units		Year	Crocodile A2M12 Mean	Crocodile A2M12 SD	Magalies A2M13 Mean	Magalies A2M13 SD	Hartbeespoort Dam Raft Mean	Raft SD	Outflow Mean	Outflow SD
Iron	$mg l^{-1}$	1984-85	134	170	205	383	106	67	54	24
		1985-86	68	59	86	57	87	37	55	32
		1986-87	133	123	280	488	50	30	43	19
DOC	$mg l^{-1}$	1984-85	7.8	1.6	3.2	0.7	7.7	0.8	7.7	0.9
		1985-86	7.0	1.3	3.0	0.7	7.5	0.9	8.1	2.6
		1986-87	6.6	1.8	3.3	1.6	8.9	1.9	7.7	1.1

* From field measurements October to April. From laboratory measurements, May September 1988, mean pH was 7.6 & SD was 0.2

The concentrations of constituents in the dam were usually intermediate between the concentrations of the two inflowing rivers. The outflow water differed significantly from surface waters of the dam only in respect of pH ($P<0.001$), Kjeldahl nitrogen ($p = <0.05$ to <0.01) and ammonium nitrogen ($P<0.01$). In the case of pH the difference was most probably an artifact due to measurement of pH in the field on the dam and in the laboratory for the inflows and outflows (see Table 7 footnote and Appendix A1, pH). The significant differences between the surface waters of the dam and the outflow with respect to Kjeldahl nitrogen and ammonium nitrogen are readily explained by the fact that the outflow water is withdrawn from below the summer thermocline, where conditions are chemically reducing.

It was only in the nutrients, bound nitrogen and phosphorus, that significant concentration changes occurred from year to year (Table 7). There was a significant ($P<0.01$) drop in the mean total phosphorus concentration from hydrological year 1984/85 to

1985/86 in the Crocodile River, in the dam and in the outflow. This coincided with the implementation of the 1 mg l^{-1} phosphate standard. As is evident from Table 7, the mean concentration of orthophosphate-phosphorus declined by approximately 30% in the Crocodile River. However, there was no significant difference ($p<0.05$) between the annual mean total phosphorus and orthophosphate-phosphorus concentrations recorded at these points from 1985/86 to 1987/88.

Nevertheless, graphical presentations (Figure 4) of successive total phosphorus and orthophosphate-P concentrations in surface (0 to 5 m) and deep (10 m to bottom) water in Hartbeespoort Dam from October 1984 to March 1989 reveal a pronounced trend of declining concentrations with time, particularly in the surface waters. (It should be pointed out that the surface water values used are not the same as those used in Tables 7 and A3, which are integrated sample values supplied by the Hydrological Research Institute). Other features revealed by the graphs are the tendency for surface concentrations to be highest during the winter, mixed period and for bottom concentrations to be highest in the summer, stratified period.

There was a significant ($p<0.01$) increase in the mean nitrate plus nitrite concentration from 1984/85 to 1985/6 in the Crocodile River, in the dam and in the outflow, but again no significant change in concentration from 1985/86 to 1987/88 (Table 7). Kjeldahl nitrogen concentrations were significantly lower ($p<0.01$) in the Crocodile River and in the dam in 1986/87 than in 1985/86 and the ammonium nitrogen concentration in the outflow was significantly higher ($P<0.01$) in 1986/87 than in 1985/86. There are no confirmed explanations for these significant changes in

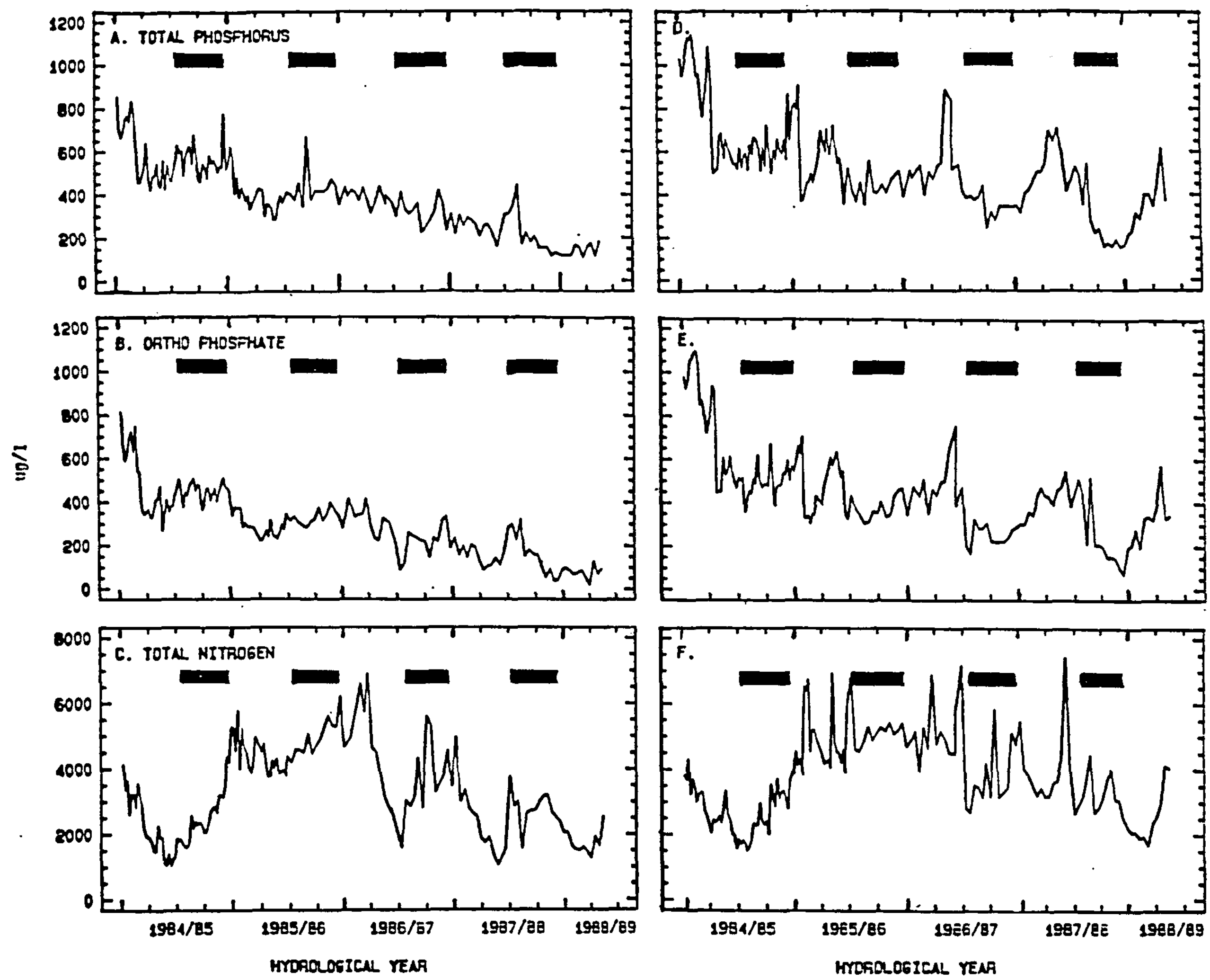

Figure 4: Hartbeespoort Dam. Variations in concentrations of total phosphorus, orthophosphate-P and total nitrogen in surface (0 to 5m), A to C, and bottom (10m to bottom), D to F, waters. 1984/85 to March 1989. Black rectangles show the winter, mixed period.

the concentrations of bound nitrogen in the river, dam and outflow.

Plots of total nitrogen concentrations in surface (0-5 m) and deep (10 m - bottom) waters from October 1984 to March 1989 (Figure 4) show that surface concentrations were low in summer 1984/85, rose considerably through the remainder of 1985, stayed high in 1986, but have subsequently declined. Summer 1985/86 was exceptional in that total nitrogen concentrations remained high whereas they declined sharply in all other summers. The general trend of concentration change in total nitrogen in the deep waters from year to year was similar to that in the surface waters. However, in summer 1986/87 and 1987/88 there were steep rises in deep water total nitrogen concentrations coinciding with the annual minimum surface concentrations.

Table 8 has been compiled to report the latest available data (up to the end of calendar year 1988) on nutrients in the Crocodile River and to compare it with previous years. In winter loads of total phosphorus, orthophosphate-P and total nitrogen followed flows, the greater the flow the greater the load. In winter flow-weighted mean concentrations of total phosphorus and of orthophosphate-P have increased from 1986 to 1988, as has the total phosphate concentration in summer. Orthophosphate-P concentrations in summer almost doubled from 1986 to 1987 but declined again in 1988 to some 20% above the 1986 concentrations. Total nitrogen concentrations declined in winter over the three years, but in summer were 50% greater in 1987 than they were in 1986 or 1988. The total phosphorus to orthophosphate-P ratio increased in both seasons over the 3 year period. The total nitrogen to total phosphorus and to orthophosphate-P ratios declined in both seasons over the three year period.

Table 8: Crocodile River. Comparison of winter (May to August) and early summer (September to December) flows, nutrient loads, flow weighted mean nutrient concentrations and nutrient concentration ratios in 1986, 1987 and 1988.

	Winter 1986	Winter 1987	Winter 1988	Summer 1986	Summer 1987	Summer 1988
Flow volume ($m^3 \times 10^6$)	24	28	32	67	57	40
Total phosphorus (TP) load t.	35	50	64	64	99	71
Orthophosphate-P (PO_4) t	30	37	47	53	79	41
Total Nitrogen (TN) t.	363	403	423	728	881	421
TP conc. $\mu g l^{-1}$	1459	1783	2004	959	1728	1805
PO_4-P conc. $\mu g l^{-1}$	1265	1339	1475	794	1386	1046
TN conc. $\mu g l^{-1}$	15206	14512	13169	10945	15392	10631
TP : PO_4-P	1.2:1	1.3:1	1.4:1	1.2:1	1.3:1	1.7:1
TN : TP	10:1	8:1	7:1	11:1	9:1	6:1
TN : PO_4-P	12.1	11.1	9.1	14.1	11.1	10.1

The data shown in Table 8 do not lend support to any suggestion that the decline in the concentration in either total phosphorus or in orthophosphate in the dam (Figure 4) from 1986 to 1989, was due to a decreased load from the Crocodile River. Nevertheless the total phosphorus to orthophosphate-P ratios in the inflowing water have increased steadily. This may be an indication that increases in orthophosphate-P concentrations are being restrained by the effluent standard.

4.2.3 <u>Nutrient loads, mass balances and volume weighted annual concentrations in the dam, inflow and outflows</u>

The volumes of inflow, outflow and of stored water, which are essential components of mass balances and volume weighted concentrations, are shown in Table 9. In 1984/85 and 1985/86 outflows were managed to approximately equal inflows, so that the stored volume did not change. Rainfall in summer 1986/87 was above average and the mean volume of stored water rose to nearly 60% (Table 2) of full supply. Inflows in 1987/88 were again substantial and the mean stored volume rose to nearly 90% of full supply.

Table 9. Hartbeespoort Dam. Inflows, outflows and mean stored volume 1984/85 to 1987/88.

Hydrological year	1984/85	1985/86	1986/87	1987/88
Inflow (10^6 m^3)	108	122	223	180
Outflow (10^6 m^3)	106	119	112	143
Mean standard volume (10^6 m^3)	74	73	116	174

The total phosphorus mass balance (Table 10) shows that between 62 and 77 per cent of the inflow load did not leave the dam in the year in which it arrived. Bringing the mass of total phosphorus in the water column at the beginning and end of each year into account, allows for the calculation of 'sedimented' or otherwise unaccounted for total phosphorus. 'Sedimented' phosphorus was by far the greatest in 1987/88 (Table 10), when it was 84% of the incoming load. At the same time the sedimentation rate in g $m^{-2}a^{-1}$ was lowest in 1987/88. Four factors are likely to have brought about this lower sedimentation rate. Firstly, the ratio of the area of anaerobic sediments to the area of aerobic sediments increased as the dam filled from 1984/85 (ratio 0.40) to 1987/88 (ratio 0.47). (These ratios are based on an anaerobic zone assumed to extend from the bottom to 8 m from the surface, the volume data in Table 9 and hypsographic data in Table 2).

Since phosphate release is greater than uptake in the anaerobic hypolimnion (Wetzel 1983), the greater the stored volume of water, the greater the hypolimnetic phosphate release and the lower the net phosphate sedimentation rate.

Table 10: Hartbeespoort Dam. Total phosphorus mass balances for the hydrological years 1984/85 to 1987/88

Hydrological year		1984/85	1985/86	1986/87	1987/88
Inflow load t	A	190	169	240	226
Mass in dam 1 Oct. (t)	B	46	36	25	49
Mass in dam 30 Sept. following year (t)	C	36	25	49*	33
Outflow load (t)	D	64	62	70	52
Retained (t)	A-D	126	107	170	174
% Retained	100 (A-D)/A	72	62	71	77
'Sedimented' (t)	A+B-C-D	136	118	146	190
% 'Sedimented'	100(A+B-C-D)/A	72	70	61	84
Mean surface area of impounded water (km^2)	E	9.6	9.4	13.8	18.5
Sedimentation rate ($g.m^{-2}.a^{-1}$)	(A+B-C-D)/E	14.2	12.6	10.6	10.3
Volume weighted mean annual impounded Total Phosphorus concentration μgl^{-1}		666	505	508	327
Water residence time (y)		0.66	0.60	0.50	0.97

*Value for 16 September, because an anomolously high volume-weighted mean total phosphorus concentration was recorded on 29 September 1989 as shown below:-

	Impounded volume	Vol. weighted mean TP	Mass TP in dam
87-09-16	119.4×10^6 m^3	414 $\mu g\ l^{-1}$	49 t
87-09-29	119	783	93
87-10-13	137	310	43

The second factor is a corollary of the first - the fuller the dam, the lower the proportion of epilimnetic sediments. Since phosphate adsorption takes place mainly under aerobic (epilimnetic) conditions, the fuller the dam the lower the proportion of sediments which adsorb phosphates. Thirdly, phosphate sedimentation rates are directly related to the phosphate concentration in the overlying water (NIWR, 1985) and this was lowest in 1987/88 (Table 10). Fourthly, Twinch (1987) concluded, from a laboratory study of the phosphorus dynamics of wet and dried sediments from Hartbeespoort Dam, that re-flooding of previously exposed sediments would result in 'a flush of phosphorus from the sediments'. These four factors, which tend to decrease the net sedimentation rate, may have been slightly ameliorated by the water residence time, which was greatest in 1987/88 (Table 10). The duration of submergence of the sediments increases with increasing water residence time, presumably allowing greater sedimentation.

Despite this reduced sedimentation rate, the mass of phosphate sedimented (Table 10) was high in 1987/88. This loss and the low annual areal (and volumetric) phosphate loading rates (see below, Table 13) were the probable causes of the sharp decline in the phosphate concentration of the dam in 1987/88, which has continued into 1988/89 (Figure 4). The extent of both processes would appear to be due primarily to the fact that the dam has filled over the past three summers, increasing phosphate losses by sedimentation and decreasing areal and volumetric loading rates.

In the case of nitrogen in lakes and reservoirs, losses may be due to sedimentation, to denitrification, to volatilization of ammonia. Although denitrification takes place under anaerobic conditions and the breakdown of organic nitrogen to ammonia under aerobic conditions, both processes can occur simultaneously in partially anaerobic Hartbeespoort Dam. Nitrogen loss rates (Table 11) through these processes were greatest in 1986/87 and 1987/88, when the volume of the anaerobic zone was greatest.

Table 11: Hartbeespoort Dam. Total nitrogen mass balances for the hydrological years 1984/85 to 1987/88.

Hydrological year		1984/85	1985/86	1986/87	1987/88
Inflow load (t)	A	935	1395	2266	2109
Mass in dam 1 Oct. (t)	B	201	257	303	577
Mass in dam 30 Sept. following year (t)	C	257	303	577	457
Outflow load (t)	D	283	580	552	495
Retained (t)	A-D	652	815	1714	1614
% Retained	100 (A-D)/A	70	58	76	77
'Denitrified/ Sedimented' (t)	A+B-C-D	596	769	1440	1734
% 'Denitrified/ Sedimented'	100(A+B-C-D)/A	64	55	64	82
Mean surface area (km^2)	E	9.6	9.4	13.8	18.5
Denitrification/ Sedimentation rate ($g.m^{-2}.a^{-1}$)	(A+B-C-D)/E	62	82	104	94

Volume weighted annual nutrient concentrations are shown in Table 12. Nitrogen concentrations were lower in 1984/85 in the inflow, the dam itself and in the outflow than in subsequent years when there was little variation. Total phosphorus and orthophosphate-P concentrations followed one another. The inflow concentration dropped sharply from 1984/85, coinciding with the introduction of the 1 mg l^{-1} effluent phosphate-P standard, but since then there has been no further downward trend. In the dam the concentration dropped markedly between 1984/85 and 1985/86 and again between 1986/87 and 1987/88. Variations in outflow total phosphorus and orthophosphate-P concentrations were less than in inflow and in-lake concentrations. However, outflow concentrations have been high relative to in-lake concentrations in 1986/87 and 1987/88, when the dam was very much fuller than in the past. These high (relative to in-lake) outflow concentrations would have contributed to a lowering of the mean in-lake concentrations.

Table 12: Hartbeespoort Dam. Volume weighted annual mean nutrient concentrations (µg l^{-1}) and nutrient ratios, 1984/85 to 1987/88.

Year		1984/85	1985/86	1986/87	1987/88
Kjeldahl-N	Inflow	1196	1852	1074	1207
	In-lake	1101	1389	1392	1072
	Outflow	1067	1227	1245	1468
NO_2+NO_3-N	Inflow	7149	9574	9113	10575
	In-lake	1454	3444	3635	2184
	Outflow	1447	3647	3729	3073
Total nitrogen	Inflow	8270	11434	10161	11782
	In-lake	2555	4833	5027	3256
	Outflow	2514	4874	4974	4541
Total phosphorus	Inflow	1687	1213	1081	1257
	In-lake	666	505	508	327
	Outflow	591	521	625	477
Orthophosphate-P	Inflow	1518	929	852	967
	In-lake	495	366	295	216
	Outflow	497	379	482	357
TN:TP ratios	Inflow	4.9:1	9.4:1	9.4:1	9.4:1
	In-lake	3.8:1	9.6:1	9.9:1	10:1
	Outflow	4.3:1	9.4:1	8.0:1	9.5:1

Nitrogen to phosphorus ratios in inflow, in-lake and outflow water (Table 12) rose sharply from 1984/85 to 1985/86 but have varied little since these. Both areal and volumetric loads of total nitrogen (Table 13) increased from 1984/85 to 1985/86, peaked in 1986/87 and then, with the very much fuller reservoir (Table 9) declined in 1987/88. For total phosphorus there was a slow decline in both the areal and volumetric load from 1984/85 to 1986/87 followed by a sharp decline from 1986/87 to 1987/88.

Table 13: Hartbeespoort Dam. Areal and volumetric nitrogen and phosphorus loads, 1984/85 to 1987/88.

Year	1984/85	1985/86	1986/87	1987/88
Areal load $g.m^{-2}.a^{-1}$				
Total nitrogen	97.4	140.5	164.0	114.0
Total phosphorus	20.2	18.6	17.4	12.2
Volumetric load $g.m^{-3}.a^{-1}$				
Total nitrogen	12.6	18.0	19.5	12.1
Total phosphorus	2.6	2.4	2.1	1.3

4.2.4 Heavy metals and total organohalogen potential in the Hartbeespoort Dam System

Concentrations of heavy metals and of total organohalogen potential were measured at quarterly intervals in 1985/86 and 1986/87 in the inflows and in the dam. Annual mean values are recorded in Table 14, where it may be seen that barium and selenium concentrations were always, and arsenic concentrations were frequently, below the limits of measurement. Aluminium, zinc and strontium were the only metals shown in the table which were recorded at concentrations greater than 100 $\mu g\ l^{-1}$. It was found that many samples had been contaminated before analysis by traces of mercury in sampling bottles. These traces remained from other water samples which had been preserved for organic analysis using mercuric chloride. Mercury values are not recorded in Table 14, but samples collected with precautions to prevent mercury contamination contained <1 $\mu g\ l^{-1}$ which is within the acceptable range of concentration.

Table 14: Hartbeespoort Dam. Heavy metals and total organohalogen potential in inflows and the dam, 1985/86 and 1986/87. All concentrations in $\mu g l^{-1}$.

Sampling point		Crocodile A2M12	Magalies A2M13	Hartbeespoort Dam Raft 0m	Raft 10m	Raft 20m	Outflow
Aluminium	1985-86	812	160	353	274	414	800
	1986-87	766	245	102	148	168	173
Arsenic	1985-86	8	5	6	5	5	5
	1986-87	<5	<5	<5	<5	<5	<5
Barium	1985-86	<500	<500	<500	<500	<500	<500
	1986-87	<500	<500	<500	<500	<500	<500
Chromium	1985-86	27	25	34	29	35	29
	1986-87	<25	26	<25	34	28	33
Cadmium	1985-86	12	7	8	7	9	9
	1986-87	6	5	<5	6	6	6
Cobalt	1985-86	40	28	33	37	36	29
	1986-87	30	26	<25	27	26	27
Copper	1985-86	33	25	67	29	30	34
	1986-87	27	27	<25	27	<25	29
Lead	1985-86	66	50	56	69	66	55
	1986-87	<50	<50	56	55	52	51
Nickel	1985-86	52	35	20	18	50	46
	1986-87	40	39	28	42	36	39
Selenium	1985-86	<5	<5	<5	<5	<5	<5
	1986-87	<5	<5	<5	<5	<5	<5
Zinc	1985-86	125	45	269	82	106	71
	1986-87	102	87	77	82	82	107
Strontium	1985-86	397	110	135	135	125	331
	1986-87	282	113	307	332	337	332
TOHp	1985-86	556	308	279	260	260	314
	1986-87	349	287	352	328	312	339

Aluminium, zinc and strontium concentrations were greater in the Crocodile River than in the Magalies. This suggests that the urban and industrial development which has taken place in the Crocodile catchment may be responsible for these higher concentrations.

There were no conclusive, consistent differences between the two rivers with regard to the other metals shown in Table 14.

Metal concentrations in the dam were either similar to concentrations in the inflows, or in the case of aluminium, zinc and strontium often intermediate between the values recorded from the two rivers. The available data do not show that concentrations of any of the metals recorded in Table 14 systematically varied with depth in the dam.

Total organohalogen potential was highest in the Crocodile River in 1985/86. Other values from all sampling points varied between only 260 and 349 $\mu g l^{-1}$. There was no evidence that total organohalogen potential increased in the impounded water.

4.2.5 The suitability of water abstracted from Hartbeespoort Dam for various uses

Thornton (1987) assessed the quality of water in Hartbeespoort Dam according to the G.D.R. Technical Standard (GDR 1982) and internationally accepted standards (Kempster *et al*. 1980). Following the GDR Standard Hartbeespoort Dam water was classified as moderately impaired, requiring comprehensive treatment for domestic and industrial use, but usable for irrigation. This classification was similar to the classification arrived at from Kempster *et al*'s internationally accepted standards.

The chemistry of the epilimnion and of the outflow for 1986/87 and 1987/88 (Table 7) shows that in respect of nitrate and nitrite-N and ammonium-N the water quality has deteriorated slightly, but not sufficiently to alter its previous classification.

4.3 The phytoplankton and zooplankton of the dam.

4.3.1 Summer physical conditions pertinent to the phytoplankton abundance and species composition.

Surface water temperatures during the summers of 1986/87, 1987/88 and 1988/89 are shown in Figure 5. Particularly in the early part of the summer (September to December), when Microcystis aeruginosa Kütz. emend. Elenkin usually establishes its dominance over other phytoplankton species (Section 4.3.2) temperatures in summer 1988/89 differed little from those of the other two summers.

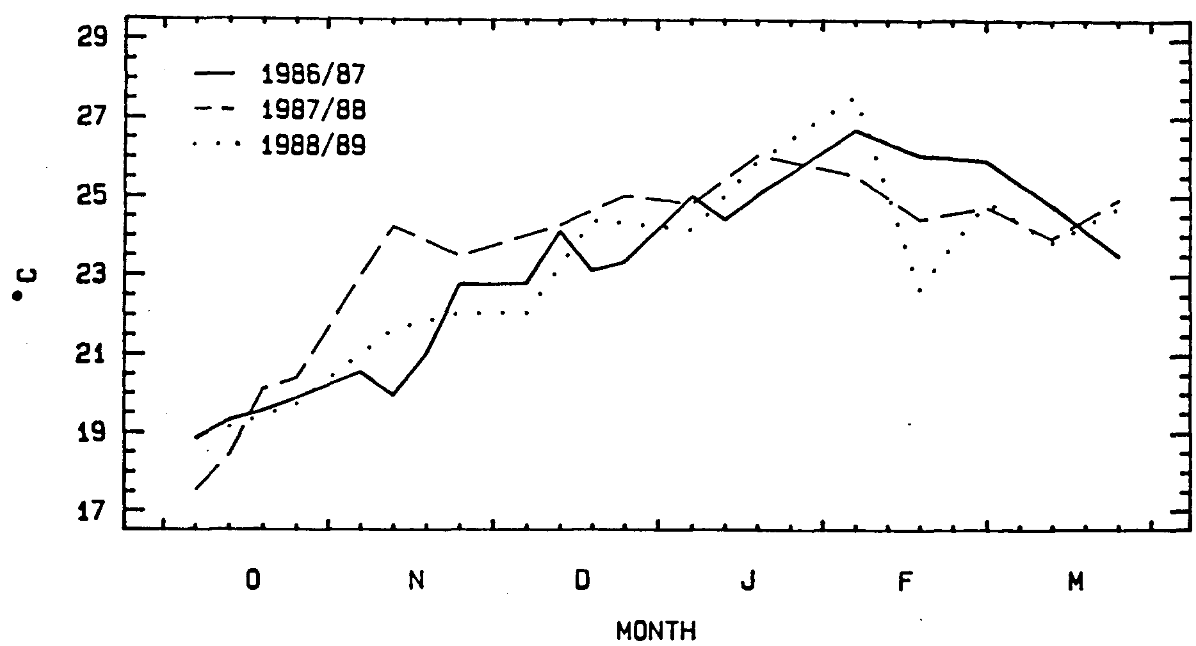

Figure 5: Hartbeespoort Dam. Mean surface water temperatures (0 to 8m). October to March 1986/87, 1987/88 and 1988/89.

Differences in mean summer temperatures from year to year over an extended period (Table 15) were small. The maximum mean temperature in summer 1988/89 was nearly 1°C higher than in other summers (Figure 10) but this occurred in February, long after Microcystis failed to dominate the phytoplankton (Section 4.3.2).

Table 15: Hartbeespoort Dam. Selected physical data, October to March, 1984/85 to 1988/89.

Year	1984/ 1985	1985/ 1986	1986/ 1987	1987/ 1988	1988/ 1989
(a) Mean surface (0-8m) water temperature (°C)					
Number of observations	25	24	19	15	13
Mean	23.0	22.8	23.0	23.2	23.3
Standard deviation	1.8	1.7	2.4	2.7	2.4
(b) Mean daily wind speed (km d^{-1})					
Number of observations	26	26	26	23	21
Mean	147	151	151	140	142
Standard deviation	27	22	28	24	30
(c) Depth of oxycline (m from surface)					
Number of observations	24	24	19	15	13
Mean	14.4	16.7	13.7	16.2	15.3
Standard deviation	4.9	4.3	2.2	6.1	4.0
(d) Depth of euphotic zone (m)					
Number of observations	25	22	13	15	13
Mean	3.0	2.87	2.75	2.56	4.15
Standard deviation	1.2	0.96	1.05	1.12	0.93

Mean daily wind speed (Table 15) was higher in summer 1985/86 and 1986/87 than in 1987/88 or in 1988/89, which differed little. The mean oxycline depth increased in 1987/88 and 1988/89 over what it had been in 1986/87 (Table 15). There are several potential reasons for this, such as a lower hypolimnetic oxygen demand or a greater stored water volume (Table 9). Patalas (1984) has shown that the depth of wind mixing is related to fetch in the direction of the prevailing wind. An increase in water surface area due to the dam filling would therefore result in a greater depth of wind mixing and of the oxycline for a given wind speed.

In Hartbeespoort Dam light penetration into the water column is governed by phytoplankton, rather than by inorganic suspensoids. The mean depth of the euphotic zone in summer (Table 15) was considerably greater and less variable (standard deviation/mean) in 1988/89 than in any of the previous four summers, which were similar to one another with respect to light penetration.

4.3.2 The phytoplankton

The mean annual phytoplankton biomass of the top 8m of the surface water varied little from year to year over the past four hydrological years (Table 16). Another measure of phytoplankton abundance, chlorophyll a concentration, was remarkably constant from year to year when calculated as a mean value for 0-15m (from surface) depths (Table 16). Euphotic zone chlorophyll a, which is the measure of phytoplankton abundance used in the O.E.C.D.-type eutrophication models (OECD 1982, Rast *et al.*, 1983), was more variable, but has shown no linear trend of concentration change over the years 1984/85 to 1987/88 (Table 16).

Table 16: Hartbeespoort Dam. Phytoplankton biomass (mg l^{-1}) and mean annual chlorophyll concentration in µg l^{-1}, 1984/85 to 1987/88.

Depth range	Biomass 0 - 8m		Chlorophyll a 0-15m		Chlorophyll a euphotic zone	
	mean	S.D.*	mean	S.D.*	mean	S.D.*
1984/85	23	20	23	18	52	58
1985/86	19	16	24	15	63	44
1986/87	22	19	26	18	75	94
1987/88	18	15	25	21	66	96

* S.D. - standard deviation of the mean.

In order to update information to include the summer 1988/89, phytoplankton data for the period October to March for the past five summers have been compiled in Table 17. The mean phytoplankton biomass has remained remarkably constant from year to year. Summer 1988/89 differed from the other four summers in that Microcystis aeruginosa did not dominate the phytoplankton biomass (Table 17 and Figure 6). In this respect the summarized data in Table 17 are misleading. In most years Microcystis dominance became

Table 17: Hartbeespoort Dam. Selected phytoplankton data for October to March, 1984/85 to 1988/89.

Year	1984/ 1985	1985/ 1986	1986/ 1987	1987/ 1988	1988/ 1989
(a) Total phytoplankton biomass (mg l^{-1})(0-8m)					
Number of observations	26	26	19	15	13
Mean	28	23	27	27	27
Standard deviation	21	19	15	13	24
(b) Microcystis biomass as percentage of total phytoplankton biomass					
Number of observations	26	26	21	15	13
Mean	62	75	42	73	3
Standard deviation	37	32	43	39	3
(c) Chlorophyll a concentration $\mu g l^{-1}$ (0-15m)					
Number of observations	25	24	13	13	13
Mean	28	26	30	39	23
Standard deviation	21	17	16	19	13
(d) Chlorophyll a concentration $\mu g l^{-1}$ (euphotic zone)					
Number of observations	25	22	13	13	13
Mean	76	67	109	118	47
Standard deviation	69	45	103	111	27

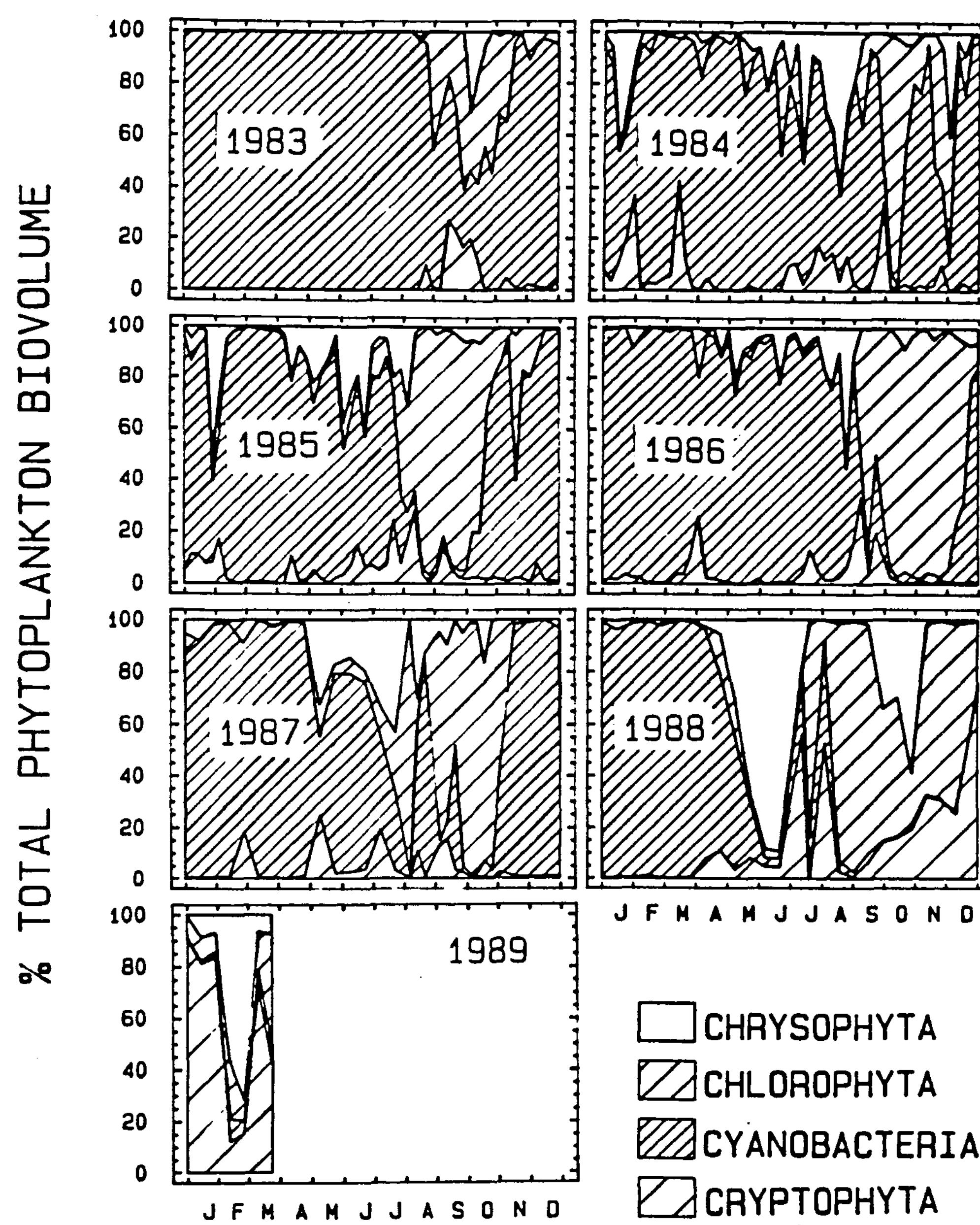

Figure 6: Hartbeespoort Dam. Phytoplankton composition. January 1983 to March 1989.
(Chrysophyta - diatoms; Chlorophyta - green algae; Cyanobacteria - blue green algae, mainly Microcystis; Cryptophyta - unicellular motile algae)

became apparent in mid to late October and rapidly increased, so that by late November, early December Microcystis made up over 90% of the phytoplankton (Figure 6). This level of dominance was maintained until early winter. In 1986/87 the low mean Microcystis biomass (Table 17) was due mainly to a delay in the onset of Microcystis dominance until the end of the first third of December (Figure 6).

As for the annual mean chlorophyll concentration variations (Table 16), variations in the summer chlorophyll concentrations depended on how the measured chlorophyll concentrations are expressed (Table 17). Mean 0-15m concentrations were high in 1987/88 and a little lower in 1988/89 than in the first three summers (1984/85 to 1986/87). In the euphotic zone chlorophyll concentrations were high in 1986/87 and 1987/88, intermediate in 1984/85 and 1985/86 and low in 1988/89. The low mean concentration in 1988/89 is to be associated with the virtual absence of Microcystis which is buoyant. When it is present the euphotic zone is limited in extent, but the chlorophyll content is great.

4.3.3 The zooplankton

Recent variation in the composition of the zooplankton of Hartbeespoort Dam is shown in Figure 7. The species composition in 1986 and 1987 was similar to that of previous years (Jarvis 1987), important aspects being prolonged mid-summer to mid-winter Ceriodaphnia dominance and mid-winter to mid-summer Daphnia dominance.

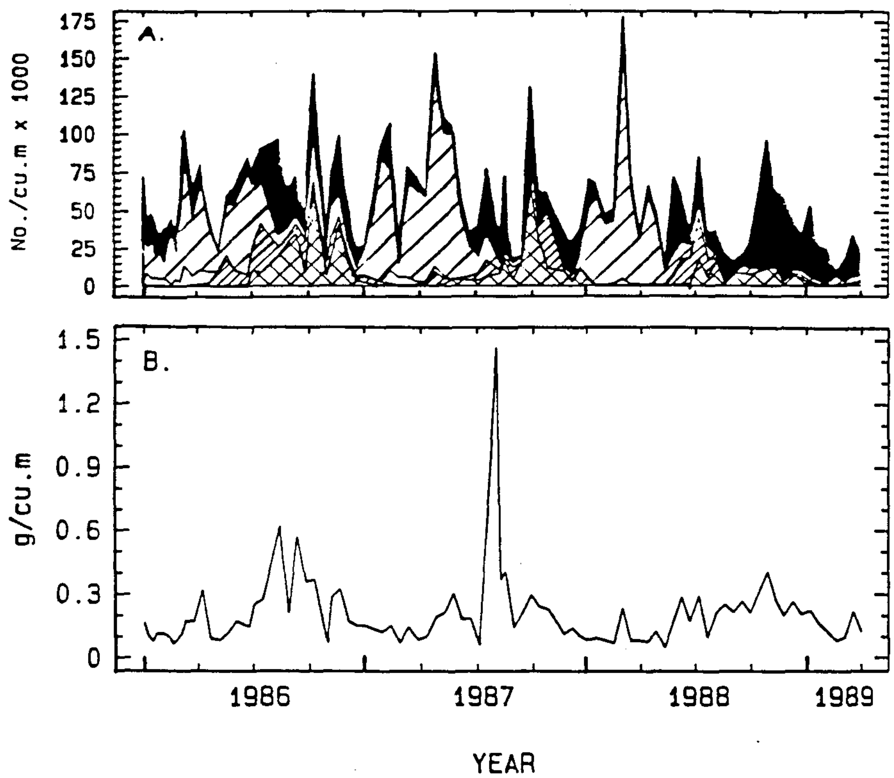

Figure 7: Hartbeespoort Dam. Zooplankton. Species abundance (A) and biomass (B). January 1986 to March 1989. ■ Thermocylops oblongalus; Ceriodaphnia; Moina and Diaphanosoma; Bosmina; Daphnia.

Jarvis suggested that Ceriodaphnia's specific feeding requirements allowed it to thrive when Microcystis was dominant (although it did not feed directly on Microcystis to any extent). Daphnia was unable to tolerate Microcystis, but thrived on species which dominated the phytoplankton community in late winter/spring. Bosmina, another phytoplankton/ detritus feeder occurred less systematically and formed the principle prey of the carnivorous species Thermocyclops oblongatus.

As can be seen from Figure 7(A), the zooplankton was dominated by Thermocyclops oblongatus in summer 1988/89, and neither Ceriodaphnia nor Bosmina occurred in large numbers. There was no spring bloom of Daphnia. Clearly, the composition of the zooplankton was unusual in spring/summer 1988/89. The overwhelming dominance by a predatory species, without supporting knowledge of what it was feeding on, precludes interpretation of the response of the non-predatory zooplankton species to the unusual phytoplankton community.

Following Jarvis's (1987) hypotheses, the phytoplankton of summer 1988/89 should have been more palatable to the grazing zooplankton species, because of the absence of Microcystis. This may have been the case, but it was not reflected in an increase in the zooplankton biomass (Figure 7(B) and Table 18).

Table 18: Hartbeespoort Dam. Zooplankton biomass (g m^{-3}), October to February, 1986/87 to 1988/89.

Year	1986/87	1987/88	1988/89
Number of estimates	12	12	11
Mean	0.24	0.15	0.22
Standard deviation	0.14	0.08	0.09

4.4 The impact of the spilling of the reservoir and the voiding of scums in 1986/87 and 1987/88 on the reservoir

A preliminary brief account of the spilling of scums from Hartbeespoort Dam in 1986/87 has been given by Zohary (1988). Table 19 provides comparative data on the phytoplankton from March to July for years when the dam spilled (1987 and 1988) and years when it did not spill (1985 and 1986).

As Zohary (1988) pointed out, in April-May the usually abundant Microcystis population of Hartbeespoort Dam becomes over-buoyant and forms massive scums, which accumulate at the dam wall. As can be seen for the biomass data for 1985 and 1986 in Table 19, this results in a general decline in the phytoplankton biomass in the main basin of the dam. However, as the scum can be temporarily blown away from the dam well into the main basin, occasional high biomasses are recorded (e.g. 28.4.1985, 9.6.1987, 14.4.1987) in the autumn and winter in the main basin.

In 1985 and 1986 Microcystis made up a large part of the biomass right through to July. However, the two years differed in May and June (and possibly in April too, but data are not available for 1985) in that the euphotic zone chlorophyll concentrations were lower and the zone deeper in 1985 than 1986.

In 1987 values of all the phytoplankton properties were high and the euphotic zone depth was shallow from February through to 12 May (Table 19). Thereafter the surface waters, carrying a massive Microcystis scum with them, were spilled. Biomass and chlorophyll concentration dropped sharply and stayed low and there was a doubling of the depth of the euphotic zone. However, Microcystis remained abundant relative to other phytoplankton species (Table 19, see also Figure 6).

In 1988 the dam spilled in March, April and June. The March spill was large in volume (Table 19) but had no evident impact on the phytoplankton abundance or species composition. There were no scums at this time. The April 1988 spill was followed by a decline in the Microcystis abundance relative to other species and there were no subsequent large phytoplankton biomasses or high chlorophyll, low transparency occurrences in the main basin. The third spill washed out another scum for it resulting in a 20% drop in the abundance of Microcystis relative to other taxa.

Zohary (1988) estimated that scums contain up to two tonnes of phosphates, which would have been washed out of the dam. Unfortunately, samples for nutrient analysis were not collected from the scum-filled spilling water. It is desirable to consider the phosphate loss with scums in the phosphate mass balance for the reservoir. Reference to Table 10 shows that 2 t phosphate is of the order of 1% of the "sedimented" phosphates in 1987/88 and

Table 19: Hartbeespoort Dam. Phytoplankton properties in the main basin and the spilling of the dam.

	Biomass mg l^{-1} (% *Microcystis*)			
Year	1985	1986	1987*	1988*
Approximate day and month				
4-2	52 (48)	11 (87)	27 (97)	9 (97)
18-2	55 (92)	76 (99)	30 (98)	30 (95)
3-3	12 (96)	22 (99)	8 (72)	8 (97)
18-3	47 (98)	13 (95)	64 (100)	38 (99)[1]
31-3	41 (97)	15 (85)	34 (96)	21 (95)
14-4	5 (59)	11 (89)	304 (99)	8 (87)[2]
28-4	48 (85)	7 (81)	10 (98)	5 (58)
12-5	10 (78)	21 (70)	32 (30)	3 (46)
26-5	5 (85)	9 (83)	3 (77)[1]	1 (23)
9-6	7 (57)	53 (93)	3 (76)[2]	5 (3)[3]
25-6	12 (50)	9 (77)	4 (72)	3 (3)
9-7	21 (74)	13 (95)	7 (36)	1 (23)
	Euphotic zone Depth m (Chlorophyll *a* µg l^{-1})			
4-2	2 (31)	3 (31)	2 (325)	4 (22)
18-2	1 (91)	-	2 (90)	3 (63)
3-3	3 (52)	1 (84)	4 (26)	3 (64)
18-3	1 (215)	-	3 (148)	2 (141)[1]
31-3	-	3 (45)	1 (298)	3 (50)
14-4	-	2 (57)	1 (1963)	5 (48)[2]
28-4	-	2 (41)	1 (214)	5 (7)
12-5	3 (19)	2 (143)	4 (31)	5 (5)
26-5	4 (10)	2 (19)	5 (5)[1]	4 (5)[3]
9-6	4 (10)	2 (119)	4 (7)[2]	4 (6)
25-6	3 (15)	3 (26)	4 (11)	5 (5)
9-7	3 (27)	2 (95)	4 (25)	6 (3)

*Spilling of the dam was as follows:-

1987 - 1 25 to 27 May 2.8×10^6 m^3 released in 3 days
2 6 to 9 June 5.5×10^6 m^3 released in 5 days

1988 - 1 12 to 21 March 15.3×10^6 m^3 released in 10 days
2 18 to 25 April 4×10^6 m^3 released in 8 days
3 31 May to 4 June 0.8×10^6 m^3 released in 6 days

would add 4% to the estimated outflow load. Even assuming that Zohary's estimate is as little as half of the true value, phosphate losses with scums make a negligible impact on the phosphate mass balance (Table 10) of the dam.

Another potentially important impact of scum spillage on the reservoir is a change in the dissolved organic carbon in the water which might be expected to result from the decay of scums. The monthly data for 1987 in Table A3 show no unusual decline in the dissolved organic carbon content of the water after the removal of the scums during May and June.

4.5 The evaluation of eutrophication models

4.5.1 The data base

Before presenting and comparing various simple relationships between phosphorus load and in-lake phosphorus and chlorophyll concentrations, it is as well to consider salient features of the summarized Hartbeespoort Dam data base (Table 20). The long-term average annual inflow to Hartbeespoort Dam is 168 x $10^6 m^3$ (NIWR, 1985). Inflow in 1980/81, 1986/87 and 1987/88 was above average. In 1981/82 it was a little below average, but thereafter through to 1985/86 it was considerably below average, with the lowest inflow in 1982/83. Management of the reservoir was such that at the onset of the drought in 1981/82 and 1982/83, considerably more water was released from the dam than flowed into it. The dam volume and mean depth consequently dropped. Although inflow exeeded outflow by 20% in 1983/84, mean dam volume continued to decline. In 1984/85 and 1985/86, inflow and outflow were very nearly equal (allowing for evaporation), but in 1986/87 and 1987/88 the dam filled considerably.

Table 20. Hartbeespoort Dam 1980 to 1988. Summarized hydrological, nutrient loading and chlorophyll data.

Hydrological year	1980/81	1981/82	1982/83	1983/84	1984/85	1985/86	1986/87	1987/88
a. Hydrological data								
1. Volume 10^6 m^3	184	168	82	69	74	73	116	174
2. Mean depth m	9.46	9.28	7.98	7.67	7.71	7.79	8.40	9.41
3. Inflow 10^6 m^3	246	158	99	119	113	122	223	180
4. Outflow 10^6 m^3	213	187	159	99	107	118	112	143
5. Water residence time y	0.75	1.07	0.83	0.58	0.66	0.60	0.52	0.97
6. Hydraulic load m	12.6	8.7	9.6	13.3	11.7	13.1	16.1	9.7
b. Nutrient data								
1. Total P load t	283	323	206	230	190	172	241	225
2. Areal P load g m^{-2}.a	14.6	17.8	20.6	25.9	20.2	18.6	17.4	12.2
3. Volumetric P load g m^{-3}.a	1.54	1.92	2.58	3.38	2.62	2.39	2.08	1.29
4. In-lake P conc. µg l^{-1}	487	543	668	750	666	505	508	327
5. Inflow P conc. µg l^{-1}	1152	2047	2085	1925	1687	1410	1081	1252
6. P sedimentation rate	1.82	2.60	2.55	2.72	2.33	2.99	2.22	2.92
7. Total N-load t	1709	1448	771	898	935	1317	2266	2109
8. Areal N-load g m^{-2}.a	88	79	76	102	97	141	164	114
9. Volumetric N-load g m^{-3}.a	9.3	8.6	9.4	8.9	12.6	18.0	19.5	12.1
10. In-lake N conc. µg l^{-1}	2105	2680	3377	2301	2555	4833	5027	3256
11. Inflow N conc. µg l^{-1}	6950	9160	7790	7530	8270	10795	10161	11743
12. N:P ratio	4.3:1	4.9:1	5.1:1	3.1:1	3.8:1	9.6:1	9.9:1	10:1
c. Chlorophyll								
1. Euphotic zone conc. µg l^{-1}	40	44	94	81	52	63	75	66

In calculating the derived hydrological properties (water residence time, hydraulic load) shown in Table 20, the inflow volumes and not the outflow volumes were used. Inflow volume and stored volume did not follow one another, so that the derived properties behaved independently of either. Thus water residence time was greatest (hydraulic load was least) in 1981/82 and least in 1986/87. Because of changes in the volume of the reservoir, water residence time was not greatest when the reservoir was fullest (1980/81), neither was it greatest when inflow was least (1982/83). Use of the outflow volume resulted in values (not shown in Table 20) of derived hydrological properties which differed considerably from those shown in the table.

Total phosphorus load increased sharply between 1980/81 and 1981/82 (Table 20), but this trend was reversed thereafter, until 1986/87. For three years (from 1982/83 to 1984/85) phosphorus loads followed inflow volumes, but in 1985/86 the load declined with an increased inflow, probably as a result of the gradual adoption of the 1 mg l^{-1} effluent phosphate standard after August 1985. Due to the varying volume of the reservoir and its associated change in surface area, the areal phosphorus load behaved independently of the total phosphorus load. It increased steadily from 1980/81 through to 1983/84, following the decreasing volume (and surface area) of the impoundment. It decreased between 1983/84 and 1987/88 again following rising lake volume trends. Annual mean in-lake phosphorus concentrations rose and fell following areal phosphorus load. Finally, annual mean inflow phosphorus concentrations increased with decreasing inflow from 1980/81 to 1982/83. Thereafter, the inflow phosphorus concentration declined in each successive year until 1986/87. It increased in 1987/88. Due again to the managed volume of the reservoir and the varying total phosphorus load, the greatest areal phosphorus load and in-lake phosphorus concentration (1983/84) did not coincide with the greatest inflow phosphorus concentration (1982/83).

The data in Table 20 indicate clearly that Hartbeespoort Dam is not a reservoir in a steady state. In the relatively short space of 8 years, covering the drought part of the long term hydrological cycle, values of properties other than mean depth shown in Table 20 varied by a factor of at least 1.5 and frequently by as much as 2. Moreover, because we are dealing with a reservoir equipped with both a spillway and deep draw-off points, properties which would be expected to follow one another in a natural lake, such as inflow volume, outflow volume, residence time and hydraulic load, did not do so. Similarly, total phosphorus load and areal phosphorus load varied independently. These reservoir properties further confirm the unsteady state of Hartbeespoort Dam.

4.5.2 The models considered and their evaluation

Dynamic models incorporating Hartbeespoort Dam data have been developed by Rossouw and Grobler (1988) and by Rossouw (1989). It is therefore not intended to consider this type of model further in this report.

The models which are evaluated here use the annual mean inflow phosphorus concentration, or the flushing corrected inflow concentration to predict the annual mean in-lake phosphorus or chlorophyll concentration. The flushing-corrected concentrations are used to account for the sedimentation (or loss within the lake) of phosphate. Grobler and Silberbauer (1984) used a model which incorporated a sedimentation rate specific to the water body concerned, which pre-supposes a fair knowledge of the water body before predictions are made.

Models which predict the annual mean in-lake phosphorus concentration are shown in Table 21. The most accurate ($r = 0.94$, $0.02>p>0.01$) model is the Grobler and Silberbauer model, which has an advantage over the other models in that it includes a sedimentation rate calculated from Hartbeespoort Dam data (Table 20). Nevertheless the OECD and Rast, Jones and Lee models were still useful and their accuracy significant ($r = 0.83$, $0.05>p>0.02$). The prediction of annual mean chlorophyll in Hartbeespoort Dam (Table 22) reveals a less satisfactory state of affairs, for not one of the three models provided a significant relationship between observed and predicted chlorophyll concentrations ($p<0.1$).

Table 21. Models which predict the annual mean in-lake phosphorus concentration (TP in µg l^{-1}), and their accuracy when applied to Hartbeespoort Dam.

a. Grobler and Silberbauer (1984)

Formulation : $TP = W/Q + s.V)$

where W = annual load of phosphorus (t)

Q = inflow volume of water (m^3)

V = mean annual volume of dam (m^3)

s = sedimentation rate = 2.46 (specific to Hartbeespoort Dam)

Accuracy : $TP_{obs} = 0.87\ TP_{pred.} + 68$ $r = 0.94$ $r^2 = 0.88$

where TP_{obs} = observed TP

TP_{pred} = TP predicted by model.

b. O.E.C.D. (1982)

Formula : $X = \text{Inflow TP}/(1 + \sqrt{T_w})$

$TP = 1.55\ X^{0.82}$

where Inflow TP = annual mean inflow TP (µg l^{-1})

T_w = water residence time (y).

Accuracy : $TP_{obs.} = 1.40\ TP_{pred} + 11$ $r = 0.83$ $r^2 = 0.68$

c. Rast, Jones & Lee (1983)

Formula : $TP = 1.81\ X^{0.81}$

where X is as in O.E.C.D. model

Accuracy : $TP_{obs.} = 1.30\ TP_{pred} + 49$ $r = 0.83$ $r^2 = 0.68$

Table 22: Models which predict the annual mean in-lake chlorophyll concentration (CHL in $\mu g\ l^{-1}$), and their accuracy when applied to Hartbeespoort Dam. (Undefined symbols are defined in Table 20).

a. **OECD (1982)**

Formula : CHL $= 0.37\ X^{0.79}$
Accuracy: $CHL_{obs} = 0.48\ CHL_{pred} + 30$ $r = 0.37$ $r^2 = 0.13$
where subscripts obs & pred. are as in Table 20.

b. **Jones & Lee (1982)**

Formula : CHL $= 0.45\ X^{0.79}$
Accuracy: $CHL_{obs} = 0.37\ CHL_{pred} + 3$ $r = 0.36$ $r^2 = 0.13$

c. **Lee, G.F. - personal communication to Grobler & Silberbauer** (1984)

Formula : CHL $= 0.45\ (\text{Inflow TP})^{0.79}$
Accuracy: $CHL_{obs} = 0.16\ CHL_{pred} + 40$ $r = 0.27$ $r^2 = 0.07$

Within the Hartbeespoort Dam data base (Table 20) there are significant relationships between annual mean in-lake phosphorus concentrations and inflow phosphorus concentrations ($0.1>p>0.05$), areal and volumetric phosphorus load ($0.02>p>0.01$) (Table 23). Once again none of the relationships between chlorophyll and phosphorus concentrations were significant ($p>0.1$) (Table 23), even though they included measured annual mean in-lake phosphorus concentrations.

Table 23: Hartbeespoort Dam. Relationships between various expressions of annual phosphate loading and mean annual in-lake total phosphate and chlorophyll a concentrations.

a. Inflow TP conc. and TP

Formula : $TP = 4.54\ (\text{Inflow TP})^{0.652}$
Accuracy : $TP_{obs} = 0.99\ TP_{cal.} + 12$ $r = 0.70$ $r^2 = 0.49$
where TP_{cal} = calculated value of TP.

b. Annual areal TP load (ATPL) and TP

Formula : $TP = 24.1\ (ATPL)^{1.08}$
Accuracy : $TP_{obs} = 0.92\ TP_{cal.} + 36$ $r = 0.94$ $r^2 = 0.89$

c. Annual volumetric TP load (VTPL) and TP

Formula : $TP = 304\ (VTPL)^{0.76}$
Accuracy : $TP_{obs} = 0.96\ TP_{cal.} + 22$ $r = 0.92$ $r^2 = 0.85$

d. Inflow TP concentration and CHL

Formula : $CHL = 10.7\ (\text{Inflow TP})^{0.24}$
Accuracy : $CHL_{obs} = 0.17\ CHL_{cal.} + 54$ $r = 0.17$ $r^2 = 0.03$

e. ATPL and CHL

Formula : $CHL = 12.7\ (ATPL)^{0.55}$
Accuracy : $CHL_{obs} = 1.09\ CHL_{cal.} - 4$ $r = 0.46$ $r^2 = 0.21$

f. VTPL and CHL

Formula : $CHL = 44\ (VTPL)^{0.46}$
Accuracy : $CHL_{obs} = 1.04\ CHL_{cal.} + 7$ $r = 0.49$ $r^2 = 0.24$

g. TP and CHL

Formula : $CHL = 9.6\ TP^{0.30}$
Accuracy : $CHL_{obs} = 1.2\ CHL_{cal.} - 14$ $r = 0.34$ $r^2 = 0.12$

4.5 Data management and availability

The data base on Hartbeespoort Dam has been maintained and updated regularly. It is no longer run on the CSIR main frame computer, having been transferred to floppy discs for operation on personal computers.

During 1988 information on Hartbeespoort Dam and its inflowing and outflowing water was made available to researchers working on contracts with the Water Research Commission. Mr Rossouw used the data to verify models for his report (Rossouw 1989) while Crocodile River data was used by Gilfillan and Swart (1989).

A copy of the Hartbeespoort Dam data base from the earliest information dating back to 1980 has been provided to the Hydrological Research Institute of the Department of Water Affairs.

5. DISCUSSION

5.1 The impact of the 1 mg l^{-1} effluent orthophosphate-P standard on effluents and on the Crocodile River inflow to Hartbeespoort Dam

It is unfortunate that the records of sewage works effluent phosphate-P concentrations and flows in the Hartbeespoort Dam catchment do not extend back to the years prior to 1985, when there was no effluent phosphate standard. It is clear that only small and few treatment plants are consistently achieving the standard (Tables 3, 4). Nevertheless, it should be recognized that the general level of concentration of orthophosphate-P in effluents of sewage treatment plants not modified to meet the standard, usually ranges from about 8 mg l^{-1} upwards (W H J Hattingh - pers. comm.). Few effluents in the Hartbeespoort Dam catchment have a mean concentration greater than 5 mg l^{-1} (Table 4).

It may be concluded that, while the effluent phosphate standard has by no means been achieved in the Hartbeespoort Dam catchment, the phosphate load emanating from sewage works is probably lower than it would have been without the standard. Some support for this conclusion may be derived from the annual data on Crocodile River mean phosphate concentrations (Table 7). These declined sharply from 1984/85 to 1985/86 with the introduction of the standard. However, since 1985/86 there is no conclusive evidence that either inflow concentrations (Table 7) or effluent concentrations have continued to decline. Indeed in winter, when trends in river concentrations are less masked by variable rainfall, run-off and non-point source loads, flow-weighted phosphate concentrations have increased from 1986 to 1989.

Recent changes in the phosphate content of the dam and in its phytoplankton cannot be ascribed to an ongoing reduction of the inflowing phosphate load or to the more effective implementation of the 1 mg l^{-1} effluent phosphate standard.

5.2 Causes of the change in nutrient concentrations and plankton populations in summer 1988/89

Lake biology is driven by physical and chemical processes, so that the key to the acharacteristic biology of summer 1988/89 must be sought in the physics and chemistry of the impounded water.

In respect of physical properties of the environment (Table 15, Figure 5) none differed in 1988/89 in a manner which would disadvantage *Microcystis*. The driving force for the change in the phytoplankton probably therefore lies in the considerable drop in the total phosphorus and orthophosphate-P concentration in the dam (Figure 4) and in the change in the inorganic N:P ratios in the surface waters. These ratios increased from 14:1 in summer 1987/88 to 27:1 in summer 1988/89. Smith (1983) has postulated that N:P ratios are important in phytoplankton species composition and concluded that low ratios favour blue-green algae such as *Microcystis*.

When a marked decrease in the phosphate content of a dam occurs after the promulgation of a low phosphate effluent standard, a superficial evaluation of the situation leads to the conclusion that the two events are directly related. As shown above (Section 5.1) they were not directly related in Hartbeespoort Dam. The sharp decline in the phosphate concentration in the dam over the recent past is due primarily to the fact that the dam has filled. There is, however, no evidence that it has filled with a water dilute in nutrients (Table 8). The drop in the phosphate concentration in the dam would appear to have been due rather to a great increase in phosphate losses due to sedimentation over a vastly increased bottom area (Table 10), to a lower areal and volumetric loading rate (Table 13) and to an increase in canal outflow concentrations relative to in-lake concentrations as the dam filled (Table 12).

At the same time as loss processes of phosphate from the lake increased as it filled, loss processes of bound nitrogen also increased. Relative nitrogen losses were not as great as phosphate losses, so that the N:P ratios increased.

Looking to the future, the nutrient content of Hartbeespoort Dam will depend on nutrient loading rates and the volume of stored water. It may be predicted that the volume of the dam will decline again in the future and that this will result in the sedimentation of a lower mass of phosphate, simply because of a smaller area available for sedimentation. Provided that there is no decrease in the phosphate and nitrogen loads, it seems likely that Microcystis will return to Hartbeespoort Dam.

5.3 Implications of conditions in summer 1988/89 for limnology

There are lessons to be learnt from the recent changes in Hartbeespoort Dam. For limnology the most important lesson is that in the type of climate and long-term rainfall cycle experienced in the interior of South Africa, studies extending over only the declining rainfall and drought part of the cycle are deficient. This is illustrated not only by the phosphate and phytoplankton species composition aspect. For instance, despite the sharp decline in the euphotic zone mean chlorophyll concentration, the phytoplankton biomass has not changed (Table 17). This is due probably to the change in the phytoplankton composition to species containing less chlorophyll per unit biomass. Nevertheless phytoplankton biomass in Hartbeespoort Dam has yet to be affected by the reduced phosphate concentrations.

There clearly are deficiencies in understanding of the factors regulating zooplankton species composition and abundance. Until summer 1988/89 the hypothesis that phytoplankton dominance by the unpalatable Microcystis was a key factor governing the seasonal cycle of zooplankton species composition was satisfactory. It is no longer so and it would appear that other factors, such as the greater light penetration, allowing more effective predation of large species by young fish, may now be governing the zooplankton species composition.

5.4. Implications of conditions in summer 1988/89 for lake management

In lake management the implications of the changes in 1988/89 are very important. A phytoplankton without Microcystis is, due to the aesthetically detracting scums, the toxicity of the species and the association of tastes and odours with Microcystis dominance, a common management objective. Had any management actions to rid the dam of Microcystis been initiated at the beginning of summer 1988/89, they would apparently have achieved their objective, even if they had no real effect on the ecosystem. They might even have changed the ecosystem so that Microcystis did not disappear. It is fundamental to lake management that, if it is to achieve its goals, it must be applied to systems whose natural behaviour is known.

On the positive side for lake management, it would appear that a reduction in the phosphate concentration and an increase in the N:P ratio really do lead to the disappearance of Microcystis. Until the beginning of summer 1988 it had been postulated that the best way to disadvantage Microcystis would be to mix the water column to carry Microcystis down into the aphotic zone, thus reducing its population growth rate. Summer 1988/89 findings suggest that through reducing the loss of nitrogen in the hypolimnion and increasing the adsorption of phosphates by eliminating the anaerobic hypolimnion, whole lake mixing would still be a good management strategy to follow. It would raise the N:P ratio and lower the phosphate concentration, simulating the chemical changes which occurred in summer 1988/89. It is to be hoped that deep aerobic waters would provide a dark refuge for sufficient large grazing zooplankton to reduce the standing phytoplankton biomass.

5.5 Phytoplankton management by the removal of Microcystis scums

The removal of Microcystis scums has a major impact on the aesthetic appearance of the dam at the wall. With the road running across the wall, scums at this site are very much in the public eye and their decay is very much in the public nose!

Close inspection of the spilled volumes in 1987 and 1988 suggests that the spillage rate of less than 0.5 x 10^6 m^3 d^{-1} in 1988 had a greater impact on the proportion of Microcystis in the total phytoplankton than did the spillage rates of more than 1 x 10^6 m^3 d^{-1} in 1987. Maximum Microcystis loss would appear to occur at a low spill volume over a longer period (cf. 8.3 x 10^6 m^3 over 8 days in 1987 and 4.8 x 10^6 m^3 over 14 days in 1988).

Microcystis scum removal can be justified on some aesthetic grounds. For abstracters of water from the dam for purification for drinking water purposes, it may be important that fragments of scum are liable to drift back into the main basin in winter. Scum removal may help a little in water purification. Scum removal cannot be motivated for its impact on the mass balance of nutrients in the dam. It is unlikely, because decay of scums takes place at the water surface, that scums have an important impact on oxygen demand in the water column. However, scum removal by flushing must have an immediate and probably short-term effect of unrecorded severity on the downstream river.

5.6 Implications of the present study for the reliability of simple models to predict phosphorus and chlorophyll in South African reservoirs

The duration and comprehensiveness of the data base on Hartbeespoort Dam is unique in South Africa. Testing predictive models using the data base shows that the Grobler and Silberbauer (1984) model is highly satisfactory for predicting the mean annual phosphorus concentrations. The O.E.C.D. (1982) and Rast *et al* models are reasonably good. The unsolved problem lies in predicting mean annual euphotic zone chlorophyll, which is the key property of concern in eutrophication. There is as yet no satisfactory model to predict this in Hartbeespoort Dam. The root of the problem lies in the lack of a systematic relationship between mean annual in-lake phosphorus concentration and mean annual euphotic chlorophyll concentration.

6. CONCLUSIONS

6.1 Up to the end of 1988, several large effluent treatment plants were not complying with the 1 mg l^{-1} effluent orthophosphate-P standard. From the fact that a disappearance of *Microcystis* coincided with a drop in the orthophosphate concentration in the dam, the full implementation of the standard should be rigorously pursued.

6.2 There was a drop in the phosphate load reaching Hartbeespoort Dam between 1984/85 and 1985/86 when the effluent phosphate standard was introduced. Thereafter the load has not declined, but data on TP:PO_4-P ratios in the Crocodile River and on phosphate concentrations in effluents, suggest that the standard has resulted in a lower phosphate load on Hartbeespoort Dam, than would otherwise have been the case.

6.3 The considerable decline in the phosphate concentrations in Hartbeespoort Dam over the past two years has not been due to a decline in the volume weighted mean concentration in the inflowing rivers.

6.4 The most probable explanation for the decline in the in-lake phosphate concentration includes the sedimentation of a large mass of phosphate, low annual areal and volumetric phosphate loading rates and an increase in the outflow phosphate concentration, relative to the mean in-lake concentration. All these factors are ascribed to the increase in the volume of the dam, resulting in a greatly increased area for sedimentation to take place and a deeper and larger hypolimnion.

6.5 The striking absence of the nuisance phytoplankter *Microcystis aeruginosa* in 1988/89 is ascribed to the low epilimnetic phosphate concentration and the greatly increased N:P ratio.

6.6 Other changes associated with the failure of *M. aeruginosa* to appear included an increase in the depth of the euphotic zone, a decrease in the chlorophyll content of the water and a change in the species composition of the zooplankton.

6.7 The changes in the zooplankton in 1988/89 were not those which would have been expected from past understanding of the phytoplankton/zooplankton relationship and new factors regulating zooplankton composition came into play in 1988/89.

6.8 There is no reason to believe that the changes which have taken place in the chemical conditions and phytoplankton in Hartbeespoort Dam in 1988/89 will be permanent.

6.9 The findings in Hartbeespoort Dam were unexpected and illustrate the fact that the limnology of the re-filling stage of hypertrophic reservoirs in South Africa was previously unknown. The findings may have important implications for places such as Inanda, Bridle Drift, Laing and Bloemhof Dams.

6.10 The 1988/89 findings, on the changes in the phytoplankton and zooplankton species composition reveal opportunities for academic research on phytoplankton/zooplankton relationships.

6.11 The direction of changes in phosphate concentrations and in N:P ratios in the dam in 1988/89 is the same as would be expected should there be no deoxygenation of the hypolimnion. This would increase phosphate sedimentation and decrease denitrification. Aeration to prevent stratification and the consequent deoxygenated hypolimnion should therefore result in desirable changes in the plankton of Hartbeespoort Dam.

6.12 Removal of Microcystis hyperscums greatly improves the aesthetic appeal of Hartbeespoort Dam and prevents the occurrence of large concentrations of phytoplankton in winter in places where raw water is withdrawn for Kosmos and Schoemansville. Scum removal has a negligible impact on chemical water quality and on mass balances of phosphates and nitrogen species in the lake. It probably has a major impact on the Crocodile River below the dam.

6.13 Comprehensive treatment of Hartbeespoort Dam water is necessary to bring it to a quality acceptable for domestic and industrial use.

6.14 Dissolved heavy metal concentrations in Hartbeespoort Dam are acceptable.

6.15 The total organohalogen potential is no higher in Hartbeespoort Dam than in the inflowing Crocodile River.

6.16 The in-lake mean annual total phosphorus concentration can be satisfactorily predicted from the hydrology and inflowing phosphorus concentration, using existing simple models. Chlorophyll prediction is not satisfactory. It is questionable whether it will ever be adequately predicted from simple models, as so many biotic and abiotic factors regulate chlorophyll concentration.

7. RECOMMENDATIONS

7.1 Application of the 1 mg l^{-1} effluent orthophosphate-P standard should be rigorously pursued.

7.2 Studies of nutrient dynamics and phytoplankton composition should be maintained to establish the permanence of the important and desirable changes which took place in 1988/89.

7.3 In deep hypertrophic impoundments with ongoing Microcystis blooms, the prevention of stratification through aeration, which drives nutrient dynamics in the direction they took in Hartbeespoort Dam in 1988/89, should be used to manage Microcystis.

7.4 Should Microcystis scums appear again in Hartbeespoort Dam, they should, if possible, be voided from the dam, provided that it can be shown that there is no unacceptable impact on the Crocodile River.

7.5 The modelling approach to the prediction of chlorophyll a in hypertrophic dams from phosphorus and hydrology has been developed as far as possible, remains inadequate and should be abandoned.

7.6 An Expert System should be developed to predict not only chlorophyll a concentration but also dominant phytoplankton species.

7.7 Until warranted by further development in the Hartbeespoort Dam catchment, no further intensive studies of the heavy metals and total organohalogen potential in the impounded water should be undertaken.

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APPENDIX 'A'

Tables of monthly effluent flows and concentrations and of monthly data on the chemistry of the Crocodile and Magalies Rivers, Hartbeespoort Dam and its outflow.

TABLE A1. Flows, orthophosphate phosphorus concentrations and orthophosphate phosphorus loads emanating from sewage treatment plants in the catchment of Hartbeespoort Dam (1986/87).
Raw data kindly provided by D.W.A. Pollution Control Division.

		MAY 86	JUN 86	JUL 86	AUG 86	SEP 86	OCT 86	NOV 86	DEC 86	JAN 87	FEB 87	MAR 87	APR 87	MAY 87	JUN 87	JUL 87	AUG 87	SEP 87	OCT 87	NOV 87	DEC 87
DRIEFONTEIN	flow (mil. cu m)	0.18	0.28	0.19	0.29	0.19	0.21	0.29	0.21	0.17	0.18	0.21	0.21	0.21	0.20	0.20	0.20	0.19	0.22	0.24	0.23
(Roodepoort)	PO_4-P load (t)	0.19	0.23	0.19	0.24	0.16	0.29	0.21	0.17	0.17	0.14	0.29	0.46	0.29	0.18	0.25	0.43	0.38	0.42	1.04	1.68
	PO_4-P conc (mg/l)	1.02	0.83	0.98	0.82	0.88	1.41	0.74	0.80	1.00	0.77	1.38	2.19	1.37	0.93	1.30	2.18	1.97	1.91	4.38	7.20
ALEXANDRA	flow (mil. cu m)	0.46	0.50	0.52	0.51	0.47	0.51	0.70	0.50	0.55	0.53	0.67	0.45	0.54	0.50	0.35	0.37	1.11	0.52	0.57	0.56
	PO_4-P load (t)	0.37	0.48	0.54	0.28	0.41	0.45	0.38	0.20	0.51	0.14	0.28	0.18	0.40	0.31	0.15	0.53	1.59	0.92	1.05	0.74
	PO_4-P conc (mg/l)	0.81	0.97	1.04	0.55	0.88	0.89	0.53	0.40	0.91	0.27	0.42	0.39	0.74	0.61	0.43	1.43	1.43	1.76	1.83	1.33
MIDRAND	flow (mil. cu m)							0.05	0.05	0.08	0.07					0.07	0.08	0.07	0.08		
	PO_4-P load t)							0.18	0.17	0.29	0.13					0.23	0.20	0.21	0.33		
	PO_4-P conc (mg/l)							3.33	3.45	3.59	1.88					3.23	2.41	3.12	3.95		
NORTHERN KELVIN	flow (mil. cu m)	1.02	0.94	1.03	1.13	0.96	0.99	0.92	0.89	0.87	0.87	0.93	0.84	0.98	0.86	0.87	0.99	0.87	0.93	0.85	0.93
	PO_4-P load (t)	11.74	10.07	10.48	8.60	4.44	3.51	5.55	5.84	4.19	1.46	1.83	1.07	1.78	3.48	0.70	3.88	2.46	3.28	6.30	4.89
	PO_4-P conc (mg/l)	11.48	10.69	10.22	7.61	4.65	3.53	6.02	6.59	4.80	1.68	1.97	1.27	1.82	4.05	0.80	3.91	2.84	3.54	7.37	5.24
NORTHERN WP5	flow (mil. cu m)	2.28	2.62	3.25	1.88	1.81	3.10	3.97	3.63	3.82	3.43	3.87	3.24	3.45	3.29	3.04	3.07	3.08	3.10	3.09	4.50
	PO_4-P load (t)	8.67	11.74	11.42	6.83	7.74	10.71	17.54	15.80	29.19	12.61	14.96	13.19	20.19	15.01	10.62	14.68	16.21	9.51	11.06	16.17
	PO_4-P conc (mg/l)	3.80	4.47	3.52	3.63	4.27	3.46	4.42	4.35	7.64	3.68	3.87	4.08	5.86	4.57	3.49	4.78	5.27	3.07	3.58	3.60
PERCY STEWART	flow (mil. cu m)		0.41	0.49	0.50	0.38	0.45	0.41	0.56	0.50	0.42	0.53	0.33	0.51	0.36		0.53	0.33			0.30
(Krugersdorp)	PO_4-P load (t)		0.23	0.36	0.29	0.21	0.37	0.32	0.34	0.26	0.23	0.36	0.15	0.28	0.22		0.39	0.21			0.16
	PO_4-P conc (mg/l)		0.55	0.73	0.59	0.55	0.82	0.79	0.62	0.53	0.55	0.69	0.46	0.55	0.62		0.74	0.63			0.55
VERWOERDBURG	flow (mil. cu m)		0.41		0.42	0.39						0.49	0.41	0.41			0.44	0.45	0.43	0.43	0.39
	PO_4-P load (t)		0.29		0.31	0.53						0.90	0.97	0.68			1.29	1.29	1.42	1.31	0.55
	PO_4-P conc (mg/l)		0.72		0.74	1.36						1.84	2.36	1.66			2.96	2.89	3.27	3.06	1.39
RIETFONTEIN	flow (mil. cu m)			0.62	0.81	0.90	1.00	1.09	1.26	1.16	1.05									0.87	1.03
(Kempton Park)	PO_4-P load (t)			6.21	6.20	7.54	9.07	8.22	7.96	6.96	6.52									5.73	5.90
	PO_4-P conc (mg/l)			10.05	7.64	8.34	9.07	7.55	6.32	6.03	6.23									6.57	5.75
HARTBEESFONTEIN	flow (mil. cu m)			0.43	0.44	0.42	0.43	0.42	0.43	0.39	0.37					0.43	0.44	0.42		0.42	0.43
(Kempton Park)	PO_4-P load (t)			5.09	3.93	3.80	4.61	2.72	3.05	2.21	1.87					6.40	3.93	3.80		2.01	1.60
	PO_4-P conc (mg/l)			11.91	9.00	8.96	10.66	6.48	7.03	5.67	5.08					14.97	9.00	8.96		4.78	3.69
RANDFONTEIN	flow (mil. cu m)				0.41	0.37	0.37	0.40	0.39		0.37		0.44	0.42	0.41	0.36	0.41	0.38	0.40	0.41	0.40
	PO_4-P load (t)				1.47	0.42	0.67	0.43	4.63		1.35		1.00	0.57	0.46	0.39	0.05	0.07	0.76	0.69	0.41
	PO_4-P conc (mg/l)				3.61	1.13	1.83	1.08	11.79		3.60		2.28	1.37	1.14	1.07	0.12	0.19	1.89	1.70	1.01
OLIFANTSFONTEIN	flow (mil. cu m)			0.57	0.57	0.55	0.64	0.62	0.77	0.72	0.53	0.59	0.78	0.67	0.52	0.56	0.62	0.62	0.75	0.58	0.77
	PO_4-P load (t)			4.92	5.25	4.67	5.86	5.14	7.48	4.87	4.07	4.08	5.34	5.86	4.88	5.11	5.04	4.17	3.84	2.12	1.48
	PO_4-P conc (mg/l)			8.68	9.23	8.41	9.19	8.25	9.70	6.77	7.65	6.88	6.87	8.75	9.37	9.17	8.14	6.72	5.09	3.66	1.92

TABLE A2. Flows, orthophosphate phosphorus concentrations and orthophosphate phosphorus loads emanating from sewage treatment plants in the catchment of Hartbeespoort Dam (1988).
Raw data kindly provided by D.W.A. Pollution Control Division.

		JAN 88	FEB 88	MAR 88	APR 88	MAY 88	JUN 88	JUL 88	AUG 88	SEP 88	OCT 88	NOV 88	DEC 88
DRIEFONTEIN	flow (mil. cu m)	0.24	0.23										
(Roodepoort)	PO_4-P load (t)	1.19	1.14										
	PO_4-P conc (mg/l)	4.92	4.95										
ALEXANDRA	flow (mil. cu m)	0.65	0.52	0.93	0.52	0.52	0.51	0.64	0.71	0.46	0.43	0.49	0.46
	PO_4-P load (t)	0.52	0.30	0.45	0.39	0.69	1.21	0.83	1.10	0.35	0.26	0.25	0.24
	PO_4-P conc (mg/l)	0.79	0.58	0.48	0.75	1.32	2.36	1.30	1.55	0.76	0.62	0.51	0.53
MIDRAND	flow (mil. cu m)												
	PO_4-P load t)												
	PO+4-P conc (mg/l)												
NORTHERN KELVIN	flow (mil. cu m)	0.92	0.88	0.93	0.90	0.90	1.01	1.11	1.06	1.03	0.91	0.89	0.90
	PO_4-P load (t)	3.46	5.14	4.70	3.70	5.85	9.17	10.82	10.52	9.87	8.37	8.68	7.91
	PO_4-P conc (mg/l)	3.76	6.18	5.06	4.13	6.51	9.05	9.74	9.89	9.60	9.25	9.81	8.82
NORTHERN NP5	flow (mil. cu m)	3.09	2.82	3.50	2.87	2.89	2.80	2.67	2.33	2.67	2.49	2.21	2.94
	PO_4-P load (t)	10.70	9.02	13.68	13.09	16.11	10.68	9.80	9.52	12.38	10.84	10.39	13.15
	PO_4-P conc (mg/l)	3.46	3.02	3.91	4.55	5.58	3.82	3.68	4.08	4.63	4.35	4.71	4.48
PERCY STEWART	flow (mil. cu m)	0.37	0.36	0.36		0.36	0.41		0.19				
(Krugersdorp)	PO_4-P load (t)	0.24	0.22	0.20		0.22	0.22		0.41				
	PO_4-P conc (mg/l)	0.66	0.62	0.57		0.62	0.55		2.08				
VERWOERDBURG	flow (mil. cu m)	0.43	0.41	0.46	0.42	0.46	0.45		0.48	0.47	0.48	0.48	0.44
	PO_4-P load (t)	0.47	0.32	0.46	0.41	0.78	0.51		1.68	1.93	1.25	2.12	2.45
	PO_4-P conc (mg/l)	1.09	0.78	1.00	0.98	1.70	1.13		3.50	4.08	2.59	4.42	5.60
RIETFONTEIN	flow (mil. cu m)	1.10	0.95	1.20	0.93	0.91	0.94	0.96	0.89	0.82	0.90		
(Kempton Park)	PO_4-P load (t)	4.38	7.23	6.53	5.42	5.47	7.94	7.37	7.57	6.95	6.45		
	PO_4-P conc (mg/l)	3.96	7.60	5.46	5.86	6.03	8.42	7.70	8.46	8.50	7.14		
HARTBEESFONTEIN	flow (mil. cu m)	0.43	0.41	0.43	0.42	0.43	0.42	0.43	0.43	0.42	0.43		
(Kempton Park)	PO_4-P load (t)	1.63	1.06	0.87	0.53	0.89	0.96	0.63	0.43	0.74	0.87		
	PO_4-P conc (mg/l)	3.75	2.62	2.00	1.25	2.06	2.29	1.45	1.00	1.75	2.00		
RANDFONTEIN	flow (mil. cu m)	0.42	0.41	0.29	0.26		0.40	0.43	0.44				
	PO_4-P load (t)	2.48	2.12	0.79	0.11		0.30	0.64	2.03				
	PO_4-P conc (mg/l)	5.97	5.20	2.72	0.42		0.75	1.49	4.61				
OLIFANTSFONTEIN	flow (mil. cu m)	0.89	0.70	0.94	0.97	0.99	0.70	1.03					
	PO_4-P load (t)	4.33	1.82	1.39	2.02	2.65	0.50	1.09					
	PO_4-P conc (mg/l)	4.86	2.60	1.48	2.08	2.67	0.72	1.06					

TABLE A3. Hartbeespoort Dam. Monthly values of chemical properties of surface (0-4 m) waters at the raft sampling point.

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
pH (field or *laboratory)		1984-85	9.2	9.1	9.6	9.5	9.8	9.5	9.1	8.9	8.8	8.5	9.0	8.7
		1985-86	9.1	9.3	9.5	9.5	9.6	9.7	9.3	9.2	8.8	8.8	9.2	8.5
		1986-87	9.1	8.7	9.2	9.6	9.8	9.4	9.3	8.9	8.4	8.4	8.6	8.4
		1987-88	9.0	9.3	9.4	9.8	9.6	9.7	8.4	7.7*	7.4*	7.4*	7.8*	7.5*
		1988-89	7.4*	7.6*	7.2*									
Conductivity	mS/m	1984-85	73.0	77.3	68.7	63.5	60.6	55.8	60.8	62.0	56.6	58.2	67.3	70.6
		1985-86	73.9	57.4	63.8	62.7	63.6	65.1	66.9	66.0	66.5	65.1	66.2	69.7
		1986-87	70.3	65.0	61.1	59.2	57.4	54.2	54.7	58.3	62.1	62.1	62.2	63.2
		1987-88	61.4	64.5	58.5	56.5	57.6	57.0	58.4	60.8	61.4	65.3	58.8	58.7
		1988-89	58.4	63.7	58.6									
Sodium	mg/l	1984-85	58	60	57	52	51	48	46	51	54	54	58	66
		1985-86	62	52	50	46	43	42	46	56	59	56	61	65
		1986-87	69	53	49	46	43	42	46	56	59	56	61	65
		1987-88	69	53	49	46	45	45	45	50	48	49	51	52
		1988-89	51	53	52									
Potassium	mg/l	1984-85	11	11	10	9	7	9	9	11	9	9	10	10
		1985-86	11	9	10	9	10	10	10	10	12	10	12	13
		1986-87	11	11	9	10	10	10	10	10	12	10	12	13
		1987-88	11	11	8	9	9	9	8	9	9	9	9	9
		1988-89	9	10	10									
Calcium	mg/l	1984-85	51	47	47	43	41	38	46	52	44	44	45	48
		1985-86	54	38	43	43	47	46	47	49	50	56	57	58
		1986-87	49	51	52	43	43	46	46	48	43	47	42	47
		1987-88	49	49	47	50	48	43	38	42	42	43	44	44
		1988-89	42	38	37									
Magnesium	mg/l	1984-85	20	20	18	17	16	15	16	17	18	18	19	20
		1985-86	19	16	15	14	13	14	16	17	16	17	18	17
		1986-87	18	16	16	15	14	14	16	17	13	16	16	17
		1987-88	17	16	15	14	14	15	16	17	17	17	18	18
		1988-89	18	18	18									

Continued/.....

Table A3 (Continued)

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Kjeldahl-N	µg/l	1984-85	925	911	862	795	987	751	811	907	791	842	835	1261
		1985-86	1305	1170	1037	827	785	760	981	766	634	651	1359	1174
		1986-87	789	1246	840	698	767	829	783	751	713	767	702	902
		1987-88	563	643	898	567	559	665	852	877	775	880	932	914
		1988-89	938	972	1280									
Ammonium-N	µg/l	1984-85	55	142	93	182	105	157	152	87	91	233	131	349
		1985-86	137	202	158	125	281	281	173	121	94	134	260	316
		1986-87	75	580	139	61	118	207	54	138	157	175	353	317
		1987-88	114	97	144	104	92	105	406	110	60	30	57	62
		1988-89	61	68	98									
Nitrate + Nitrite N	µg/l	1984-85	2314	2126	1483	814	499	469	898	1052	1370	1543	1959	2049
		1985-86	3612	2510	3289	3273	3218	2828	3519	3647	4178	3948	4049	4043
		1986-87	3698	3640	5530	4912	3358	2159	1555	2839	6075	2216	2522	3103
		1987-88	6827	2272	1833	1555	1373	885	1644	2327	2180	2060	1798	1950
		1988-89	1844	1384	905									
Nitrite-N	µg/l	1984-85	116	149	121	129	120	99	91	66	50	82	108	123
		1985-86	144	287	371	302	410	362	162	225	178	82	87	101
		1986-87	116	251	320	341	315	340	117	103	61	113	71	81
		1987-88	105	171	72	248	275	108	307					
		1988-89												
Silica	mg/l	1984-85	2.6	3.8	3.4	4.7	3.8	5.0	5.1	4.8	4.7	4.3	3.9	3.6
		1985-86	3.8	4.2	4.3	4.7	5.0	4.6	10.9	14.2	13.7	12.4	4.0	4.0
		1986-87	3.3	4.6	5.8	5.3	6.0	5.8	6.4	6.5	6.2	5.1	3.8	3.6
		1987-88	4.8	6.0	5.9	6.9	5.8	6.8	6.4	5.0	4.6	3.1	3.8	3.1
		1988-89	1.9	1.0	1.9									
Sulphate	mg/l	1984-85	128	129	124	96	78	92	97	100	102	111	109	126
		1985-86	116	97	103	93	91	103	96	114	121	120	125	132
		1986-87	129	109	97	93	91	103	96	114	121	120	125	132
		1987-88	117	111	96	95	91	87	84	85	91	93	87	94
		1988-89	93	93	95									

Continued /.....

Table A3 (Continued)

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Total-P	mg/l	1984-85	779	811	560	549	543	549	620	585	609	550	632	704
		1985-86	391	413	255	251	319	355	394	407	394	445	412	397
		1986-87	335	423	402	409	342	391	387	384	348	330	286	329
		1987-88	269	292	401	247	241	274	226	345	241	158	155	125
		1988-89	171	112	122									
Orthophosphate-P	µg/l	1984-85	713	645	463	382	407	378	453	443	436	464	453	469
		1985-86	391	314	255	251	257	288	336	319	300	220	346	361
		1986-87	271	376	357	366	252	329	294	276	276	240	206	258
		1987-88	215	192	184	101	136	233	222	60	196	121	5	33
		1988-89	9	7	16									
Chloride	mg/l	1984-85	64	55	50	44	48	48	40	44	47	50	53	54
		1985-86	59	45	50	43	44	48	42	48	57	54	55	56
		1986-87	57	51	48	46	45	43	46	50	70	52	49	51
		1987-88	55	56	50	50	50	52	52	49	49	52	49	55
		1988-89	57	56	54									
Alkalinity	mg $CaCO_3$/l	1984-85	152	147	136	131	121	123	132	135	138	141	140	143
		1985-86	133	111	108	103	104	78	107	108	107	116	120	118
		1986-87	110	117	108	100	94	96	121	114	101	108	110	104
		1987-88	97	110	108	108	111	115	100	107	115	119	116	119
		1988-89	115	109	110									
Iron	mg/l	1984-85	117	174	79	291	85	91	91	94	71	35	68	79
		1985-86	87	166	62	57	145	80	104	53	57	57	69	102
		1986-87	98	113	72	56	26	29	31	26	39	46	33	28
		1987-88	106	27	26	<25	77	<25	<25					
		1988-89												
DOC	mg/l	1984-85	-	-	-	8.6	8.8	-	-	6.6	7.0	7.5	7.8	7.8
		1985-86	8.5	7.5	5.8	7.1	8.3	9.1	7.1	8.4	7.0	6.9	7.0	7.0
		1986-87	9.8	-	7.3	10.6	7.3	11.1	12.5	8.9	8.6	7.2	7.6	7.0
		1987-88	8.4	8.0										
		1988-89												

Table A4. Crocodile River, Weir A2M12. Monthly values of chemical properties of river water.

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
pH		1984-85	7.5	7.3	7.6	7.5	7.4	7.2	7.6	7.6	7.5	7.6	7.9	6.8
		1985-86	7.1	6.9	7.2	8.0	7.2	7.2	7.2	7.0	7.3	7.5	7.4	7.7
		1986-87	7.6	7.0	7.2	7.0	7.1	6.9	7.2	7.2	7.0	6.9	6.9	6.8
		1987-88	6.8	7.5	7.3	7.3	7.3	7.4	7.3	7.4	7.7	7.7	7.4	7.4
		1988-89	7.5	7.5	7.2									
Conductivity	mS/m	1984-85	69.6	64.6	68.0	53.6	78.2	65.5	87.3	86.8	72.2	68.2	90.5	87.6
		1985-86	77.2	67.0	74.9	66.4	80.2	84.7	73.5	88.6	79.1	80.1	77.3	79.3
		1986-87	61.5	66.5	62.5	54.8	62.9	63.0	77.8	84.4	81.5	82.7	82.6	69.2
		1987-88	74.3	74.7	59.8	57.7	60.7	62.2	77.1	68.3	78.0	78.6	78.5	76.1
		1988-89	72.6	69.9	54.4									
Sodium	mg/l	1984-85	55	51	57	42	54	49	76	89	81	72	82	79
		1985-86	60	56	54	41	54	61	52	79	66	71	71	79
		1986-87	60	54	43	61	42	48	54	71	68	66	72	55
		1987-88	52	59	53	43	44	48	49	65	62	65	72	62
		1988-89	57	53	39									
Potassium	mg/l	1984-85	11	10	9	7	10	11	11	13	11	12	13	13
		1985-86	13	11	10	9	11	13	10	12	13	12	13	13
		1986-87	10	11	6	7	7	9	8	11	7	11	12	12
		1987-88	8	11	7	9	9	8	9	11	10	11	12	11
		1988-89	10	10	9									
Calcium	mg/l	1984-85	44	46	46	39	49	46	58	53	54	51	57	59
		1985-86	52	49	49	44	57	59	50	63	57	62	59	51
		1986-87	46	48	39	33	44	48	66	71	55	48	53	47
		1987-88	56	52	52	51	47	51	51	55	48	53	54	51
		1988-89	48	47	38									
Magnesium	mg/l	1984-85	17	15	17	13	19	19	22	20	21	19	21	20
		1985-86	16	16	16	14	18	19	16	21	17	18	18	16
		1986-87	12	17	15	14	15	15	24	24	16	20	19	17
		1987-88	19	18	15	15	15	16	20	21	18	20	20	18
		1988-89	17	16	13									

Continued /.....

Table A4. (Continued)

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Kjeldahl-N	µg/l	1984-85	1550	876	686	722	972	794	1034	1130	2228	2330	2447	2618
		1985-86	1682	1306	1004	3743	1835	879	1099	2170	1395	1705	1690	1089
		1986-87	1090	1337	1256	671	616	928	850	742	1097	1759	1162	971
		1987-88	1161	975	927	696	686	681	795	2046	1715	1978	1852	2155
		1988-89	2023	1440	2231									
Ammonium-N	µg/l	1984-85	389	162	59	68	177	141	77	82	1093	868	484	931
		1985-86	210	336	148	2613	1240	190	195	445	310	195	142	118
		1986-87	352	776	872	273	199	505	119	121	300	932	250	302
		1987-88	230	569	636	371	329	346	362	472	263	410	133	459
		1988-89	393	189	390									
Nitrate + Nitrite N	µg/l	1984-85	6011	6913	7387	4725	9336	8441	7129	10349	10704	9432	14266	14148
		1985-86	10923	10604	10336	9225	10494	10691	9931	14281	12592	15513	12297	8536
		1986-87	6201	12008	13284	10258	7838	7481	17331	12394	10899	14847	14999	9755
		1987-88	14037	9865	9846	8719	9473	14516	18010	13578	7800	12248	11368	12440
		1988-89	10490	8800	8194									
Nitrite-N	µg/l	1984-85	199	124	41	143	122	131	31	56	178	300	497	473
		1985-86	229	311	436	546	362	383	235	308	259	183	87	72
		1986-87	98	761	575	307	226	205	325	140	157	481	206	314
		1987-88	378	480										
		1988-89												
Silica	mg/l	1984-85	7.3	7.6	6.9	6.2	6.7	7.5	6.4	5.7	6.1	5.6	5.0	5.3
		1985-86	7.1	6.4	6.2	5.8	6.6	6.0	15.9	16.4	15.4	8.0	3.5	6.6
		1986-87	7.7	7.7	7.7	7.0	6.8	7.2	8.7	6.6	5.1	6.3	4.9	7.2
		1987-88	8.0	7.9										
		1988-89												
Sulphate	mg/l	1984-85	103	105	110	82	109	105	167	146	133	122	146	151
		1985-86	111	110	88	103	125	129	98	142	123	125	140	129
		1986-87	103	101	102	83	93	94	125	142	129	127	120	101
		1987-88	112	139	92	83	86	85	96	124	95	112	127	105
		1988-89	94	84	70									

Table A4 (Continued)

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Total-P	µg/l	1984-85	1923	1490	1293	1841	1423	1483	2279	2866	2802	2566	2683	2751
		1985-86	2848	2138	1333	1631	1282	1550	1499	1443	1739	1437	1351	1654
		1986-87	1858	1135	1135	1111	958	1005	1287	1935	2000	1644	2031	2001
		1987-88	1321	1195	871	980	981	1038	2206	2906	1715	1619	1769	1793
		1988-89	2232	1873	1677									
Orthophosphate-P	µg/l	1984-85	1842	1299	1242	765	1305	1377	2049	2757	2589	2438	2544	1761
		1985-86	2207	1546	627	807	1103	1301	1137	1277	1487	1098	1217	1358
		1986-87	1517	1016	879	811	603	863	1098	1318	1540	1097	1698	1529
		1987-88	975	1005	741	822	652	843	2099	2210	1278	1184	1277	1260
		1988-89	1456	1383	882									
Chloride	mg/l	1984-85	59	54	51	42	41	59	65	80	77	68	81	92
		1985-86	60	56	67	63	76	107	62	68	56	68	50	58
		1986-87	56	48	50	35	39	53	62	49	46	84	50	41
		1987-88	51	62	65	54	59	64	51	62	57	63	67	60
		1988-89	57	54	43									
Alkalinity	$mgCaCO_3/l$	1984-85	115	101	103	94	116	84	122	116	126	133	104	80
		1985-86	95	86	64	74	60	47	59	91	90	101	103	116
		1986-87	90	56	56	57	66	64	83	95	101	74	92	84
		1987-88	64	80	69	69	78	76	96	99	121	114	117	106
		1988-89	109	114	83									
Iron	µg/l	1984-85	328	147	196	587	27	110	25	37	32	55	30	35
		1985-86	35	58	52	239	109	66	83	25	45	36	35	32
		1986-87	66	269	225	331	292	219	26	25	25	27	26	65
		1987-88	45	29	103	163	117	357						
		1988-89												
DOC	mg/l	1984-85	10.2	9.1	9.2	7.3	7.1	7.6	6.8	4.5	6.3	8.0	7.5	9.8
		1985-86	8.4	7.1	4.5	5.9	5.1	8.1	6.6	8.6	6.9	7.4	7.1	8.1
		1986-87	8.2	-	5.3	2.0	6.0	7.0	7.1	6.9	7.8	6.1	8.2	8.5
		1987-88	6.3	7.9										
		1988-89												

Table A5. Magalies River, Weir A2M13. Monthly values of chemical properties of river water.

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
pH		1984-85	8.1	8.1	8.2	8.0	7.9	8.1	8.1	8.0	8.1	8.1	8.1	8.2
		1985-86	8.2	8.0	7.8	8.6	8.0	8.1	8.1	8.0	7.9	7.9	8.0	8.0
		1986-87	8.1	8.2	8.0	8.1	8.0	8.0	8.0	8.1	8.2	8.3	7.7	7.9
		1987-88	7.7	7.9	8.2	8.1	8.2	8.2	7.8	8.0	8.0	8.0	7.9	7.7
		1988-89	7.9	8.1	7.9									
Conductivity	mS/m	1984-85	48.6	48.9	43.7	32.7	44.6	44.6	48.1	45.8	42.2	39.6	47.2	50.1
		1985-86	53.9	39.6	50.3	48.9	48.5	51.0	52.8	55.5	52.6	50.7	50.9	51.1
		1986-87	47.9	41.9	42.9	37.2	40.9	38.0	41.3	43.3	47.8	46.7	47.0	38.2
		1987-88	42.0	41.6	39.2	42.6	44.0	38.5	44.7	47.3	49.1	46.4	47.2	46.9
		1988-89	47.3	48.4	46.0									
Sodium	mg/l	1984-85	14	13	10	10	12	19	10	7	10	12	11	16
		1985-86	16	10	13	10	9	7	7	13	17	17	15	15
		1986-87	15	8	8	8	8	8	9	7	10	10	11	11
		1987-88	11	7	12	30	8	10	10	15	15	12	13	13
		1988-89	13	14	14									
Potassium	mg/l	1984-85	2	1	2	3	2	2	2	1	1	1	1	2
		1985-86	2	2	2	2	2	2	1	2	2	2	2	2
		1986-87	2	2	2	2	2	2	2	2	2	2	2	2
		1987-88	2	2	2	2	2	4	1	1	1	1	1	1
		1988-89	1	1	1									
Calcium	mg/l	1984-85	40	40	36	26	33	39	41	39	42	42	42	43
		1985-86	42	38	36	38	44	36	43	46	43	50	52	46
		1986-87	45	38	40	25	39	39	42	42	42	43	36	31
		1987-88	38	39	36	43	41	32	39	41	40	41	40	41
		1988-89	41	39	36									
Magnesium	mg/l	1984-85	31	30	26	21	24	21	28	28	29	29	32	33
		1985-86	33	27	31	26	29	28	31	35	34	30	33	33
		1986-87	31	27	23	21	25	24	27	29	25	26	29	23
		1987-88	26	24	24	27	27	32	28	32	31	29	30	30
		1988-89	32	33	30									

Continued /.....

Table A5 (Continued)

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Kjeldahl-N	µg/l	1984-85	26	27	29	107	124	67	54	298	290	280	291	410
		1985-86	304	408	351	336	368	365	197	279	241	253	155	196
		1986-87	204	167	182	296	700	292	365	278	326	223	198	251
		1987-88	168	190	167	161	143	278	483	632	448	255	284	266
		1988-89	371	375	670									
Ammonium-N	µg/l	1984-85	26	27	29	107	124	67	54	41	89	92	96	109
		1985-86	96	117	107	133	133	113	59	73	83	98	77	59
		1986-87	119	69	88	137	499	61	136	53	49	114	101	88
		1987-88	33	51	64	48	98	65	60	42	28	55	47	40
		1988-89	53	38	106									
Nitrate + Nitrite N	µg/l	1984-85	214	198	357	814	661	614	595	793	678	621	516	128
		1985-86	70	453	76	131	156	105	327	116	255	227	152	144
		1986-87	151	372	375	508	1630	775	955	725	917	919	2751	1268
		1987-88	563	618	508	376	376	1452	1123	916	770	1003	873	812
		1988-89	467	232	404									
Nitrite-N	µg/l	1984-85	16	12	12	52	9	6	6	7	7	12	14	10
		1985-86	6	25	18	14	22	13	9	6	12	8	6	8
		1986-87	10	12	13	31	129	15	7	7	6	7	7	15
		1987-88	11	17	7	8	16	19						
		1988-89												
Silica	mg/l	1984-85	14.3	14.7	11.6	10.6	11.7	13.0	12.4	11.5	12.2	12.5	12.4	13.5
		1985-86	16.0	12.2	15.0	15.1	14.2	13.8	19.6	26.1	26.6	27.3	12.3	13.0
		1986-87	12.9	12.2	14.2	9.2	9.0	11.3	10.6	11.5	11.5	11.9	14.1	9.0
		1987-88	10.8	11.4	13.4	15.0	13.1	11.6						
		1988-89												
Sulphate	mg/l	1984-85	21	15	12	17	23	26	20	14	17	21	19	22
		1985-86	27	15	11	10	20	21	12	17	12	24	19	19
		1986-87	20	19	20	22	15	13	14	17	22	20	18	21
		1987-88	21	16	18	28	11	23	18	21	20	14	17	14
		1988-89	12	10	9									

Continued /.....

Table A5 (Continued)

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Total-P	µg/l	1984-85	163	169	151	154	147	131	122	162	178	200	231	184
		1985-86	160	214	191	179	125	133	102	132	158	240	150	150
		1986-87	150	150	150	164	456	365	150	150	150	150	150	207
		1987-88	150	150	150	175	100	113	48	48	46	23	27	18
		1988-89	35	32	496									
Ortho-phosphate-P	µg/l	1984-85	38	59	37	105	48	43	43	38	41	37	42	42
		1985-86	38	48	34	41	47	39	34	33	37	62	23	20
		1986-87	42	15	16	67	205	47	62	58	27	26	53	85
		1987-88	32	25	25	12	39	38	18	23	18	8	9	6
		1988-89	11	13	388									
Chloride	µg/l	1984-85	11	10	9	9	9	15	9	8	9	11	11	11
		1985-86	13	9	8	7	13	20	8	15	25	19	13	10
		1986-87	12	8	9	8	8	9	10	9	10	9	8	10
		1987-88	9	9	8	11	10	10	11	12	13	12	12	12
		1988-89	13	13	14									
Alkalinity	mgCaCo$_3$/l	1984-85	229	213	198	159	181	195	223	201	218	222	228	242
		1985-86	234	201	234	206	198	163	196	248	218	236	236	226
		1986-87	240	180	168	131	182	168	187	182	218	208	188	158
		1987-88	183	173	179	225	200	148	184	199	205	198	201	207
		1988-89	213	221	203									
Iron	µg/l	1984-85	81	52	130	1405	289	80	65	74	63	65	55	98
		1985-86	94	257	68	61	94	80	30	43	82	79	62	78
		1986-87	289	162	41	737	38	170	25	27	57	57	68	1694
		1987-88	53	55	69	<25	65	348						
		1988-89												
DOC	mg/l	1984-85	3.2	2.9	3.4	3.9	4.5	2.8	2.6	2.9	2.4	2.6	4.1	2.7
		1985-86	4.4	4.1	2.9	2.9	2.7	3.0	2.2	3.4	2.0	2.7	2.5	2.6
		1986-87	3.8	-	1.8	7.2	2.2	3.2	2.8	2.1	4.4	2.4	2.3	4.3
		1987-88	2.9	2.6										
		1988-89												

Table A6. Hartbeespoort Dam, outflow canal. Monthly values of chemical properties of water.

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
pH		1984-85	8.5	8.5	8.4	8.0	7.6	7.8	7.8	8.4	7.9	7.9	7.9	7.3
		1985-86	7.4	7.3	7.3	8.2	7.4	7.4	7.8	7.4	7.5	7.5	7.5	7.7
		1986-87	8.2	7.9	7.7	7.7	7.6	7.5	7.5	8.2	7.6	8.1	7.9	7.6
		1987-88	7.5	7.6	7.6	7.5	7.5	7.6	7.4	7.8	7.7	7.4	7.5	7.6
		1988-89	7.3	7.8										
Conductivity	mS/m	1984-85	75.7	74.6	71.8	59.5	57.3	58.7	64.2	63.4	56.4	57.6	66.8	71.5
		1985-86	75.3	51.2	60.7	64.6	69.3	68.7	70.2	68.8	68.6	69.5	77.0	72.8
		1986-87	70.0	65.4	60.3	57.2	56.2	53.0	57.9	60.5	61.3	62.3	63.6	62.6
		1987-88	59.7	63.9	60.2	61.8	63.3	59.4	51.7	62.7	61.0	67.0	62.0	58.0
		1988-89	65.4	65.1										
Sodium	mg/l	1984-85	61	62	57	51	41	45	50	52	56	54	56	63
		1985-86	62	45	45	44	46	38	49	57	56	58	58	64
		1986-87	55	46	45	26	39	39	36	49	48	46	49	50
		1987-88	43	43	49	50	47	41	42	45	48	50	49	52
		1988-89	52	53										
Potassium	mg/l	1984-85	12	11	10	9	7	10	8	9	9	10	10	10
		1985-86	11	9	8	10	10	10	10	10	12	12	12	13
		1986-87	12	12	7	7	9	9	8	10	6	9	9	9
		1987-88	8	9	8	9	10	9	8	8	9	9	9	9
		1988-89	9	9										
Calcium	mg/l	1984-85	50	52	48	41	33	38	42	42	45	44	46	50
		1985-86	47	40	38	39	47	46	47	47	52	55	56	59
		1986-87	57	47	40	37	43	44	46	48	44	46	46	46
		1987-88	45	47	52	80	50	57	38	41	41	47	43	45
		1988-89	44	42										
Magnesium	mg/l	1984-85	22	21	19	17	15	16	17	17	18	18	19	19
		1985-86	20	15	14	14	15	16	17	17	16	16	17	17
		1986-87	17	17	14	14	14	14	13	17	11	16	17	15
		1987-88	16	12	16	16	17	16	15	17	17	18	17	18
		1988-89	18	18										

Continued /.....

Table A6. (Continued)

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Kjeldahl-N	µg/l	1984-85	1335	1101	902	1346	1487	886	815	750	731	739	1148	1296
		1985-86	1587	1585	1112	1016	1054	864	897	810	851	983	1029	1260
		1986-87	1350	1281	1279	1186	1566	2200	1284	1083	844	863	1107	975
		1987-88	1380	1188	1473	1643	1937	2073	1330	679	855	435	767	985
Ammonium-N	µg/l	1984-85	432	429	294	695	991	387	158	140	170	212	396	378
		1985-86	389	642	495	437	609	228	215	101	226	162	253	485
		1986-87	519	590	807	689	1017	1946	660	404	243	276	586	523
		1987-88	1001	1424										
Nitrate + Nitrite N	µg/l	1984-85	2107	2184	1447	763	707	700	1124	1204	1693	1679	1986	2630
		1985-86	3360	3748	3002	2973	3619	2650	3963	3807	4348	4815	4316	3690
		1986-87	3805	4298	4880	3977	3061	1648	4110	3194	3763	3210	6363	2715
		1987-88	3763	2737	1830	1179	1207	4624	3700	2830	2377	1722	2699	2554
Nitrite-N	µg/l	1984-85	158	224	180	170	193	136	108	82	65	76	108	139
		1985-86	118	319	509	350	489	379	285	205	199	78	96	137
		1986-87	182	303	314	530	539	340	395	207	81	104	107	119
		1987-88	213	237										
Silica	mg/l	1984-85	2.4	3.5	4.0	4.4	4.0	5.1	4.9	4.8	4.7	4.2	3.9	3.6
		1985-86	3.9	3.8	3.7	4.5	5.0	5.0	12.6	15.2	14.0	10.7	4.4	3.9
		1986-87	3.8	4.7	5.6	4.7	5.5	6.6	6.6	6.7	7.0	6.6	5.6	4.5
		1987-88	4.4	5.9										
Sulphate	mg/l	1984-85	128	124	114	93	76	89	101	101	103	101	107	119
		1985-86	118	91	84	89	95	93	103	102	111	128	122	137
		1986-87	120	114	100	94	89	81	84	93	73	98	101	98
		1987-88	98	96	97	90	91	81	69	79	86	92	91	87
		1988-89	94	92										

Continued /......

Table A6. (Continued)

Parameter	Units	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept
Total-P	µg/l	1984-85	936	808	555	469	449	370	442	680	670	656	644	663
		1985-86	663	534	440	482	552	467	449	427	361	422	483	457
		1986-87	496	452	469	499	719	832	561	541	403	411	356	376
		1987-88	340	335	411	537	726	676	441	453	410	275	176	207
Ortho-phosphate-P	µg/l	1984-85	863	711	488	356	378	265	316	492	508	477	517	567
		1985-86	535	447	114	293	478	336	369	265	232	264	403	408
		1986-87	435	394	416	387	549	540	440	349	310	311	253	259
		1987-88	294	283	391	423	585	544	387	369	299	223	132	113
Chloride	µg/l	1984-85	60	60	53	54	48	56	45	55	55	54	54	55
		1985-86	55	49	54	58	69	58	53	50	49	48	53	54
		1986-87	59	51	42	39	38	39	51	49	49	51	58	47
		1987-88	44	50	50	49	50	47	48	46	49	53	53	50
		1988-89	55	57										
Alkalinity	mgCaCo$_3$/l	1984-85	154	142	133	124	105	107	129	126	136	138	139	135
		1985-86	133	93	93	103	93	73	92	105	106	110	111	122
		1986-87	116	110	89	92	95	104	87	105	116	112	108	115
		1987-88	108	119	122	127	134	124	108	114	111	116	114	120
		1988-89	121	119										
Iron	µg/l	1984-85	64	54	52	109	56	33	31	32	28	55	43	86
		1985-86	58	137	74	<25	57	64	27	36	36	35	43	78
		1986-87	57	64	70	32	<25	44	46	<25	37	42	40	64
		1987-88	64	<25	<25	<25	25	52						
DOC	mg/l	1984-85	8.8	9.1	7.5	7.1	7.5	6.5	7.4	6.9	7.9	9.1	7.7	6.8
		1985-86	11.9	8.9	3.5	5.0	5.8	10.5	7.2	8.8	7.4	9.9	11.2	7.3
		1986-87	8.6	-	6.2	6.5	6.6	7.6	7.8	7.8	10.0	7.0	8.3	8.4
		1987-88	7.7	7.0										