The Chemical Composition of the Upper Hennops River and its Implications on the Water Quality of Rietvlei Dam

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Abstract

A chemical investigation of the upper Hennops River between 1973 and 1975 revealed that the Kempton Park sewage works, situated in the headwaters of the river, is a major contributor to mineral loading and water flow. Concentrations of most dissolved constituents in the river decreased with distance from the sewage works, although magnesium levels increased as a result of dolomitic influences in the catchment. Reduction in the levels of dissolved phosphorus and nitrogen compounds was more pronounced after the river had passed through vlei systems, suggesting a potential of these systems for the removal of nutrients. Despite the pollution of the upper Hennops River with secondary treated sewage effluents, chemical quality conformed to prescribed potable water standards. On the basis of the 1973/74 dissolved phosphorus and nitrogen surface loading rates (13,05 g m^{-2} a^{-1} phosphate as P and 8,54 g m^{-2} a^{-1} nitrogen as N, respectively), Rietvlei Dam may be considered a eutrophic impoundment, in which algal growth is nitrogen limited.

Introduction

Rietvlei Dam, situated at 25,87°S and 28,26°E on the Hennops River, has been a source of water supply to the city of Pretoria since 1933. Secondary treated sewage effluents from Kempton Park are discharged into the upper Hennops River (also known as the Swartspruit) some 25 km upstream from Rietvlei Dam. On the basis of the annual effluent volumes discharged from the Kempton Park sewage works and the annual inflow into the impoundment, Walmsley, Toerien and Steÿn (1978) estimated that up to 73 per cent of the annual inflow into Rietvlei Dam may consist of discharged secondary treated sewage effluents.

Rietvlei Dam has been ranked (according to phosphate availability) as the most eutrophic of 98 impoundments studied by means of algal bioassays (Toerien, Hyman and Bruwer, 1975). Algal bioassays have also shown that the waters of this impoundment are nitrogen growth-limiting (Steÿn, Scott, Toerien and Visser, 1975; Walmsley and Ashton, 1977) and show a high potential for the growth of nitrogen-fixing blue-green algae (Walmsley and Ashton, 1977). As a result of nitrogen fixation in the impoundment, nuisance blooms of algae develop (Ashton, 1976) and when present, increase the treatment costs for potable water production at the Rietvlei water works (Toerien, 1975).

Walmsley *et al.* (1978) have discussed the eutrophication of Rietvlei Dam and compared it with that of other impoundments. This paper deals with the general chemical composition of the waters of the upper Hennops River, which is the major inflow to the impoundment.

Description of Study Area

The catchment of Rietvlei Dam is 492 km^2 in area and contains the industrial town of Kempton Park. The geology consists mainly of dolomites as well as shales, quartzites and conglomerates of the Pretoria Series. Shales of the Dwyka and Ecca Series also occur in isolated areas of the catchment (Du Toit, 1954). Bond (1946) classified the underground waters of the area as being of the temporary hard carbonate type. The Hennops River is the main stream draining the catchment, but is joined by smaller non-perennial tributaries (Figure 1). The river rises in a marshy area (vlei) a few kilometres east of Kempton Park and passes through a swamp before receiving the discharge of the Kempton Park sewage treatment plant. During the course of its flow to

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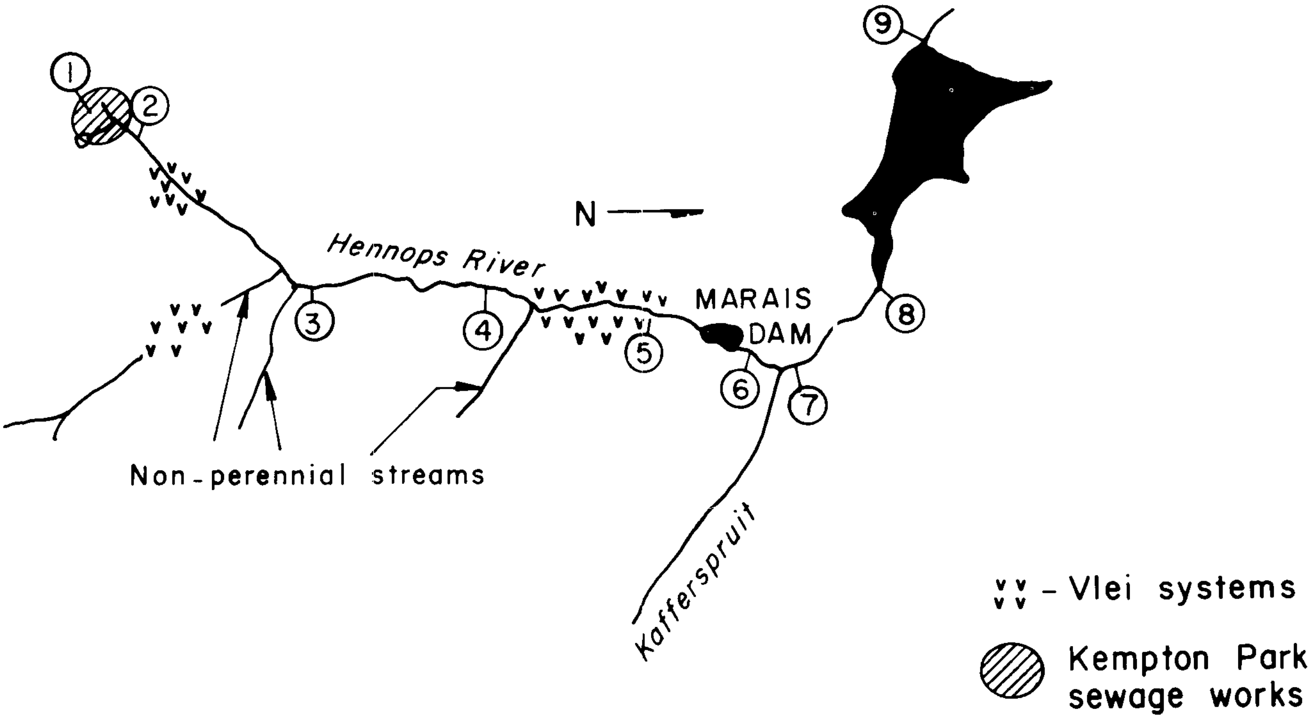

Figure 1
Rietvlei Dam catchment showing sampling stations and vlei systems

Rietvlei Dam, the river passes through two other vlei systems, in which a distinct channel is always visible from the air. Palynological studies have shown that the vlei system in the vicinity of Rietvlei Dam may be as old as 10 000 years (L. Scott, 1977 – personal communication). Before flowing into Rietvlei Dam, the river passes through a small dam (Marais Dam). The catchment area is extensively utilized agriculturally and use is made of river water for irrigation purposes, but the quantities involved are unknown.

Material and Methods

Sampling: Localities and Frequency

Sampling stations were selected at intervals along the course of the river to estimate the change in composition of the water with distance from the sewage treatment plant (Figure 1). Station 1 was sited at the Kempton Park sewage treatment plant, where the maturation pond effluent was sampled. Station 2 was placed at a point where the river passes under the Kaalfontein/Benoni road, shortly before the river enters the first vlei system. Station 3 was placed where the river passes the Kaalfontein/Bapsfontein road and station 4 was sited at a bridge crossing the river near Elandsfontein. Stations 5, 6, 7 and 8 were in the Van Riebeeck Nature Reserve at points where small dirt roads cross the river. Station 8 was about 1 km above Rietvlei Dam at the flow-measuring weir operated by the municipality of Pretoria. Station 9 was situated at the Rietvlei water works at an outflow pipe which received bottom waters from the impoundment.

Water samples were collected at these sampling stations at 14-day intervals during the period February 1973 to January 1974. From February 1974 to January 1975, samples were obtained at monthly intervals. Treatment of samples prior to analysis was carried out using the methods of Toerien and Walmsley (1978).

Chemical Analyses

Analyses for individual chemical species were conducted using the automated techniques of the Water Quality Division of the National Institute for Water Research (National Institute for Water Research, 1974). Since these analyses could not be performed on samples containing particulate material, filtered samples had to be used.

The constituents analysed included sodium, potassium, calcium, magnesium, chloride, sulphate, conductivity, ammonia, nitrate, nitrite, Kjeldahl nitrogen, orthophosphate, total dissolved phosphate, silica, alkalinity (as $CaCo_3$), and chemical oxygen demand.

Load calculations

Smith and Stewart (1977) have pointed out the inaccuracies which may arise in the estimation of mineral loads carried by rivers. Similar difficulties were encountered for estimates of the loadings of a sewage works in the catchment of Roodeplaat Dam (Walmsley and Toerien, 1978). In order to obtain the best possible estimates of mineral loading, three methods were used to approximate the loads in the Hennops River just above Rietvlei Dam. The first was to total the products of the total flow between sampling periods and the concentration value for the sampling period. The second was to total the products of the mean chemical concentration of the dry weather period of 1973 (May to September 1973, Figure 2) and the total flow for this period with the same for the 1973/74 wet weather period (February 1973 to April 1973 and October 1973 to January 1974). The third method was to determine the product of the mean chemical concentrations and the total flow of the study period.

The flow figures used were obtained by the Municipality of Pretoria at station 8. The monthly flow figures are presented in Figure 2. During January 1975 there was a large flood which contributed 56 per cent of the total flow during the study period. Since load calculations incorporating a large flood can be totally erroneous, data from the second year of study were ignored in the load calculations (Smith and Stewart, 1977).

Results

Water quality changes in the Upper Hennops River with distance and season

To obtain an idea of the water quality trends in the Hennops River from Kempton Park to Rietvlei Dam, the concentrations of the various chemical constituents for stations 2, 4, 8 and 9 were compared (Figures 3 to 6).

Dissolved Minerals

In the cases of sodium, potassium, chloride and sulphate (Figures 3A, 3B, 4A and 4B, respectively) the concentrations were higher at station 2 and decreased towards station 9. The concentrations were higher during the period of lowest flow (May to October) and lower during the wet months (November to April). The impoundment of water in Rietvlei Dam tended to smooth out variations in the chemical quality of the water, as

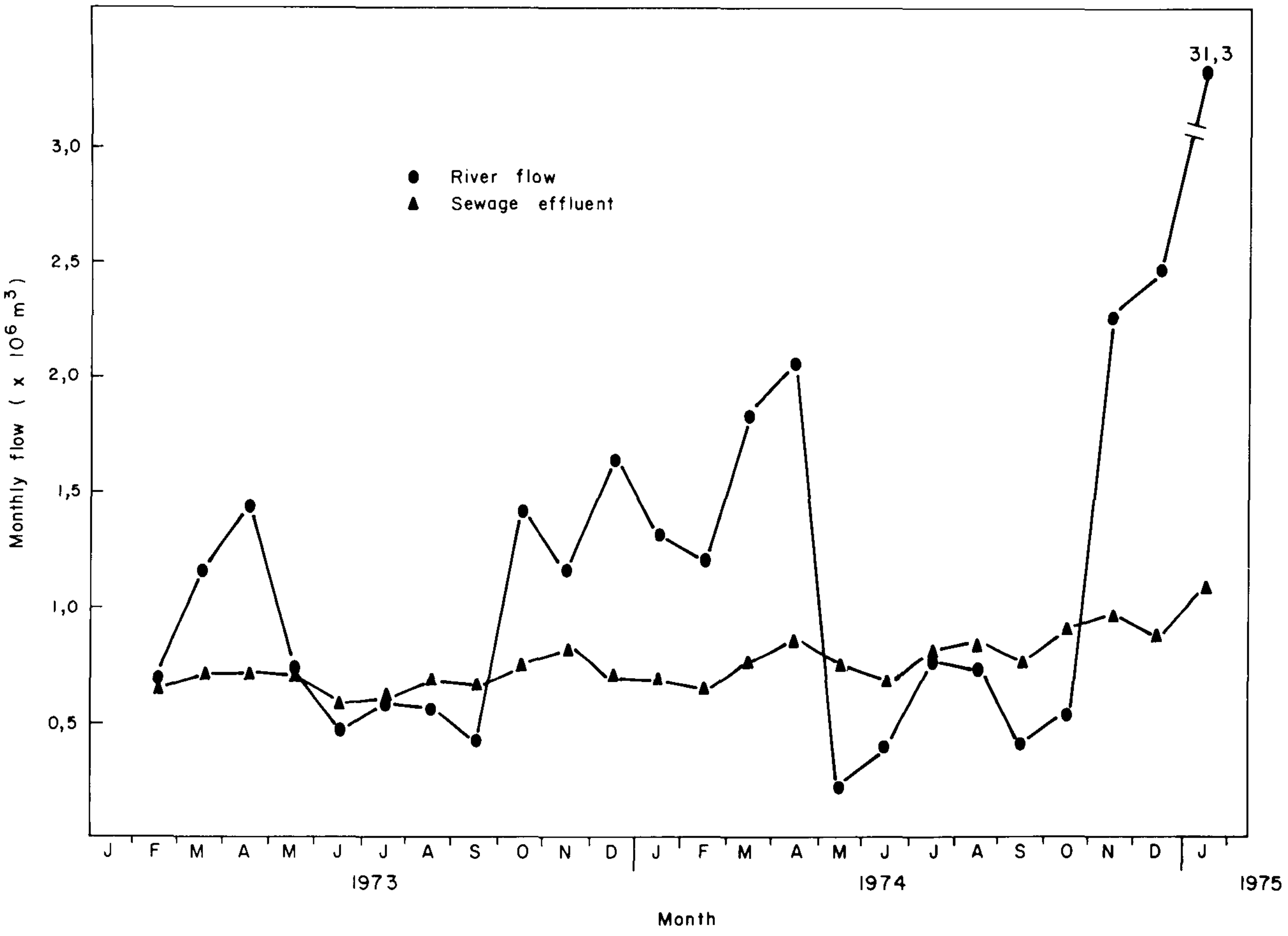

Figure 2
Monthly river flow in the upper Hennops River above Rietvlei Dam and monthly sewage effluent discharge from the Kempton Park sewage works

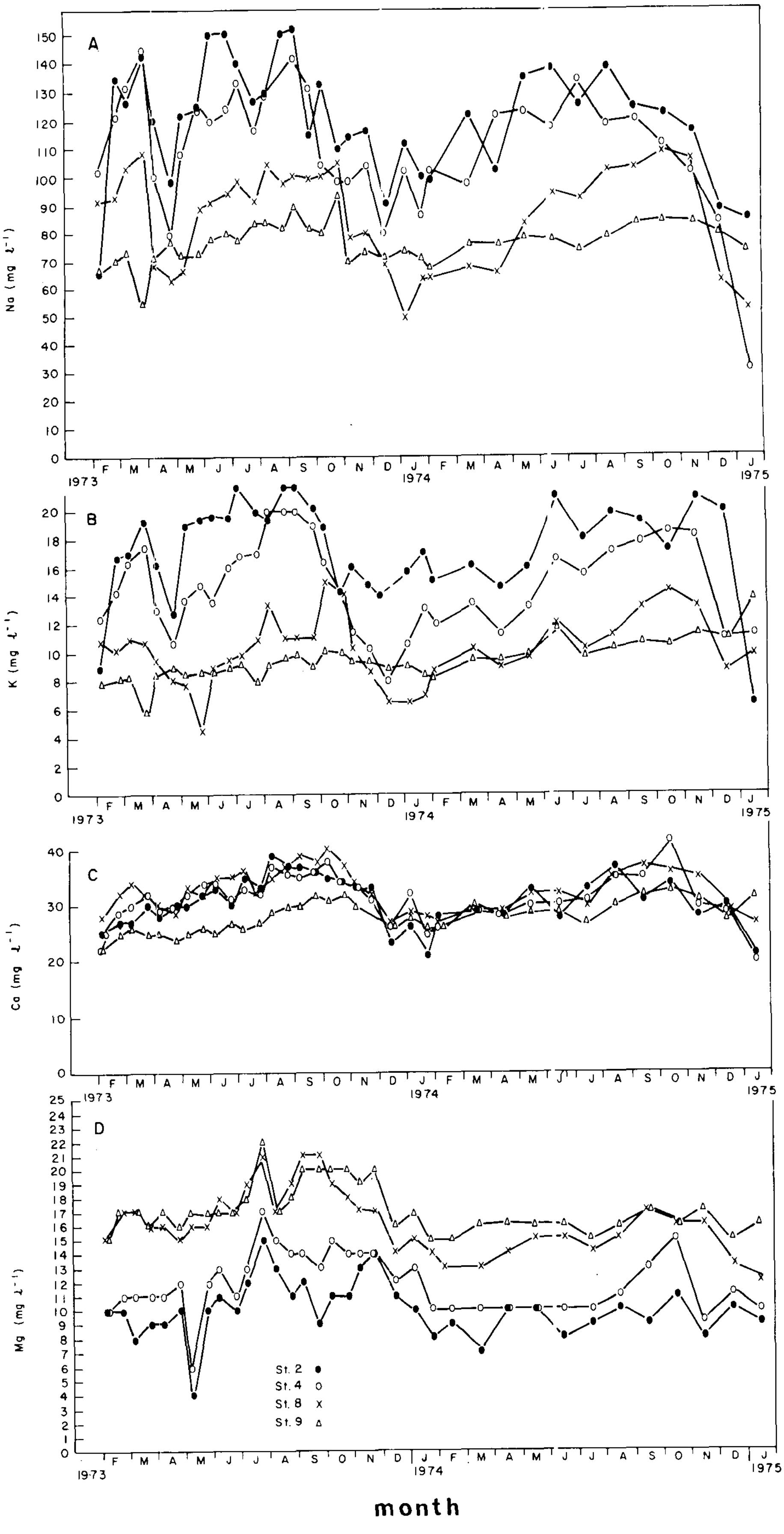

Figure 3

Sodium, potassium, calcium and magnesium concentrations in the water at stations 2, 4, 8 and 9 on the upper Hennops River during the study period (February 1973 to January 1975)

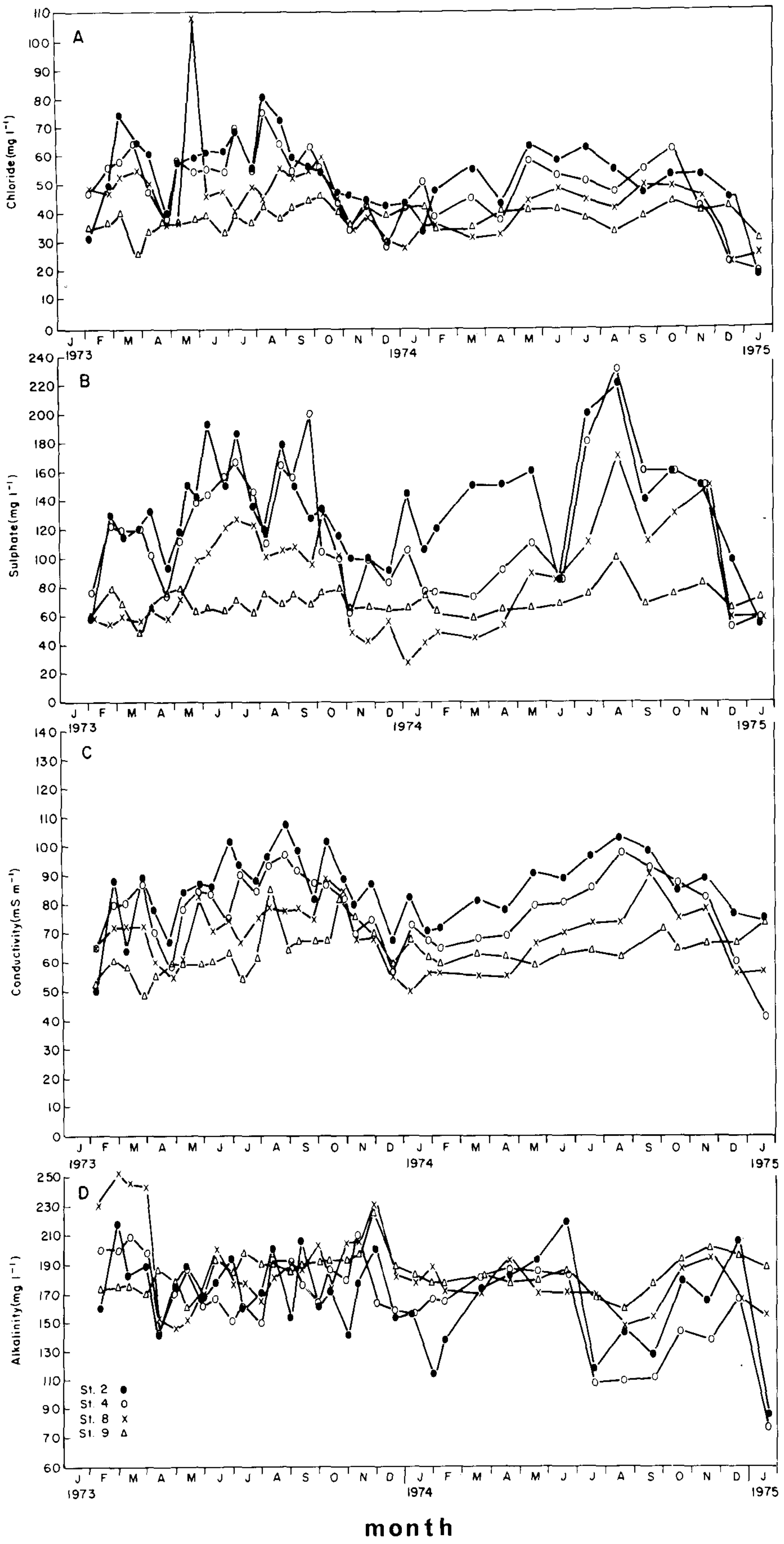

Figure 4
Chloride, sulphate, conductivity and alkalinity values in the water at stations 2, 4, 8 and 9 in the upper Hennops River during the study period (February 1973 to January 1975)

evidenced by the fact that the concentrations of these constituents were lower in the dam outflow than in waters of station 8 during the dry weather period and higher during the wet period (Figures 3A, 3B, 4A, 4B).

The concentrations of calcium did not fluctuate very much in the Hennops River above Rietvlei Dam, but the concentrations in the outflow from the dam were usually lower, especially during the first study year (Figure 3C). This indicates that there was a reduction in the calcium content during water storage in the dam, possibly by way of the precipitation of calcium compounds. The calcium concentrations were also higher during the low flow periods and lower during the wet weather period.

In contrast to the above, the magnesium concentrations were lower at station 2 and increased towards Rietvlei Dam (Figure 3D). This may be due to the influence of dolomitic rock in the catchment area on the composition of the river water. The magnesium concentrations also tended to be higher during the low flow periods and lower during the wet weather flow periods. As a result of the variation in the ionic species present, the conductivity of the water in the Hennops River decreased towards Rietvlei Dam (Figure 4C), although this reduction was not as pronounced as that of sodium for example (Figure 3A). The reason for this is that the sodium, potassium, sulphate and chloride concentrations in the upper stretch of the river were probably diluted by water high in magnesium, but low in these ions. Consequently, the decrease in the conductivity downstream was less pronounced.

Alkalinity

The alkalinities of waters at stations 8 and 9 were fairly similar and showed no distinct patterns (Figure 4D). The alkalinity of waters at stations 2 and 4 were more varied, but, again, no distinct patterns were discernible, although the large flood of January 1975 resulted in a distinct reduction (from 200 to 70 mg ℓ^{-1} as $CaCO_3$) in the alkalinity of the upper river water. It appears that heavy rain may result in a reduction in alkalinity, but that the influence of the catchment, especially through the dissolution of magnesium, causes a rapid increase in alkalinity.

Nitrogen, phosphorus and reactive silicate compounds

The ammonium nitrogen (NH_4-N) concentrations in the water at station 2 were very high, especially during the second year of the study (Figure 5A). Similarly, the nitrate (NO_3-N) concentrations in waters at this station were also high (Figure 5C), but in contrast to the NH_4-N, the NO_3-N concentrations were higher during the first than the second year. It is possible that the secondary effluent discharged from the Kempton Park sewage treatment plant was better nitrified during the first year of study than during the second year. Nitrification also took place in the river between stations 2 and 4, as evidenced by the increase in NO_3-N and decrease in NH_4-N concentrations between stations 2 and 4, especially in the second year of the study. Incomplete nitrification in the sewage treatment plant probably resulted in appreciable concentrations (about 0,6 mg l^{-1}) of nitrite (NO_2-N) being present at station 2 (Figure 5B). Nitrification between stations 2 and 4 may also have resulted in the rapid decrease of NO_2-N concentrations at station 4 ($< 0,1$ mg ℓ^{-1}).

NH_4-N diminished rapidly in the upper stretches of the river and there was little difference between NH_4-N concentrations at stations 4 and 9 (Figure 5A). Although station 4 had fairly high NO_3-N concentrations (about 4 mg l^{-1}), the lower river (station 8) had low NO_3-N concentrations (< 1 mgℓ^{-1}) in addition to low NO_2-N and NH_4-N concentrations.

The concentration patterns of Kjeldahl nitrogen and NH_4-N were very similar (Figures 5D and 5A, respectively) except that more dissolved organic nitrogenous compounds were present lower down the river. In general however, it appeared as though the role of dissolved organic nitrogenous compounds was rather minor in the lower stretches of the river.

The reactive silicate (Si) concentrations in waters at station 9 were consistently lower than at the rest of the sampling stations (Fig. 6A). This clearly indicates that silica was lost from solution in the impoundment by way of diatom growth, or chemical precipitation, or both. During the wet months there was little difference in the reactive silicate concentrations of waters at stations 2, 4 and 8, but in the dry months, the silica concentration decreased between stations 2 to 8 (Figure 6A). This may also point to the growth of epiphytic diatoms in the river during colder months.

The total dissolved phosphate (expressed as phosphorus and abbreviated as TDP) and the dissolved orthophosphate (PO_4-P) decreased substantially between stations 2 and 9 (Figures 6B and 6C). This reduction appeared to be the result of either biological activity, chemical precipitation or adsorption processes in the river system. The PO_4-P and TDP concentrations in the upper Hennops River and the waters flowing out of the impoundment appeared to be lower during the wet weather flow periods than during the dry weather flow periods. This pattern is similar to that for silicate and possibly indicates that diatom growth could also be responsible for the uptake of PO_4-P during the winter months.

It may also be significant that the PO_4-P and TDP concentrations of the outflow from Rietvlei Dam (station 9) increased from values of about 0,2 mg l^{-1} to about 1 to 2 mg l^{-1} by the end of the study period. The reason for this increase is uncertain but may reflect the magnitude of algal growth in the impoundment. Massive blooms of *Anabaena circinalis* and *Microcystis* spp. occurred in the summer of 1972/73 when the study was initiated, but in the two following summers, cooler and wetter conditions prevented the development of *A. circinalis* and, as a consequence, also the growth of non-nitrogen fixing algae (Ashton, 1976). Under these circumstances, less dissolved phosphate would have been utilized in algal growth and more would have passed through the outflow of the impoundment.

Chemical oxygen demand

The chemical oxygen demand (COD) decreased between station 2 and station 8, which had a similar COD to station 9 (Figure 6D). The COD of the water just below the Kempton Park sewage works appeared to increase between May and August and to decrease at the onset of warmer weather. This may be a reflection of decreased efficiencies during winter of the stabilization of organic compounds in the treatment plant and the self-purification capacity of the river system. Sudden increases in the COD, e.g. in November 1973 (Figure 6D), cannot be explained.

Removal of dissolved plant nutrients in the upper Hennops River

The potential contribution of the Kempton Park sewage works effluent to water flow in the Hennops River is extremely high, approximately 70 per cent of annual flow (Walmsley *et al.*,

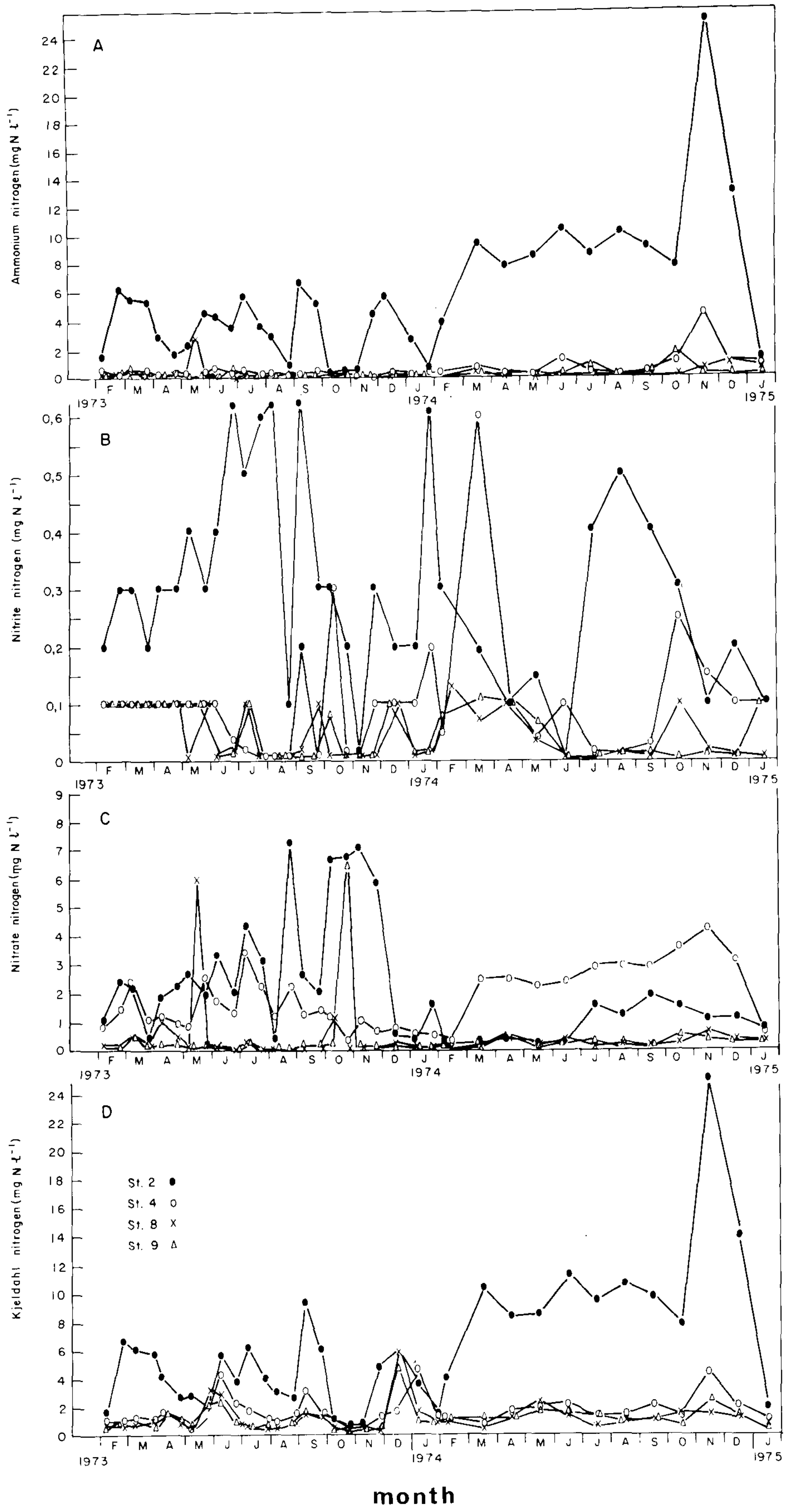

Figure 5
Ammonium, nitrite, nitrate and Kjeldahl nitrogen concentrations in the water at stations 2, 4, 8 and 9 on the upper Hennops River during the study period (February 1973 to January 1975)

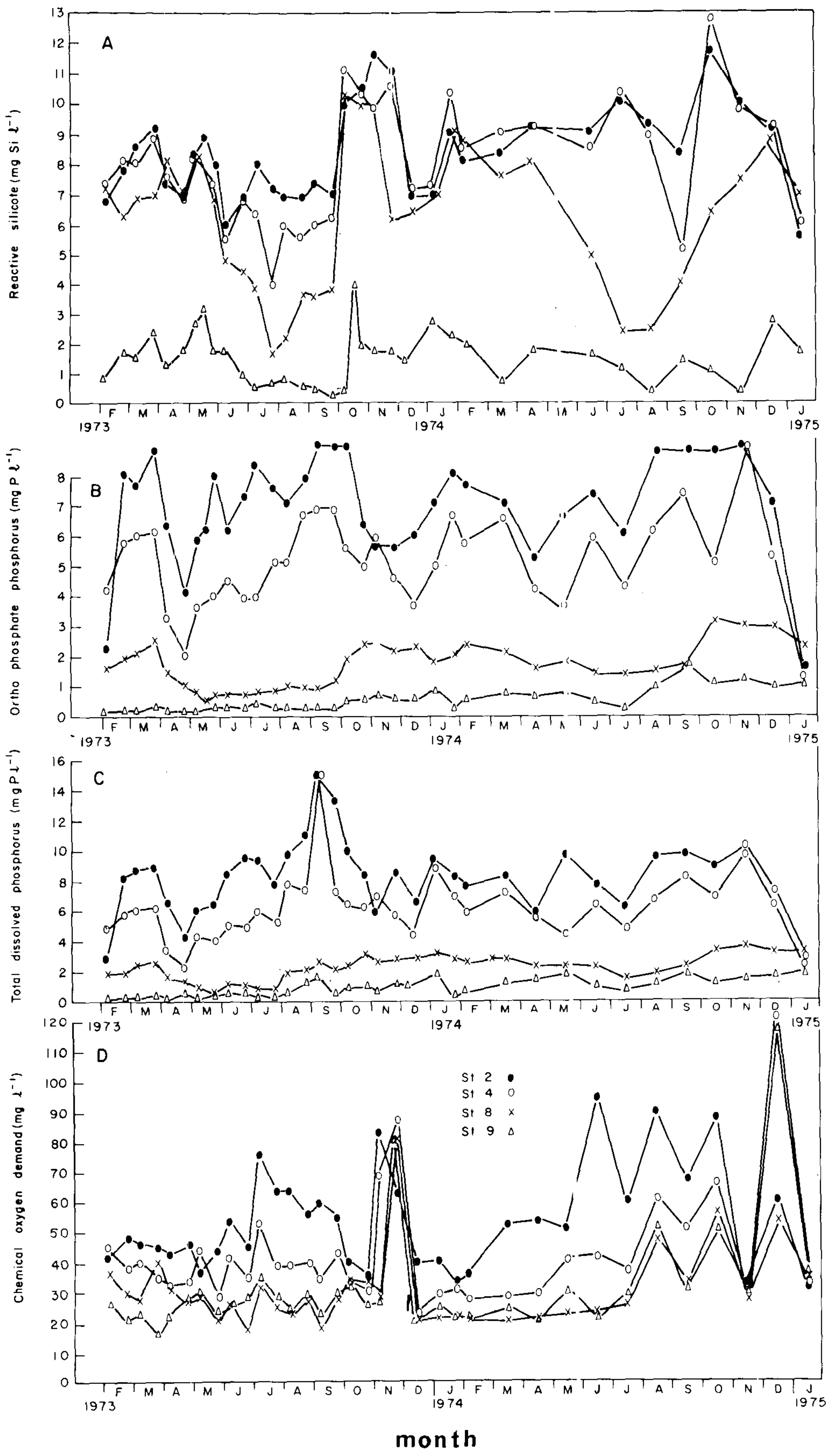

Figure 6

Reactive silicate, orthophosphate, total dissolved phosphate and chemical oxygen demand values of the water at stations 2, 4, 8 and 9 in the upper Hennops Rivier during the study period (February 1973 to January 1975)

1978). At times, particularly during the dry winter months, water flow in the Hennops River was less than the volume of effluents discharged from the sewage works (Figure 2). This indicates that during certain months, almost the entire flow in the river originates from the sewage works and that water is lost through evaporation or irrigation practices. However, during most summer months, contributions to water flow from run-off were more significant and obviously resulted in a greater dilution of the sewage effluents.

The results indicate that the concentrations of the dissolved nitrogenous, phosphate and silicate compounds were considerably reduced during passage of water from Kempton Park to Rietvlei Dam (Figures 5, 6). The question arises as to whether this decrease was due to dilution with a better quality water or to the removal of plant nutrients from the soluble state by biological or chemical processes, or both.

Assuming that the sewage effluents were the only significant source of certain constituents in the catchment, one could use the following equation:

$$V_1C_1 = V_8C_8$$

therefore

$$V_1/V_8 = C_8/C_1$$

where

V_1 = Volume of sewage effluents at station 1
V_8 = Volume of water at station 8
C_1 = Concentration of a specific constituent at station 1
C_8 = Concentration of that constituent at station 8

to obtain an idea of the dilution effect.

The mean concentrations of selected constituents for dry weather and wet weather flow conditions are summarized in Table 1.

The C_8/C_1 or V_1/V_8 ratios of the different constituents are summarized in Table 2. The concentrations of conservative elements, sodium and potassium, indicated that between 51 and 66 per cent of the flow at station 8 could possibly be treated sewage effluents. The indications from conductivity values are 76 to 80 per cent, but earlier results (Figures 3D and 4C) suggest that magnesium originating from the catchment influences the conductivity values at station 8. Consequently, the indications obtained from chloride and conductivity may be overestimating the flow contribution of the sewage effluents. From the data of Toerien and Walmsley (1978) and Walmsley and Toerien (1978) on the feeder streams of Hartbeespoort and Roodeplaat Dams respectively, it appears that potassium is a good indicator of

TABLE 1
MEAN DISSOLVED CONCENTRATIONS OF SELECTED CHEMICAL CONSTITUENTS IN THE CATCHMENT OF RIETVLEI DAM (mg l^{-1})

Sampling stations

	1		2		3		4		5		6		7		8		9	
	D*	W**	D	W	D	W	D	W	D	W	D	W	D	W	D	W	D	W
Parameter																		
NH_3-N	5,40	4,53	3,83	3,03	0,62	0,43	0,39	0,32	0,21	0,24	0,17	0,23	0,25	0,24	0,18	0,19	0,26	0,26
NO_2-N	0,54	0,23	0,58	0,33	0,06	0,12	0,06	0,09	0,04	0,08	0,06	0,09	0,04	0,07	0,05	0,07	0,05	0,06
NO_3-N	2,06	1,85	2,90	2,78	1,95	1,28	1,69	0,91	0,22	0,19	0,11	0,16	0,09	0,20	0,08	0,30	0,12	0,17
Kj-N	5,95	6,00	4,47	3,47	1,95	1,47	1,80	1,33	1,31	1,00	1,27	0,90	1,97	1,03	1,24	1,16	1,18	1,11
PO_4-P	7,42	7,45	7,57	6,71	5,94	5,66	5,03	5,00	2,23	3,38	1,27	2,50	0,92	2,03	0,81	1,99	0,30	0,43
TDP	9,42	7,96	9,65	7,42	7,46	6,49	6,69	5,67	3,38	4,03	1,96	3,31	1,54	2,54	2,56	2,38	0,65	0,63
Si	7,49	9,30	7,44	8,68	7,08	8,89	6,41	8,76	4,83	8,27	3,82	7,77	4,56	7,76	5,02	7,81	1,17	1,99
Cl	60,4	54,7	63,3	48,9	62,3	48,7	61,0	46,6	58,0	42,5	55,1	42,9	48,3	40,0	48,6	42,6	39,1	38,6
K	19,2	17,6	20,2	15,5	17,8	13,2	17,1	12,9	14,3	11,2	13,1	11,4	10,7	9,6	9,0	9,7	8,9	8,6
Na	134,9	128,3	135,8	111,5	129,4	106,4	127,1	103,8	117,5	94,5	110,6	91,8	95,1	88,8	89,6	81,0	77,6	74,3
Conductivity (mS m^{-1})	90,4	86,5	91,8	77,5	87,8	72,0	86,9	72,3	82,5	68,9	78,7	69,1	74,3	67,7	72,3	65,8	64,7	63,2

* D = Dry weather flow (May to September 1973)
**W = Wet weather flow (February to April 1973 and October 1973 to January 1974)

the presence of sewage effluents in the Johannesburg-Pretoria area. Consequently, the C_8/C_1 ratios for potassium which suggest a treated sewage effluent flow contribution at station 8 of approximately 51 to 55 per cent, may be considered more reliable.

When the C_8/C_1 ratios of various plant nutrients are evaluated against the potassium C_8/C_1 ratio, it is evident that the decreases in NH_4-N, NO_2-N, NO_3-N, total dissolved nitrogen, PO_4-P and TDP downstream greatly exceeds the reduction that could be ascribed solely to dilution with better quality water. Conversely, silicate and organic nitrogen compounds seem to originate in the catchment during the flow of water to the Rietvlei Dam, although Figure 6A suggests that silicate may be utilized during the dry weather flow period.

Dissolved mineral loads into and out of Rietvlei Dam

To obtain an idea of the dissolved chemical loads entering (via the Hennops River) and leaving Rietvlei Dam, use was made of the results obtained from February 1973 to January 1974 when the sampling frequency was biweekly and no uncommonly high floods entered the dam as in the following year.

The results of the three different methods of estimating the loads which entered the impoundment are summarized in Table 3. The agreement between the different methods of estimating loads was good, as illustrated by the following regression analyses based on the loading of all constituents:

Method B = 11,49 + 0,85 (Method A), r = 0,989, n = 15
Method C = 7,84 + 0,91 (Method A), r = 0,998, n = 15
Method C = 1,05 (Method B) — 1,49, r = 0,996, n = 15

Calculation of the loads from the mean annual concentration and the total flow (Method A) gave the highest estimates and the other estimates were about 10 to 15 per cent lower. The lowest estimates were obtained when using the mean concentration values of the dry and wet weather flow conditions and their respective total flow values. Since the differences between the different estimates were not more than about 15 per cent (reflected by the regression coefficients), the use of the mean of the three methods appears to be acceptable for a representative load estimate (Table 3).

Comparison of these estimates with the output from the impoundment (Table 4), taking into account that the water level of the dam fluctuated and therefore normalized results should be used (see also Toerien and Walmsley, 1978), indicated that some constituents might be retained and others be lost from the impoundment. The loads of dissolved PO_4-P, TDP and silicate which left the impoundment were considerably less than those entering through the Hennops River. This suggests that these constituents are removed from the soluble state by way of biological or chemical activity, or both. The dissolved nitrogenous compounds, especially NO_3-N, did not behave similarly and more left the impoundment than entered through the Hennops River. Ashton (1976) indicated that nitrogen-fixation by blue-green algae, notably *A. circinalis,* takes place in the impoundment and this probably affects the loads of dissolved nitrogenous compounds leaving the impoundment.

Sodium, potassium, magnesium and sulphate appeared not to be retained in the impoundment to any great extent. Some calcium and chloride may be retained, the former probably by way of $CaCO_3$ formation during high pH conditions created by algal growth, whilst the retention mechanism, if it exists, for the latter cannot be explained. The load of COD leav-

TABLE 2
THE RATIOS (C_8/C_1) OF MEAN CONCENTRATIONS OF SELECTED CHEMICAL CONSTITUENTS FOR STATIONS 8 AND 1

Constituent	C_8/C_1 Dry weather	C_8/C_1 Wet weather
NH_3-N	0,03	0,04
NO_2-N	0,09	0,30
NO_3-N	0,04	0,16
Organic N	1,93	0,66
Total dissolved nitrogen	0,16	0,19
PO_4-P	0,12	0,27
TDP	0,27	0,32
Si	0,67	0,84
Cl	0,80	0,78
K	0,50	0,55
Conductivity	0,80	0,76
Na	0,66	0,63

TABLE 3
CHEMICAL LOADS WHICH ENTERED RIETVLEI DAM THROUGH THE HENNOPS RIVER DURING THE PERIOD FEBRUARY 1973 TO JANUARY 1974

Constituent	Loads ($t\ a^{-1}$) estimated by			
	Method A	Method B	Method C	Mean
Na	1025	964	957	982
K	116	113	111	113
Ca	388	365	372	375
Mg	211	188	195	198
Cl	543	511	524	526
SO_4	970	715	835	840
NH_3-N	2,09	2,18	3,23	2,50
NO_2-N	0,81	0,76	0,66	0,74
NO_3-N	2,67	2,87	3,51	3,02
Organic N	11,7	11,5	6,73	9,98
Total dissolved N	17,27	17,31	14,13	16,23
PO_4-P	16,10	17,79	20,00	18,63
TDP	21,30	28,10	25,00	24,80
Si	74,1	82,8	82,4	79,8
COD	351	359	371	360

Method A = Mean concentration for year x total flow per year

Method B = Mean concentration for dry weather period x total flow for dry weather period plus mean concentration for wet weather period x total flow for wet weather period

Method C = $F_1C_1 + F_2C_2 + \ldots + F_nC_n$

where F = Total flow between sampling periods
C = concentration values
1,2, ..., n = two-weekly sampling periods

Conclusions

Rietvlei Dam is highly eutrophic as far as phosphorus is concerned, a fact supported by algal bioassay data (Walmsley and Ashton, 1977). Because the impoundment is more eutrophied by phosphorus than nitrogen, ideal conditions for the growth of nitrogen-fixing blue-green algae are created (Ashton, 1976) and, under suitable climatic conditions, this potential is realized. The nitrogen-removal mechanisms in the catchment of the impoundment therefore tend to safeguard the impoundment against algal blooms. Since the nitrogen-fixing algae grow well in hot and dry periods (Ashton, 1976), it can be expected that algal growth problems will be experienced in Rietvlei Dam during periods of low rainfall. It is therefore important that the phosphorus contribution via the Hennops River should be reduced considerably.

At present, the capacity of the Kempton Park sewage works is 40 Mℓ d^{-1}. A new proposed plant will discharge an additional 30 Mℓ d^{-1} into the upper Hennops River (De Lange, 1978 — personal communication). These effluents may not be subjected to the same degree of nitrogen and phosphate removal since the point of discharge will be below the upper vlei system. This might have significant effects on Rietvlei Dam, particularly as an increase in nitrogen loading might increase the frequency of *Microcystis* spp. blooms in the system.

Since the evidence of the present study suggests that vlei systems may be important in removing both available nitrogen and phosphorus from the water of the Hennops River, the artificial establishment of vlei systems either in the river or at the new sewage treatment plant should be considered. It is possible that such systems may be an effective way of dealing with residual loads of nitrogen and phosphorus leaving the sewage treatment plant.

Acknowledgements

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References

ASHTON, P.J. (1976) *Nitrogen fixation in Rietvlei Dam: Causes and consequences.* Paper presented at a First Interdisciplinary Conference on Marine and Freshwater Research in Southern Africa, Port Elizabeth, 5—10 July 1976.

BOND, G.W. (1946) A geochemical survey of the underground water supplies of the Union of South Africa with particular reference to their utilization in power production and industry. *Geological Survey Memoirs* No. 41, Government Printer, Pretoria.

DU TOIT, A.C. (1954) *The Geology of South Africa.* 3rd Edition, Oliver and Boyd, London.

HARRISON, A.D., KELLER, P. and DIMOVIC, D. (1960) Ecological studies on Olifantsvlei, near Johannesburg. *Hydrobiologia* 15 89—134.

NATIONAL INSTITUTE FOR WATER RESEARCH (1974) *Analytical guide I. Laboratory techniques. II. Theoretical aspects and analytical methods.* Edited by J.R.H. Hoffmann, National Institute for Water Research, Pretoria.

SMITH, R.V. and STEWART, D.A. (1977) Statistical model of river loadings of nitrogen and phosphorus in the Lough Neagh system. *Wat. Res.* 11 631—636.

SOUTH AFRICAN BUREAU OF STANDARDS (1971) Specification of water for domestic use. First Review. *Report No. SABS 241,* Pretoria.

STEŸN, D.J., SCOTT, W.E., TOERIEN, D.F. and VISSER, J.H. (1975) The eutrophication levels of some South African impoundments:1. Rietvlei Dam. *Water S.A.* 1(2) 45—52.

TOERIEN, D.F. (1975) South African eutrophication problems. A perspective. *J. Wat. Pollut. Control* 74 134—142.

TOERIEN, D.F., HYMAN, K.L. and BRUWER, M.J. (1975) A preliminary trophic status classification of some South African impoundments. *Water S.A.* 1 (1) 15—23.

TOERIEN, D.F. and STEŸN, D.J. (1973) Application of algal bioassays in eutrophication analyses. *S. Afr. J. Sci.* 69 79—82.

TOERIEN, D.F. and WALMSLEY, R.D. (1977) Tussentydse riglyne vir die beheer van eutrofikasie. *Tegniese Verslag No. 1,* Water Research Commission, Pretoria.

TOERIEN, D.F. and WALMSLEY, R.D. (1978) The dissolved mineral composition of the water flowing into and out of the Hartbeespoort Dam. *Water S.A.* 4 (1) 25—38.

VOLLENWEIDER, R.A. (1968) *Scientific fundamentals of the eutrophication of lakes and flowing waters, with particular reference to nitrogen and phosphorus as factors in eutrophication,* O.E.C.D. Report, Paris.

VOLLENWEIDER, R.A. (1975) *Advances in defining critical loading levels for phosphorus in lake eutrophication.* Unpublished report of the Canada Centre for Inland Waters, Burlington.

WALMSLEY, R.D. and ASHTON, P.J. (1977) Algal growth potential and the succession of algae in a nitrogen-limited impoundment. *S.Afr. J. Sci.* 73 151—152.

WALMSLEY, R.D. and TOERIEN, D.F. (1978) The chemical composition of the waters flowing into Roodeplaat Dam. *Water S.A.* 4 (4) 192—202.

WALMSLEY, R.D., TOERIEN, D.F. and STEŸN, D.J. (1978) Eutrophication of four Transvaal Dams. *Water S.A.* 4 (2) 61—75.

ing the impoundment was about 87 per cent of that entering the impoundment through the Hennops River. The dynamics of dissolved organic compounds in the impoundment through mineralization processes by micro-organisms on the one hand and production by algal growth on the other hand, may be quite complex.

Discussion

Water quality

The water quality just above Rietvlei Dam is generally good. Despite the fact that from February 1973 to January 1974, 70 per cent of the potential inflow into the dam consisted of secondary treated sewage effluents, the recommended limits for potable water (South African Bureau of Standards, 1971) were in no way exceeded for any of the parameters determined in this study. However, the chemical results (especially potassium data, (Table 2)) suggest that only 50 per cent of the flow at station 8 consisted of sewage effluents. The difference (20%) can possibly be attributed to irrigation practices along the river.

A comparison of the chemical quality of the Hennops River just above Rietvlei Dam with that of the Crocodile River just above Hartbeespoort Dam (Toerien and Walmsley, 1978) shows several similarities and some differences. The mineral contents of the two rivers are fairly similar, e.g. sodium concentrations of approximately 52 and 85 mg l^{-1}, chloride concentrations of approximately 53 and 45 mg l^{-1}, sulphate concentrations of approximately 85 and 72 mg l^{-1}, and conductivity values of approximately 64 and 68 mS m^{-1} for the Crocodile and Hennops Rivers, respectively (Toerien and Walmsley, 1978; Table 1).

TABLE 4
A COMPARISON OF THE DISSOLVED LOADS WHICH ENTERED AND LEFT RIETVLEI DAM AND THOSE EMANATING FROM KEMPTON PARK SEWAGE TREATMENT PLANT DURING THE PERIOD FEBRUARY 1973 TO JANUARY 1974

Parameter	Total input ($t\ a^{-1}$)	Total output ($t\ a^{-1}$*)	% annual Change**	Load leaving Kempton Park sewage treatment plant*
Na	982	839	14,6	1038
K	113	105	7,1	176
Ca	375	298	20,5	255
Mg	198	196	1,0	88
Cl	526	426	19,0	463
SO_4	840	719	14,4	1116
NH_3-N	2,50	2,85	−14,0	41,3
NO_2-N	0,74	0,66	10,8	3,0
NO_3-N	3,02	4,83	−59,9	13,8
Organic N	9,98	9,88	1,0	5,6
Total dissolved N	16,23	18,22	−12,3	63,7
PO_4-P	18,63	3,73	80,0	62,1
TDP	24,8	6,58	73,5	68,8
Si	79,8	16,8	78,9	69,4
COD	360	314	12,8	455
Water x $10^6 m^3$	11,60	10,97	5,41	8,167

* Calculated from annual mean multiplied by annual flow

$$\text{**\% annual change} = \frac{\text{total input} - \text{total output}}{\text{total input}} \times 100$$

The total dissolved nitrogen concentration in the waters entering Rietvlei Dam (1,3 to 1,5 mg l^{-1} as N) is much lower than in those that enter Hartbeespoort Dam (about 15 mg l^{-1} as N), despite the fact that higher inflows of treated sewage effluents probably enter Rietvlei Dam (Walmsley *et al.*, 1978). This difference in inflowing nitrogen concentrations can partly be ascribed to a difference in the quality of the sewage effluents discharged in the two catchments; i.e. total dissolved nitrogenous compounds of about 21 mg l^{-1} as N (Northern sewage works, Diepsloot) in the case of Hartbeespoort Dam and 10 mg l^{-1} as N (Kempton Park sewage works) in the case of Rietvlei Dam. However, the reduction in dissolved nitrogen discharged into the Jukskei River between the point of discharge at the Northern sewage treatment plant and Hartbeespoort Dam is only from about 21 to 10 mg l^{-1} as N (50% reduction), despite the large dilution effect of the Crocodile and Hennops Rivers joining the flow from the Jukskei River. In the case of the Hennops River, the reduction is from about 10 to 1,4 mg l^{-1} as N (86%). The self-purification capacity of the river course of the Hennops River appears to be more marked than that of the Jukskei-Crocodile River.

This reduction (in the nitrogen status of the waters) appears to have a significant effect on the condition of Rietvlei Dam. Ashton (1976) indicated that the low input of nitrogen and high input of phosphorus results in a potential for growth of the nitrogen-fixing blue-green algae, notably *A. circinalis.* He cited an incidence of a massive bloom of this alga during the summer of 1972/73 when the fixation of gaseous nitrogen could have been equivalent to the nitrogen input via the Hennops River. As postulated earlier, the higher output of dissolved nitrogenous compounds compared to the input via the feeder streams (Table 4) could have been caused by the fixation of gaseous nitrogen during the summer of 1972/73. The presence of algal blooms in Rietvlei Dam interferes with the production of potable water and escalates its production costs (Toerien, 1975).

Comparisons of the dry and wet weather mean flow concentrations of dissolved nitrogenous compounds in the Hennops River (Table 1) indicate that, in all instances, the most substantial reductions occurred between sampling stations 2 and 3, and 4 and 5 (Table 5). Examination of 1:50 000 trigonometric maps of the catchment area indicated the presence of vlei systems between these sampling stations. Consequently, the self-purification of dissolved nitrogen in this river may be mostly associated with these vlei systems, as suggested by Toerien and Steÿn (1973) and Walmsley *et al.* (1978).

Harrison, Keller and Dimovic (1960) studied the Olifantsvlei to the south of Johannesburg and found that nitrate was not effectively removed during the winter when the reeds died down. However, in the present study, the removal of nitrate, as in the case of all other inorganic nitrogenous compounds, was higher during the dry weather (winter) than during wet weather (summer) conditions. This difference in behaviour cannot be explained and indicates the necessity for further research.

The concentrations of PO_4-P and TDP also decreased between Kempton Park and Rietvlei Dam (Table 1). As with the

TABLE 5
DECREASES IN CONCENTRATIONS OF DISSOLVED PLANT NUTRIENTS BETWEEN DIFFERENT SAMPLING STATIONS

Between sampling stations	Reduction in concentration (mg l^{-1})					
	Dry weather flow			Wet weather flow		
	Total inorganic N	PO_4-P	TDP	Total inorganic N	PO_4-P	TDP
2 and 3	−4,68	−1,63	−2,19	−4,31	−1,05	−0,93
3 and 4	−0,49	−0,91	−0,77	−0,48	−0,66	−0,82
4 and 5	−0,67	−2,80	−3,31	−0,87	−1,62	−1,64
5 and 6	−0,13	−0,96	−1,42	−0,03	−0,88	−0,72
6 and 7	+0,04	−0,35	−0,42	−0,05	−0,47	−0,77
7 and 8	−0,07	−0,11	+1,02	+0,05	−0,04	−0,16
8 and 9	+0,12	−0,51	−0,91	−0,07	−1,56	−1,75

− indicates decrease between sampling stations
+ indicates increase between sampling stations

nitrogenous compounds, the most distinct changes in PO_4-P and TDP concentrations occurred between stations 2 and 3, and 4 and 5 (Table 5). This suggested that the vlei systems may also be involved in the decrease in phosphate concentrations along the Hennops River. However, phosphate concentrations also decreased between the other sampling stations, probably indicating that other mechanisms of removal, for example soil-binding, may be very important. The impoundment also appeared to be a significant sink for phosphates (Table 5).

Trophic status of Rietvlei Dam

The hydrological and nutrient loading characteristics of Rietvlei Dam from February 1973 to January 1974 are summarized in Table 6. Vollenweider (1975) suggested that the equation —

$$Lc\,(g\,m^{-2}\,a^{-1}\text{ as P}) = 0{,}01.q_s\,(1 + \sqrt{Z/q_s}) \qquad (1)$$

where

Lc = critical phosphorus loading rate (g m^{-2} a^{-1} as P)
q_s = surface overflow rate (m a^{-1})

and

Z = mean depth (m)

defines the critical phosphorus loading rate for lakes which, when exceeded, leads to eutrophic conditions. Toerien and Walmsley (1977) suggested that this equation be modified for use on data of South African impoundments to:

$$Lc\,(g\,m^{-2}\,a^{-1}\text{ as P}) = 0{,}025.q_s\,(1 + \sqrt{Z/q_s}) \qquad (2)$$

To develop critical loading levels of lakes for biochemically active nitrogen and phosphorus, Vollenweider (1968) made use of a N/P ratio of 15:1 (by mass). A similar approach would then suggest that the critical loading rate for available nitrogen for Rietvlei Dam would be —

$$Lc\,(g\,m^{-2}\,a^{-1}\text{ as N}) = 0{,}375.q_s\,(1 + \sqrt{Z/q_s}) \qquad (3)$$

Based on equations 2, 3 and Table 6, the critical loading rates for available phosphorus and nitrogen for Rietvlei Dam are approximately 0,30 g m^{-2} a^{-1} as P and 4,4 g m^{-2} a^{-1} as N, respectively. The estimated loading rate of inorganic nitrogen (3,29 g m^{-2} a^{-1} as N) is below the critical value whilst that of total dissolved nitrogen (8,5 g m^{-2} a^{-1} as N) is higher. Therefore in terms of its river nitrogen loading, the Rietvlei Dam appears not to be eutrophic. By contrast, the PO_4-P and TDP loading rates exceed the estimated critical phosphorus loading rate by factors of 23 and 37, respectively (Toerien and Walmsley, 1977).

TABLE 6
HYDROLOGICAL AND NUTRIENT LOADING CHARACTERISTICS OF RIETVLEI DAM FOR THE PERIOD FEBRUARY 1973 TO JANUARY 1974

Characteristic	Magnitude
Mean capacity	11,672 x 10^6 m^3
Mean area	190 ha
Mean depth (Z)	6,1 m
Water outflow	10,973 x 10^6 m^3
Water residence time	1,06 a
Surface overflow rate (qS)	5,75 m a^{-1}
PO_4-P loading rate	9,81 g m^{-2} a^{-1}
TDP loading rate	13,05 g m^{-2} a^{-1}
Inorganic N loading rate	3,29 g m^{-2} a^{-1}
Total dissolved N loading rate	8,54 g m^{-2} a^{-1}