The Chemical Composition of the Waters Flowing into Roodeplaat Dam

R.D. WALMSLEY AND D.F. TOERIEN*
[NATIONAL INSTITUTE FOR WATER RESEARCH, COUNCIL FOR SCIENTIFIC AND INDUSTRIAL RESEARCH, P.O. BOX 395, PRETORIA, 0001]

Abstract

The results of a chemical study of the inflowing and outflowing waters of the Roodeplaat Dam between 1973 and 1975 are presented. Discharges of sewage and industrial effluents had significant effects on the chemical composition of the water in stretches of the Pienaars River and the Morelettaspruit. The Pienaars River was the major contributor of water inflow and dissolved mineral loading to Roodeplaat Dam, contributing between 65 and 99 per cent of the annual loading of certain chemical constituents. The Baviaanspoort sewage works contributed 25 and 9% of the impoundment's annual inflow for the 1973/74 and 1974/75 study years respectively, and between 5 and 91% of the annual loading of dissolved chemical constituents. On the basis of the extremely high nutrient loading rates ($>8,0$ g P m^{-2} a^{-1} and >44 g N m^{-2} a^{-1}), Roodeplaat Dam may be classified as a highly eutrophic water body.

Introduction

Roodeplaat Dam is an impoundment which receives discharges of sewage and industrial effluents (Walmsley, Toerien and Steÿn, 1978a). Algal assays have indicated that the waters are highly eutrophic (Toerien, Hyman and Bruwer, 1975; Steÿn, Toerien and Visser, 1976). Information on the factors affecting the water quality of impoundments is essential if trends are to be predicted and water management programmes applied. Walmsley *et al.* (1978a) have discussed the eutrophication of Roodeplaat Dam and made a comparison with some other impoundments. This paper deals with the dissolved chemical constituents in the waters flowing into and out of the impoundment and discusses the significance of certain cultural activities in the catchment.

Description of Area

Roodeplaat Dam, situated approximately 20 km north-east of Pretoria, (25° 37'S; 28° 23'E) is used as an irrigation and potable water supply and serves as an important recreational centre. The catchment has an area of 668 km^2 and is situated in a summer rainfall area which receives an average annual rainfall of approximately 700 mm. Approximately 12% of the catchment is urban/industrial, 23% is cultivated land and the remainder comprises sour grassland and mixed bushveld (these figures are based on the 1972 land use maps of the Department of Planning).

Geologically, the catchment area comprises shale and quartzite of the Magaliesberg Stage, overlain by shale, siltstone and minor quartzite bands belonging to the Smelterskop Stage of the Pretoria Series (Verwoerd, 1967). Grey dolomite fragments can be found as medium-grained irregular patches associated with brecciation of the rock and intrusive beds of limestone are also found in the catchment. Bond (1946) has classified the underground waters of the area as being of the temporary hard carbonate type.

Three river systems contribute to the water flow into the impoundment (Figure 1). The Morelettaspruit/Hartbeesspruit system originates in an urban area of Pretoria and bypasses an industrial area (Silverton). The Pienaars River, the major contributor to inflow, originates in a rural area, flows through the Mamelodi Township and then passes the Baviaanspoort sewage works. The Edenvalespruit, situated to the east of the impoundment, drains agricultural land and grassland. The Baviaanspoort sewage works discharges between 220 and 470 x 10^3 m^3 of treated effluent per month into the Pienaars River and Walmsley *et al.* (1978a) have estimated that this volume of water can represent up to 25% of the annual water inflow to Roodeplaat Dam. The sewage works which was commissioned in 1966, treats effluents from the Mamelodi Township (population in 1975 approximately 120 000, according to the Department of Statistics) and has been cited as the major cause of the eutrophic condition of Roodeplaat Dam (Walmsley *et al.* 1978a).

Sampling and Laboratory Procedures

Sampling stations were sited at accessible points on each of the

*Present address: Institute for Environmental Sciences, University of the Orange Free State, P.O. Box 339, Bloemfontein, 9300

month October was selected to illustrate the dry spell distribution because it is transitional between the dry and wet seasons in Natal.

Research is currently in progress to determine the minimum seasonal rainfall for an area to be considered drought stricken, by plotting cumulative percentage frequencies of a series of wet season (i.e. the planting and growing as well as the baseflow accumulating season) rains. Following Gibbs and Maher's (1967) concepts, the degree of drought strickenness is delimited by assuming that rainfall amounts within the first decile constitute severe droughts and between the first and second deciles less severe droughts. In Figure 13 the first decile rainfall amounts of severe droughts thus delimited, are illustrated for the Drakensberg region.

The above type of research could provide an interesting and scientific basis for payment of drought relief subsidies or for crop risk insurance claims.

Conclusions

Several other areas of hydrometeorological and climatological research are also pursued in the Agricultural Catchments Research Unit. The above review, has, however, examined the two main lines of rainfall analysis viz. studies based on break-point digitizing and on daily rainfall records. The research emphasis, it should be stressed again, is on applied aspects of rainfall climatology that are used in the fields of hydrology, engineering, water resources and regional agricultural planning.

Acknowledgements

The writer wishes to acknowledge the Water Research Commission, which funded the greater part of the research on which this review was based. The Department of Forestry is also thanked for its co-operation in regard to data from its Cathedral Peak hydrological research station. Many people have, over several years, been involved in data manipulation in this project, and the writer acknowledges in particular the contributions of Misses P. Mapstone and D. Camons, Dr. J.R. Burney, Messrs. D. Lüdemann, N. Hendry and G. Lumsden; also the Computer Centre — all of the University of Natal, Pietermaritzburg.

References

DE JAGER, J.M. and SCHULZE, R.E. (1977) The broad geographic distribution in Natal of climatological factors important to agricultural planning. *Agrochemophysika,* **8** 81–91.

ELWELL, H.A. and STOCKING. M.A. (1973) Rainfall parameters for soil loss estimation in a subtropical climate. *Jour. Agric. Engng. Res.* **18** *169–177.*

GIBBS, W.J. and MAHER, J.V. (1967) *Rainfall deciles as drought indicators.* Bureau of Meteorology, Melbourne. Bull. No. 48, 33 pp.

HUDSON, N.W. (1963) Raindrop size distribution in high intensity storms. *Rhod. Jour. Agric. Res.* **1** 6–11.

LAWS, J.O. (1941) Measurements of fall velocities of waterdrops and raindrops. *Trans. Am. Geophys. Un.* **22** 709–712.

WEATHER BUREAU (1974) *Extreme values of rainfall, temperature and wind for selected return periods.* Department of Transport, Pretoria. Climate of South Africa, Part II, WB. 36. 29 pp.

WIEDERHOLD, J.F.A. (1969) Design storm determination in South Africa. Wits Univ. *HRU Report,* 1/69.

WISCHMEIER, W.H. and SMITH, D.D. (1958) Rainfall energy and its relationship to soil loss. *Trans. Am. Geophys. Un.* **39** 285–291.

three inflowing systems, at the outflow of the Baviaanspoort sewage works and at the irrigation canal which is situated at the base of the dam wall (Figure 1). Water samples were collected at 14-day intervals from February 1973 to December 1973, and then at monthly intervals until February 1975. The pH of the water samples was determined in the field by means of a portable Metrohm pH meter. Treatment of water samples was carried out using the methods outlined by Walmsley *et al.* (1978a). Analyses for sodium, potassium, calcium, magnesium, sulphate, chloride, reactive silicate, ammonia, nitrate, nitrite, Kjeldahl nitrogen, orthophosphate, total dissolved phosphate, chemical oxygen demand, alkalinity and conductivity were conducted on filtered water samples using the methods adopted by the National Institute for Water Research (1974).

Results

Water Flow Characteristics

The monthly water flows for the Pienaars River, the Edenvalespruit, the Hartbeesspruit and the monthly effluent discharges from the Baviaanspoort sewage works during the study are shown in Table 1 (Data for the river flows were provided by the Department of Water Affairs whilst the discharge data for the Baviaanspoort sewage works were provided by the Pretoria Municipal Chemist). Flows for the Pienaars River, the Hartbeesspruit and the Edenvalespruit represent the flows recorded at sampling stations 4, 9 and 10 respectively. Flow figures for the Pienaars River, therefore, represent the contribution from natural flow plus that discharged from the sewage works.

Water flow in all three inflow systems showed a seasonal variation, with higher flow occurring during the rainy summer months (November to May). Discharge from the Baviaanspoort sewage works was, however, fairly constant. The Pienaars River contributed 83,5 and 65% of the total annual inflow into Roodeplaat Dam during the first and second years of the study respectively. By contrast, the Hartbeesspruit and the Edenvalespruit contributed higher percentages to total annual inflow in the second year (22,0 and 13,0%, respectively) than in the first year (8, 7 and 7,7%, respectively). These figures indicate that during a dry year, the Pienaars River contributes higher percentages to the total annual water inflow of Roodeplaat Dam because of the constant input from the Baviaanspoort sewage works. On a monthly basis, it may be estimated that the effluents discharged from the sewage works represents up to 75% of the inflow to Roodeplaat Dam and up to 83% of the flow in the Pienaars River (e.g. August month, 1973). On an annual basis, however, the percentage contribution from the sewage works is obviously less, being 25,3 and 9,2% of the total inflow for the first and second study years respectively.

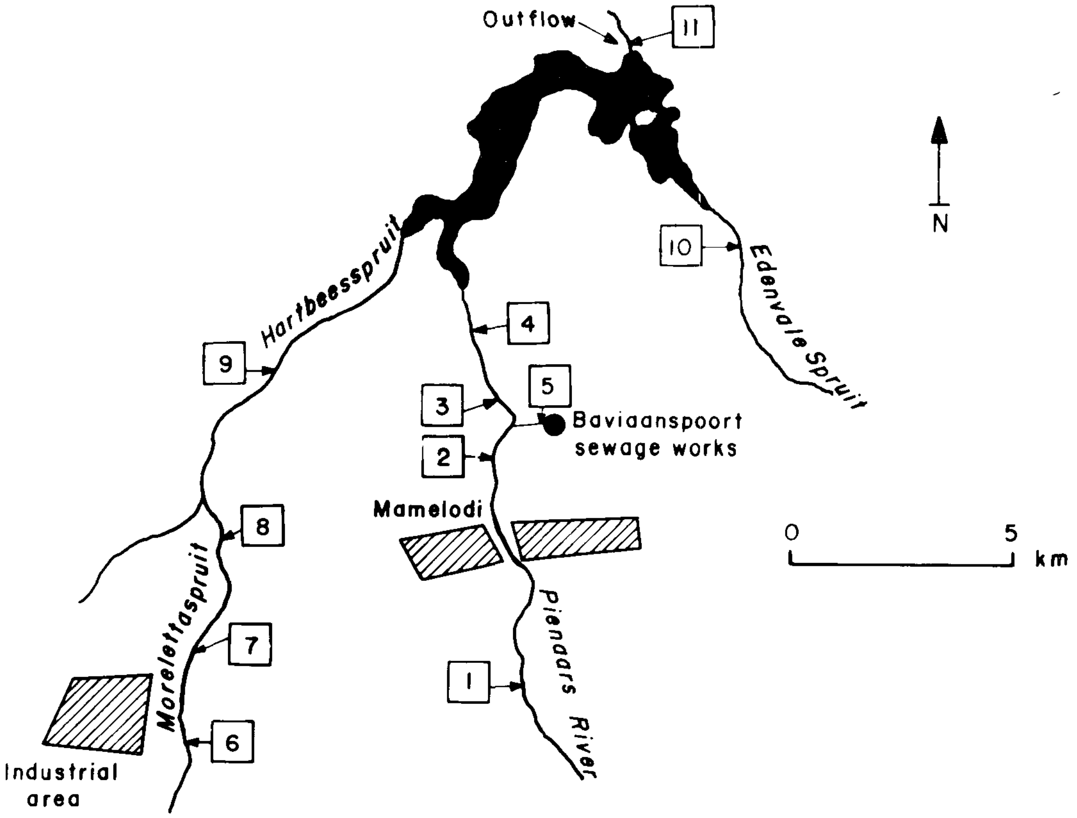

Figure 1
Roodeplaat Dam showing the position of sampling stations in the catchment area

TABLE 1
MONTHLY FLOW (x 10^6 m^3) FOR THE PIENAARS RIVER, THE HARTBEESSPRUIT, THE EDENVALESPRUIT AND FROM THE BAVIAANSPOORT SEWAGE WORKS DURING THE STUDY PERIOD (FEBRUARY 1973 TO JANUARY 1975)

Month	Monthly water flow							
	Pienaars River*		Hartbeesspruit		Edenvalespruit		Baviaanspoort sewage works	
	Station 4		Station 9		Station 10		Station 5	
	1973/74	1974/75	1973/74	1974/75	1973/74	1974/75	1973/74	1974/75
February	0,280	1,113	0,094	0,004	0,017	0,762	0,238	0,305
March	0,305	0,844	0,127	0,017	0,003	0,041	0,260	0,288
April	1,072	1,871	0,350	0,028	0,022	0,033	0,248	0,233
May	0,355	0,753	0,026	0,005	0,007	0,056	0,234	0,265
June	0,293	0,477	0,018	0,003	0,004	0,042	0,224	0,237
July	0,313	1,016	0,015	0,003	0,010	0,050	0,228	0,251
August	0,282	0,432	0,019	0,001	0,008	0,022	0,233	0,256
September	0,471	0,433	0,333	0,002	0,010	0,024	0,272	0,271
October	0,522	0,427	0,020	0,143	0,037	0,005	0,293	0,295
November	0,433	1,180	0,110	1,222	0,019	0,101	0,291	0,302
December	3,808	1,150	0,510	0,908	0,079	0,355	0,351	0,306
January	2,534	14,700	0,580	5,929	0,768	3,414	0,365	0,471
Annual total	10,668	24,396	1,122	8,264	0,984	4,905	3,240	3,475
Percentage of total annual inflow into impoundment	83,5	65,0	8,7	22,0	7,7	13,0	25,3	9,2

*Flow figures for the Pienaars River represent natural flow plus effluent discharges from the sewage works.

Chemical Composition of the Inflowing Waters

The chemical composition of the waters in the three inflowing systems showed a distinct seasonal variation with the highest concentrations of dissolved minerals being recorded during the dry winter months. Mean values for the concentrations of the dissolved constituents in the waters during the wet and dry weather flow periods are presented in Figures 2, 3, 4 and 5. Wet weather flow values are based on concentrations recorded between November and April, whilst dry weather values represent the mean concentration between May and October. The range of pH values during wet and dry weather flow as well as mean pH values (calculated by determining the mean hydrogen ion concentration) are presented in Table 2.

As a means of illustrating the major changes in the chemical composition of the waters in each inflow system along its course, mean ionic ratios for sodium:potassium, sodium:chloride, calcium:magnesium, chloride:sulphate and mean atomic ratios for total dissolved nitrogen:total dissolved phosphate are presented in Figure 6.

TABLE 2
MAXIMUM, MINIMUM AND MEAN pH VALUES FOR THE WATERS TAKEN FROM STATIONS IN THE ROODEPLAAT DAM CATCHMENT AREA

	Station Number																			
	1		2		3		4		5		6		7		8		9		10	
	D	W	D	W	D	W	D	W	D	W	D	W	D	W	D	W	D	W	D	W
Maximum	8,6	8,4	8,9	8,3	8,6	8,4	8,7	8,5	8,6	8,2	8,4	8,3	8,6	8,2	8,7	8,4	8,6	8,4	8,2	8,5
Minimum	7,5	7,1	7,8	7,1	7,0	7,1	7,4	7,4	7,0	7,0	7,8	6,6	7,9	6,5	7,3	6,9	7,7	7,3	7,7	7,8
Mean	8,1	7,8	7,9	7,6	7,6	7,6	7,7	7,7	7,9	7,4	7,9	7,6	8,0	7,7	7,6	7,7	8,2	7,7	7,9	8,1

D = dry weather flow
W = wet weather flow

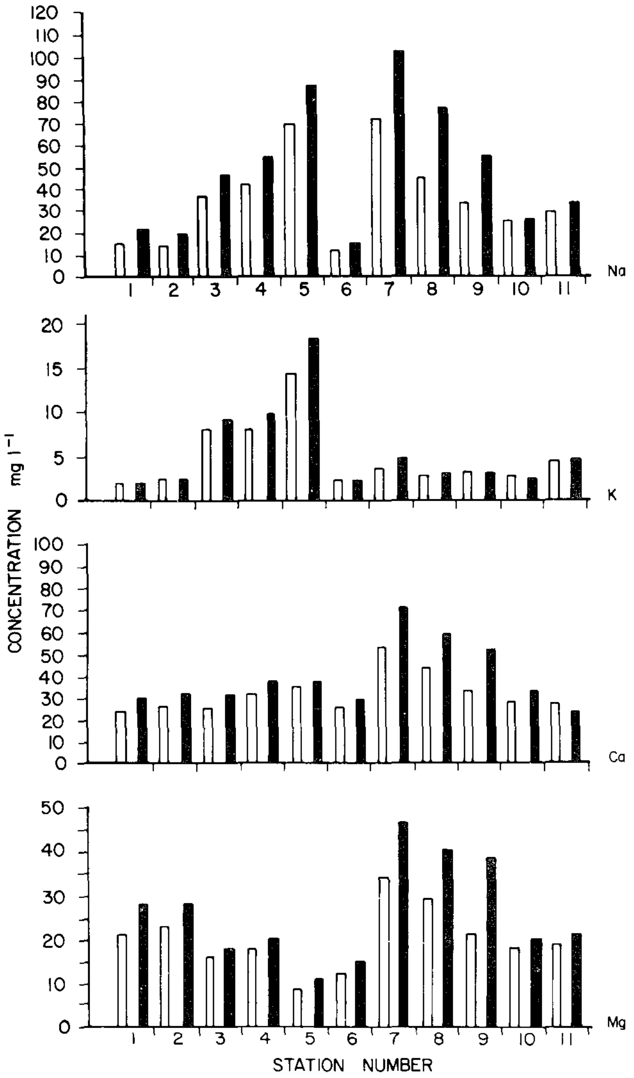

Figure 2
Mean values for sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg) concentrations in the waters from stations sited in the Roodeplaat Dam catchment (□wet weather flow, ■dry weather flow)

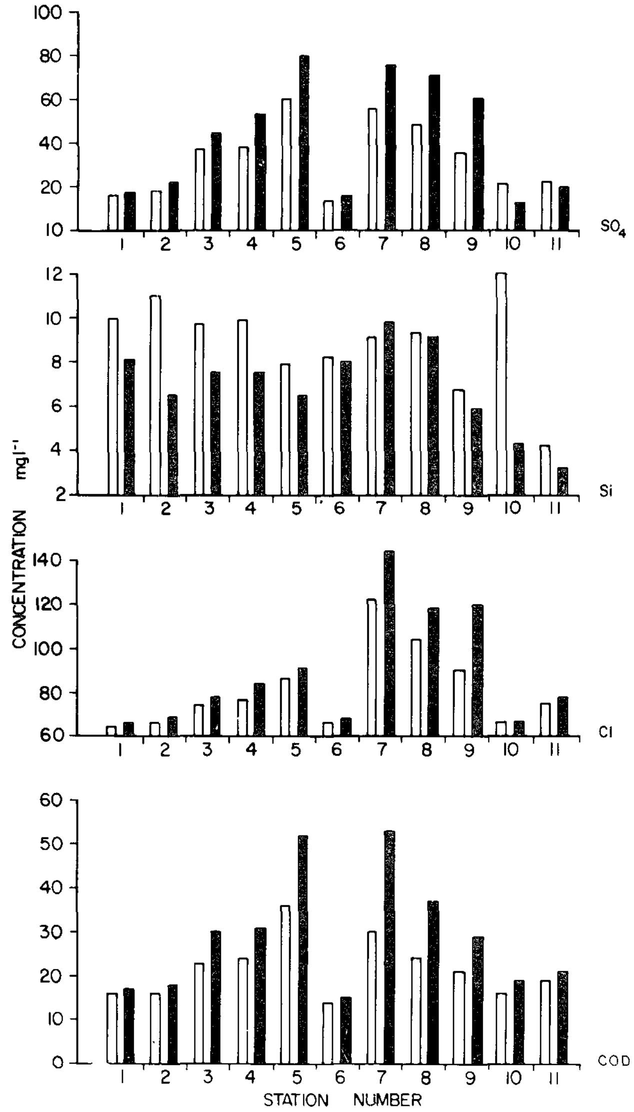

Figure 3
Mean values for sulphate (SO_4), reactive silicate (Si), chloride (Cl) and chemical oxygen (COD) concentrations in the waters from stations sited in the Roodeplaat Dam catchment. (□wet weather flow, ▩dry weather flow)

The Pienaars River and the Baviaanspoort Sewage Works (Stations 1,2,3,4, and 5)

Waters from stations 1 and 2, situated above and below the Mamelodi Township, respectively, showed no marked differences with respect to chemical composition. It was therefore evident that runoff from the Mamelodi Township had little influence on the waters of the Pienaars River. Because the pH of these waters was usually below 8,4 and the levels of the anions (chloride and sulphate) were low by comparison of the sum of their milli-equivalents with those of the major cations (sodium, potassium, calcium and magnesium), these waters may be classified as bicarbonate waters. This appears to be consistent with the conclusions of Bond (1946) in his classification of the underground water supplies of the area. The low calcium:magnesium ratio and the high alkalinity (>140 mg l^{-1} of $CaCO_3$) may be attributed to the influence of dolomitic rock which is present in the catchment (Verwoerd, 1967). Low calcium:magnesium ratios with high levels of both these elements is a characteristic which is typical of waters flowing over dolomitic regions (Wagner, Steele, Macdonald and Coughlin, 1976).

After receiving the effluents from the Baviaanspoort sewage works, waters of the Pienaars River showed major changes, with large increases in the mean concentrations of sodium, potassium, sulphate, chloride, chemical oxygen demand, ammonia, nitrate, nitrite, dissolved Kjeldahl nitrogen, orthophosphate and total dissolved phosphate. No changes in calcium, reactive silicate and alkalinity were recorded whilst a decrease in mean magnesium concentrations was noted. The observed changes corresponded to the quality of the effluents from the Baviaanspoort sewage works (station 5).

The most significant changes, however, were the increases in the nitrogen and phosphorus content of the water in the Pienaars River below the sewage works, total dissolved nitrogen and total dissolved phosphate increased more than five-fold. The data also indicated that bacterial nitrification was in operation during both dry and wet weather flow. This may be deduced from the fact that mean ammonia concentrations in the sewage effluents were considerably higher than nitrate (>20 mg NH_3-N l^{-1} compared with < 2 mg NO_3-N l^{-1}) whilst nitrate concentrations in the Pienaars River increased with distance below the sewage works. This increase in nitrate occurred at the expense of ammonia concentrations which decreased with distance from the sewage works (Figure 4).

The mean ionic ratio for sodium:potassium decreased below the sewage works, that for calcium:magnesium increased slightly, whilst other ionic ratios were not altered appreciably (Figure 6). The total dissolved nitrogen:total dissolved phosphorus atomic ratio in the Pienaars River (approximately 7:1) may be considered low by comparison with that ratio required for the balanced nutrition of algae (approximately 16:1, Stumm and Leckie, 1970) and therefore these waters can be considered to be nitrogen growth-limiting. This ratio in the Pienaars River water was not affected by the discharges of sewage effluents since the sewage effluents had a similar ratio to that of waters above the point of discharge (Figure 6).

The Morelettaspruit/Hartbeesspruit System (Stations 6,7,8 and 9)

Waters from station 6 were similar to those encountered in the Pienaars River at stations 1 and 2, i.e. they were bicarbonate waters with a low calcium:magnesium ratio and a relatively high alkalinity (< 100 mgl^{-1} $CaCo_3$). After the industrial area at Silverton, the conductivity of the Morelettaspruit more than doubled (compare stations 6 and 7, Figure 5), indicating that highly mineralized effluents were discharged from the area. These effluents caused the sodium, calcium, magnesium, sulphate, chloride and nitrate concentrations to increase whilst little increase in potassium, reactive silicate, ammonia, nitrite, dissolved Kjeldahl nitrogen, orthophosphate or total dissolved phosphate was recorded. Since trebling of the sodium:potassium and the chloride:sulphate ratios was experienced with little change in the sodium:chloride or calcium:magnesium ratios, these observations indicate that this mineralization was dominated by sodium and chloride ions. The total dissolved nitrogen:total dissolved phosphorus atomic ratio in the waters of the Morelettaspruit also showed an increase (from approximately 10:1 to >30:1) and the waters of station 8 had the highest ratio of any of the other inflowing waters (Figure 6).

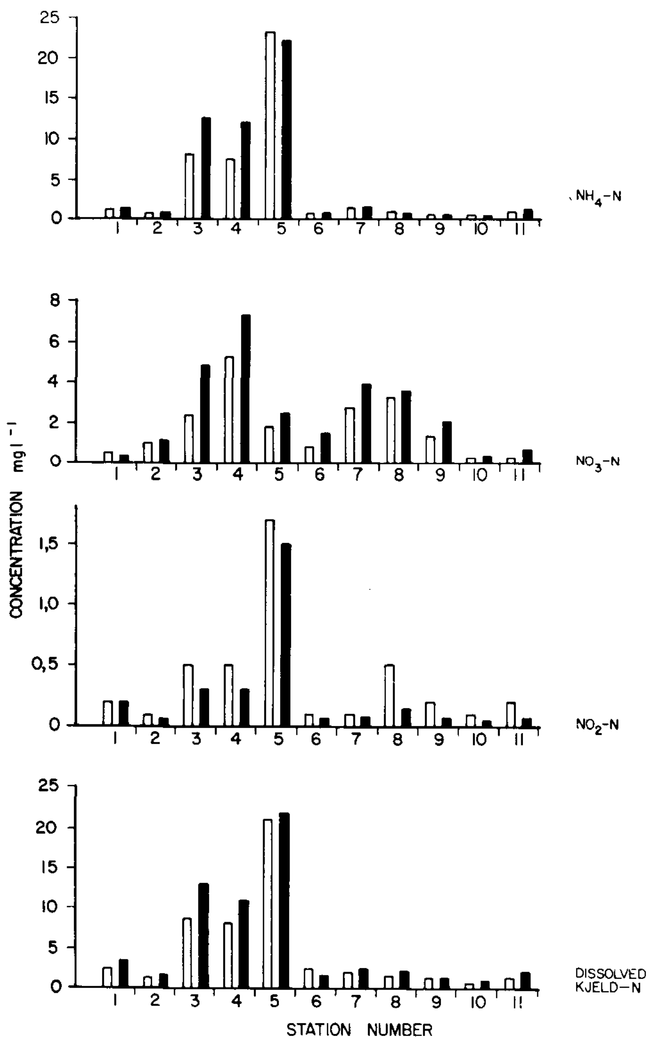

Figure 4

Mean values for ammonia (NH_4-N), nitrate (NO_3-N), nitrite (NO_2-N) and dissolved Kjeldahl nitrogen (dissolved Kjeldahl-N) concentrations in the waters from stations sited in the Roodeplaat Dam catchment (□wet weather flow, ■dry weather flow)

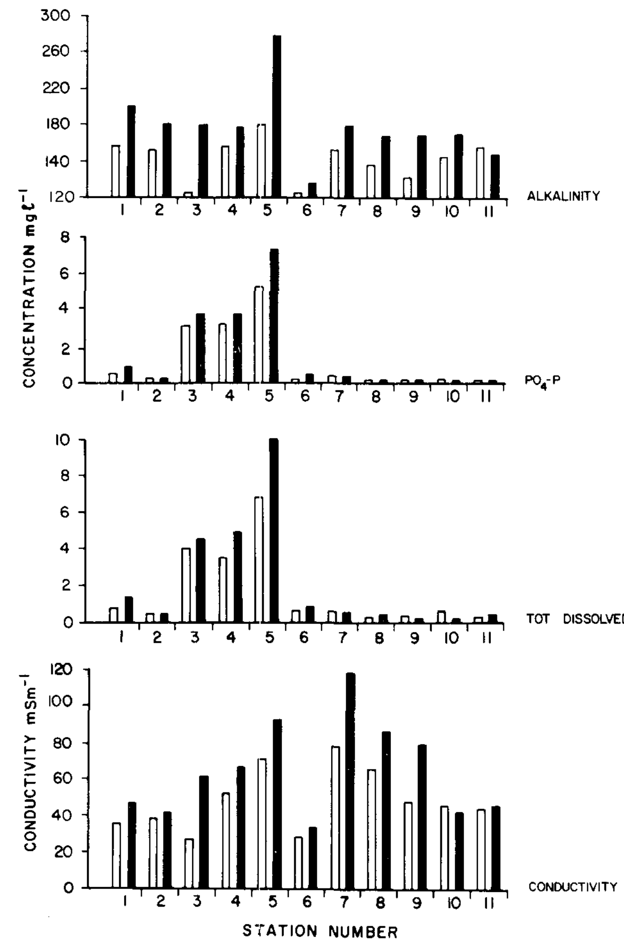

Figure 5

Mean values for the alkalinity, orthophosphate (PO_4-P), total dissolved phosphate (Total dissolved P) concentrations and conductivity in the waters from stations sited in the Roodeplaat Dam catchment (□wet weather flow, ■dry weather flow)

The Edenvalespruit (Station 10)

Waters of the Edenvalespruit had a low calcium:magnesium ratio and a high mean alkalinity ($>$140 mgl^{-1} as $CaCO_3$) and could therefore also be classified as hard bicarbonate waters. Mean concentrations of most constituents did not differ from those in waters from the Morelettaspruit (station 6) and the Pienaars River above the sewage works (stations 1 and 2). Mean concentrations of phosphorus and nitrogen compounds were the lowest of all inflowing waters and indicated that little enrichment was taking place from this stream's catchment.

Outflow from Roodeplaat Dam (Station 11)

Outflowing waters from the impoundment's irrigation canal showed characteristics intermediate between those of the inflowing systems, and there was less of a seasonal influence on the chemical composition of these waters. The concentrations of reactive silicate and dissolved nitrogen and phosphorus compounds were considerably lower than concentrations in the Pienaars River above the dam, showing the extent by which these constituents were affected by chemical and biological processes in the impoundment.

Mineral Loading

The influence of the three inflowing systems on the dissolved chemical composition of the waters in Roodeplaat Dam cannot be assessed unless their contributions to the mineral loading of the impoundment are compared. For each inflowing system, the annual loading for each study year (February to January) was estimated by the method of summing the products of monthly mean concentrations (in 1974/75 only single monthly values were available) and monthly water flow (Toerien and Walmsley, 1978). The reliability of loading estimates using this method of calculation has caused some concern since it can result in the gross overestimation of loading (Smith and Stewart, 1977). However, it was possible to check the accuracy of load estimates for the Pienaars River, the major contributor to flow, since the loading contribution from the Baviaanspoort sewage works could be estimated by two methods. The first estimate was made by calculating the annual loading for the Pienaars River above (station 2 data) and below (station 4 data) the sewage works and then subtracting the two loads to obtain the annual contribution from the sewage works. The water flow for the Pienaars River above the sewage works was obtained by subtracting monthly flow values for the Baviaanspoort sewage works from the monthly flow of the Pienaars River as recorded at station 4. The second estimate was obtained from the sum of the products of the mean monthly concentrations in the sewage effluents and the monthly water flow from the sewage works.

The estimates for both study years are presented in Table 3. Better agreement between the two independent estimates was obtained for the 1973/74 loadings than for the 1974/75 loadings. In the case of the first method, a negative loading for magnesium from the sewage works was obtained for both years of study, indicating an error in the loading estimates and no significance can be attached to these negative loadings. Furthermore, the sewage works appeared to contribute more to the mineral loading during 1974/75 than 1973/74. By the second calculation method, loading from the sewage works appeared to be constant for both years of study. This would be expected since the sewage works discharged a more or less constant volume of water for the two years. It can therefore be concluded

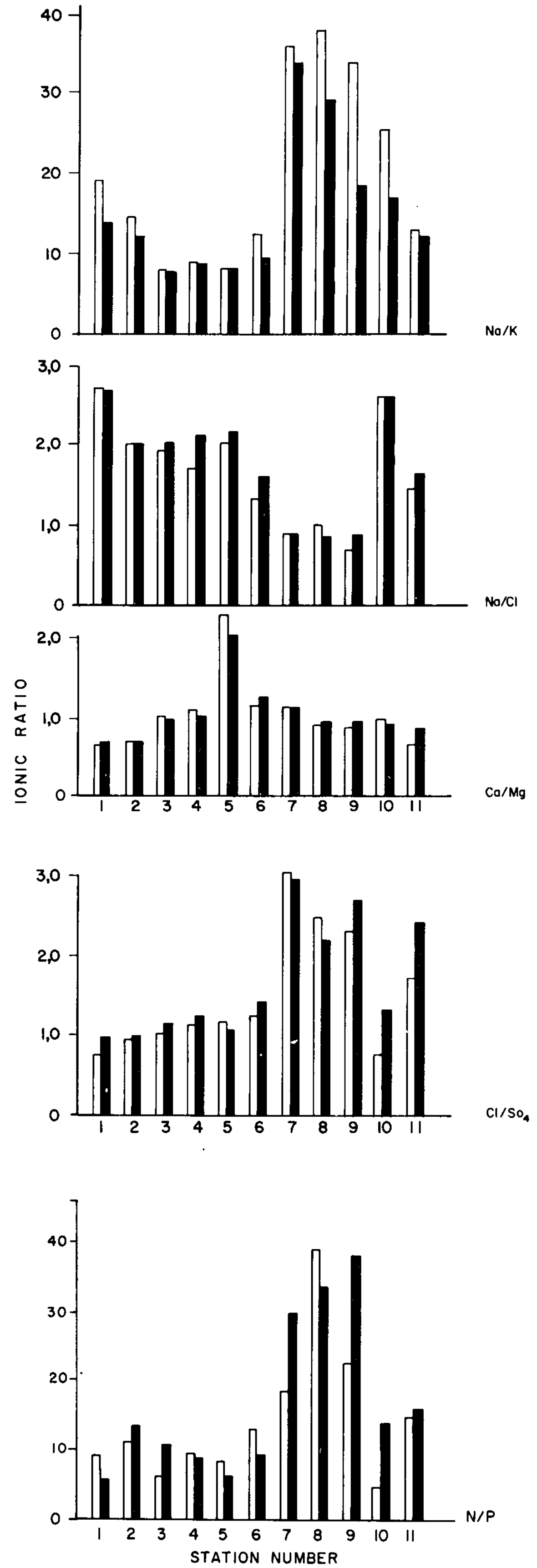

Figure 6
Mean ionic ratios for sodium:potassium (Na:K), calcium:magnesium (Ca:Mg), sodium:chloride (Na:Cl), chloride:sulphate (Cl:SO_4) and atomic ratios for total dissolved nitrogen to total dissolved phosphorus (N:P) in the waters from stations sited in the Roodeplaat Dam catchment (□ wet weather flow, ■ dry weather flow)

TABLE 3
A COMPARISON OF THE ANNUAL MINERAL LOADING FROM THE BAVIAANSPOORT SEWAGE WORKS, CALCULATED BY
1. THE SUM OF THE PRODUCTS OF THE MONTHLY MEAN CONCENTRATION AND THE MONTHLY WATER FLOW AT STATION 4 MINUS THE SAME AT STATION 2, AND
2. THE SUM OF THE PRODUCTS OF THE MONTHLY MEAN CONCENTRATIONS AND THE MONTHLY WATER FLOW OF THE SEWAGE EFFLUENT (FIGURES IN TONS)

Constituent	Year of study 1973/74		1974/75	
	a	b	a	b
Na	208	252	578	271
K	63	52	152	55
Ca	30	106	161	118
Mg	−23	32	−34	33
SO_4	207	223	545	295
Si	28	21	34	28
Cl	192	178	526	212
Total dissolved N	94	75	246	93
PO_4-P	20,7	24	67	21,2
Total dissolved P	22,2	29	68	27,1

that the second calculation method represents a more accurate estimate of the loading from the sewage works. The inaccuracies obtained by the first method of calculation may be attributed to the occurrence of flash floods during the study period and the fact that no sampling dates coincided with peak flow. Because of this,' insufficient data was available to obtain a concentration/flow relationship for the Pienaars River and to allow for a more accurate estimation of load using flow-weighted figures.

In order to give the most reliable estimate of loading from the Pienaars River, the loading contribution has been approximated by adding the estimate for the Baviaanspoort sewage works (by method 2) to that for the Pienaars River above the sewage works. In the case of the other two inflowing systems, where no check on accuracy has been possible, loading has been approximated by summing the products of monthly concentration and monthly water flow at stations 9 and 10 for the Hartbeesspruit and the Edenvalespruit respectively. It is unlikely that such high inaccuracies would be made in the case of these two inflows since water flows were less than that of the Pienaars River. It should however be realized that the loading figures presented in Table 4 are rough estimates and that a more detailed study is required in order to quantify the loading more accurately.

The loading estimates (Table 4) showed that the Pienaars River contributed from between 79 and 99% of the loading of the individual constituents during the first year of study whilst during the second year these percentages were lower (53 to 92%). The Hartbeesspruit and the Edenvalespruit each contributed less than 10% of the annual loading for most constituents during the first year and 20% or less in the second year.

TABLE 4
MINERAL LOADING CONTRIBUTIONS TO THE ROODEPLAAT DAM FROM THE PIENAARS RIVER, THE EDENVALESPRUIT AND THE HARTBEESSPRUIT (LOADING IN TONS, FIGURES IN PARENTHESES REPRESENT THE PERCENTAGE CONTRIBUTION TO THE TOTAL ANNUAL LOADING)

Constituent	Pienaars River 1973/74	Pienaars River 1974/75	Hartbeesspruit 1973/74	Hartbeesspruit 1974/75	Edenvalespruit 1973/74	Edenvalespruit 1974/75	Total 1973/74	Total 1974/75
Na	393 (88)	580 (67)	36 (8)	171 (20)	16 (4)	112 (13)	445	863
K	65 (93)	100 (68)	3 (4)	29 (20)	2 (3)	18 (12)	70	147
Ca	345 (86)	675 (66)	36 (9)	211 (20)	18 (5)	135 (14)	399	1021
Mg	233 (86)	434 (65)	23 (8)	131 (20)	15 (6)	105 (15)	271	670
SO_4	387 (87)	645 (76)	45 (10)	157 (18)	15 (3)	48 (6)	447	850
Si	80 (82)	199 (65)	6 (7)	44 (15)	11 (11)	60 (20)	97	303
Cl	290 (79)	439 (53)	58 (18)	356 (43)	10 (3)	37 (4)	368	832
Total dissolved N	97 (97)	149 (86)	2,50 (2)	18,20 (10)	1,02 (1)	6,60 (4)	100	173
PO_4-P	26 (99)	27 (92)	0,2 (< 1)	1,6 (5)	0,1 (< 1)	0,7 (3)	26,3	28,3
Total dissolved P	33 (99)	29 (92)	0,2 (< 1)	1,6 (5)	0,2 (< 1)	0,9 (3)	33,4	31,5

TABLE 5
A COMPARISON OF THE RANGES IN CONCENTRATION OF SELECTED CONSTITUENTS IN THE WATERS AT STATIONS 3, 7 AND 11 WITH THE SABS RECOMMENDED SPECIFICATIONS FOR DOMESTIC WATER (VALUES IN MG l^{-1})

Constituent	SABS standard				
	Recommended limit	Maximum allowable	Station 3	Station 7	Station 11
Mg	100	150	9 – 21	9 – 88	17 – 24
SO_4	250	400	18 – 100	19 – 200	12 – 82
Cl	250	600	10 – 56	17 – 250	8 – 51
Alkalinity (as $CaCO_3$)	200	1000	81 – 272	72 – 250	132 – 185
NO_3-N	10	–	0,6 – 15	0,1 – 8,6	0,1 – 2,8

This was not the case for the chloride load from the Hartbeesspruit (18 and 43% for each study year respectively). Comparing the load contributions from the Baviaanspoort sewage works (c f. method 2, Table 3) to those of the inflow systems, it can be seen that the sewage works plays an important role in regulating the chemical composition of Roodeplaat Dam. During 1973/74 and 1974/75, the sewage works contributed from 12 to 91% and 5 to 86%, respectively of the total annual loading of the individual constituents. The contributions to total annual loading were least for magnesium and highest for phosphate during both years.

Discussion

Since there have been no previous investigations of the chemical quality of the rivers flowing into Roodeplaat Dam, it is not possible to directly relate the present situation to that of past studies. However, the differences between the sections of the Pienaars River and the Morelettaspruit above and below the points of discharge of either sewage and industrial effluents, indicate the extent to which the chemical composition of these two streams has been affected. Waters from stations 3 and 7 may be considered to represent the lowest quality water since they were in stretches of river which had been most affected by sewage and industrial effluents. The ranges of concentrations of some selected constituents in these waters are compared with the South African Bureau of Standards (SABS, 1971) specifications for domestic water in Table 5. Levels of magnesium, sulphate and chloride were always well below these recommended limits, however the alkalinity at both stations was at times above the recommended limit and nitrate levels at station 3, sometimes reached levels considered toxic to infants (>10 mg NO_3-N l^{-1}). If usage of the water of the Pienaars River below the Baviaanspoort sewage works is envisaged for drinking purposes, caution should be exercised, since the mean concentration of nitrate at station 4 during dry weather flow was not far below the prescribed maximum limit. With regards to usage of drinking water from the impoundment, however, nitrate does not pose a problem.

On the evidence from this study it would appear that waters in the impoundment have a chemical quality which is compatible for most uses. However, there have been reports of water treatment problems at the Baviaanspoort Prison where high manganese (>1 mg l^{-1}) levels have been encountered and nitrite has caused meat cooked in water to change colour (De Villiers, 1978).

This study also allowed for the monitoring of the performance of the Baviaanspoort sewage works over a representative period of time. Based on the general standards prescribed by the Minister of Water Affairs (Department of Water Affairs, 1962), it is apparent that this sewage works released effluents which were consistently below the specified levels for most constituents. However, the ammonia concentrations (usually greater than 20 mg NH_3-N l^{-1}) were consistently higher than the maximum ammonia concentration prescribed by these standards (10 mg NH_3-N l^{-1}). Water entering the sewage works is Rand Water Board water and is transported to the Mamelodi Township from outside the catchment. This possibly explains certain basic differences between the chemical composition of the sewage effluents and the Pienaars River water. For example, magnesium concentrations in the effluents were lower than in the Pienaars River and there were indications that the effluents actually diluted the river water of this cation.

High concentrations of combined nitrogen and phosphate in the inflowing waters of a water body are the main cause of eutrophication and its associated problems (Vollenweider, 1968). Increased levels of these two nutrients lead to an increase in the primary productivity within a water body and a transformation in trophic status. Such a transformation is exemplified by the changes which have occurred in the nearby Hartbeespoort Dam following an increase in the nitrogen and phosphorus status of the waters (Hutchinson, Pickford and Schuurman, 1932; Allanson and Gieskes, 1961; Scott, Seaman, Connell, Kohlmeyer and Toerien, 1977; Toerien and Walmsley, 1978). This impoundment was originally classified as oligotrophic (Hutchinson *et al.*, 1932), but at present may be considered as hypereutrophic (Scott *et al.*, 1977). In such water bodies the development of nuisance algal blooms and aquatic weeds leads to a deterioration in water quality since it interferes with usage of water for domestic and recreational purposes. Roodeplaat Dam has experienced large blooms of *Melosira* spp. and *Microcystis* spp. (Walmsley, Toerien and Steÿn, 1978b). Some of the *Mycrocystis* blooms which have appeared in the Roodeplaat Dam have been shown to be toxic (Scott, 1978) and the implications of this for the continued usage of the impoundment as a recreational centre and as a source of potable water requires investigation.

At present, the Pienaars River is the major contributor to the mineral loading of Roodeplaat Dam, and the Baviaanspoort sewage works plays an important role in regulating both mineral and water inputs. The contribution of the sewage works effluent to the annual water income of Roodeplaat Dam (9—25%) obviously varies from year to year, but may be considered extremely high by comparison with other situations. Eutrophic Shagawa Lake in Minnesota receives only 2% of its annual water income from wastewaters (Malueg, Larsen, Schults and Mercier, 1975), whilst Lake Esrom in Denmark receives up to 5,5% (Jonassen, Lastein and Rebsdorf, 1974).

The trophic status of Roodeplaat Dam has been briefly compared with three other Transvaal impoundments by Walmsley *et al.* (1978a). The enriched condition of this impoundment is further accentuated by a comparison of the nitrogen and phosphorus surface loading rates of several well-known water bodies with the estimated rates for Roodeplaat Dam (Table 6). Walmsley *et al.* (1978a) estimated the nitrogen and phosphorus loading rates for Roodeplaat Dam by utilising the product of the total annual river flow and the annual mean concentration. Smith and Stewart (1977), however, suggested that better estimates of loading rates could be obtained by summing the products of concentrations and flow figures taken at shorter intervals, e.g. weekly, fortnightly or monthly. For this reason the latter approach was taken in this present paper. It should be noted, that owing to the different method in load calculation, the loading rates for Roodeplaat Dam reported here are lower than those reported by Walmsley *et al.* (1978a). Furthermore, these estimated loading rates for Roodeplaat Dam have not considered particulate nitrogen and phosphorus or atmospheric contributions. Wood and Gibson (1973) state that Lough Neagh is amongst the most eutrophic of the world's major lakes, yet the surface loading rates for nitrogen and phosphorus are considerably lower than those for Roodeplaat Dam. It can therefore be concluded that Hartbeespoort, Rietvlei and Roodeplaat Dams possibly represent some of the most eutrophic water bodies yet reported.

The present condition in Roodeplaat Dam can therefore be attributed to the high loading of nitrogen and phosphorus, most of which originates from the Baviaanspoort sewage works. Rehabilitation of water systems which have become affected by sewage or industrial discharges can be achieved by reducing nutrient inputs, particularly by action at point sources (Dunst, Born, Uttormark, Smith, Nichols, Petersen, Knauer, Serns, Winter and Wirth, 1974). Since the Baviaanspoort sewage works represents a point source, the possible changes which would be achieved by nutrient removal or sewage diversion are therefore of interest. Nutrient removal would reduce the inputs of nitrogen and phosphorus, but the sewage works would still contribute to water flow. Sewage diversion, on the other hand, would eliminate both water and nutrient inputs from this source. Using current nutrient removal technology more than 80% of the phosphorus and 50% of the nitrogen can be removed from sewage effluents (Dunst *et al.*, 1974). Since the Baviaanspoort sewage works at present contributes approximately 90% of the dissolved phosphate and 50 to 75% of the dissolved nitrogen loading, nutrient removal might result in the reduction of the dissolved phosphate and nitrogen loading by 70 and 35%, respectively. Nutrient removal would, however, not make any great difference to the loading of minerals such as sodium, potassium, sulphate and chloride.

The changes which would be achieved if complete sewage diversion were practised would be more pronounced since the loading of all dissolved minerals would be affected. Table 7 shows the mean theoretical concentrations for the analyzed constituents which would have been encountered in the impounded waters for both years when the contribution from the sewage works is considered and ignored. These values were obtained by dividing total annual load by total water inflow and ignoring both the mineral loading and water flow from the sewage works in the latter case. Assuming no contribution from the sediments in the impoundment and the attainment of a steady state, it can be postulated that complete diversion of sewage effluents might have resulted in significant decreases in all constituents with the

TABLE 6

A COMPARISON OF THE TOTAL NITROGEN AND PHOSPHORUS LOADING RATES OF SOME WATER BODIES WITH THE DISSOLVED NUTRIENT LOADING RATES FOR THE ROODEPLAAT DAM

Water body	Year	Nitrogen loading rate ($g\ N\ m^{-2}\ .\ a^{-1}$)	Phosphorus loading rate ($g\ P\ m^{-2}\ .\ a^{-1}$)	Source
Lake Zurich	1953	26,2	1,32	Landner (1976)
Lake Constance	1960	20,8	4,07	,,
Lough Neagh	1965	23,9	0,54	,,
Lake Washington	1957	31,4	1,34	,,
Lake Tahoe	1961	0,23	0,04	,,
Lake Mälaren	1967	11,3	0,74	
Lake Kinneret	1966/74	9 — 25	0,6 — 1,3	Serruya, Pollingher & Gophen (1975)
Lake Shagawa	1967/72	7,6	0,73	Malueg *et al.*, (1975)
Lake Esrom	1969/70	> 2,9	> 0,61	Jonassen *et al.*, (1974)
Hartbeespoort Dam	1973	> 78,9	> 13,2	Walmsley *et al.*, (1978a)
Rietvlei Dam	1973	> 8,8	> 13,1	,,
Buffelspoort Dam	1974	> 13,5	> 2,70	,,
Roodeplaat Dam	1973/74	44	8,0	This study

TABLE 7
MEAN THEORETICAL CONCENTRATIONS FOR CONSTITUENTS IN ROODEPLAAT DAM WATER DURING THE TWO STUDY YEARS WHEN THE BAVIAANSPOORT SEWAGE WORKS' CONTRIBUTION IS CONSIDERED AND IGNORED (CONCENTRATIONS IN MG l^{-1}. FIGURES IN PARENTHESES REPRESENT THE MEAN CONCENTRATION AT THE OUTFLOW FROM THE IMPOUNDMENT)

Constituent	+ Sewage works		– Sewage works		Expected percentage decrease
	1973/74	1974/75	1973/74	1974/75	
Na	34,8 (28)	22,9 (29)	20	17	26 – 43
K	5,5 (3,7)	4,0 (4,7)	1,9	2,7	33 – 65
Ca	31,2 (26)	27,1 (25)	30	26,5	2 – 4
Mg	21,2 (20)	17,8 (19)	25	18,7	5 – 18 Increase
SO_4	35 (21)	22,6 (21)	23	16,3	28 – 34
Si	7,6 (3,1)	8,0 (3,7)	7,9	8,0	0 – 4
Cl	29 (32)	22,1 (29)	20	18	19 – 31
Total dissolved N	7,8 (2,1)	4,6 (2,8)	2,6	2,35	49 – 67
PO_4 – P	2,05 (0,1)	0,80 (0,2)	0,2	0,2	75 – 90
Total dissolved P	2,60 (0,2)	0,83 (0,6)	0,5	0,5	40 – 81

exception of calcium, magnesium and dissolved silica (Table 7).

A comparison of the mean theoretical concentrations of each constituent (calculated by dividing the total annual load by the total annual water inflow) with the mean values at station 11, the outflow from the impoundment (Table 7) showed that there was fair agreement between the two values for conservative elements such as sodium, potassium, calcium, magnesium and chloride. The larger differences between values for sulphate, silica, combined nitrogen and phosphate can be attributed to chemical and biological transformations in the impoundment. These figures provide a further indication of the accuracy of the load calculations and the fair agreement suggests a reasonable measure of accuracy.

At present the discharges of sewage and industrial effluents into the inflowing streams of the Roodeplaat Dam have not produced any serious consequences in the usage of the water for irrigation. However, biological conditions in the reservoir have reached the stage where they may be considered detrimental to its recreational usage (Walmsley *et al.*, 1978b). The remedial action of sewage diversion or nutrient removal does not provide the complete answer to this situation since such practices need not necessarily produce an improvement in the condition of receiving waters (Dunst *et al.*, 1974). Despite this, however, the practice of nutrient removal or sewage diversion is advocated since it is likely that the Baviaanspoort sewage works will be expanded (Meiring, 1978). Of the two options, nutrient removal is the better one since diversion would merely create problems elsewhere. Caution should also be exercised if nutrient removal is practised, since, although nitrogen and phosphorus would be removed, other minerals would not, and levels in the receiving waters might be increased to the extent that water quality becomes unsuitable even for irrigation. The development of water standards to cover the multi-purpose usage of impoundments is necessary to ensure that quality is compatible with usage.

Conclusions

1. The natural chemical composition of the waters flowing into Roodeplaat Dam has been greatly altered by discharges of sewage and industrial effluents. The chemical quality of this water however, remains compatible with prescribed standards for domestic requirements.
2. The Baviaanspoort sewage works represents an important source of mineral and water input to Roodeplaat Dam, contributing between 5 and 91% of the total annual loading for certain dissolved constituents and between 9 and 25% of the annual water input.
3. The loading of nitrogen and phosphorus compounds into Roodeplaat Dam may be considered excessive by comparison with other well-known eutrophic water bodies. The Baviaanspoort sewage works is responsible for up to 75 and 87% of the dissolved nitrogen and phosphorus annual loading respectively. Successful rehabilitation of Roodeplaat Dam would require either sewage diversion or the utilization of a more efficient nutrient removal process at the sewage works.

Acknowledgements

This research programme was sponsored by the Water Research Commission and is published with the approval of the Director of the National Institute for Water Research. Thanks are extended to Mr S. Fourie, Miss K. Hyman and Mr D.J. Steÿn who assisted in the collection of water samples and also to the staff of the Division of Water Quality of the National Institute for Water Research who conducted the chemical analyses. Water flow data from the Pretoria City Chemist and the Department of Water Affairs are gratefully acknowledged. The discussions held with Mr W.E. Scott of the National Institute for Water

Research, Mr A. de Villiers of the Department of Public Works and Mr P.G.J. Meiring, consultant engineer, are greatly appreciated.

References

ALLANSON, B.R. and GIESKES, J.M.T.M. (1961) Investigations into the ecology of polluted inland waters in the Transvaal. Part II: An introduction to the limnology of Hartbeespoort Dam with special reference to the effect of industrial and domestic pollution. *Hydrobiologia* **18** 77—94.

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, Memoir No. 41, Government Printer, Pretoria.

DEPARTMENT OF WATER AFFAIRS (1962) Regional standards for industrial effluents. *Government Gazette,* 5th April, Government Printer, Pretoria.

DE VILLIERS, A. (1978) Personal communication. Department of Public Works.

DUNST, R.C., BORN, S.M., UTTORMARK, P.D., SMITH, S.A., NICHOLS, S.A., PETERSON, J.O., KNAUER, D.R., SERNS, S.L., WINTER, D.R. and WIRTH, T.L. (1974). *Survey of lake rehabilitation techniques and experiences.* Technical Bulletin No. 75. Department of Natural Resources, Madison, Wisconsin.

HUTCHINSON, G.E., PICKFORD, G.E., and SCHUURMAN, J.F.M. (1932) A contribution to the hydrobiology of pans and other inland waters of South Africa. *Arch. Hydrobiol.* **24** 1—136.

JONASSEN, P.M., LASTEIN, E. and REBSDORF, A. (1974) Production, insolation and nutrient budget of eutrophic Lake Esrom. *Oikos* **25** 255—277.

LANDNER, L. (1976) *Eutrophication of lakes.* World Health Organization, Regional Office for Europe, Geneva.

MALUEG, K.W., LARSON, D.P., SHULTS, D.W. and MERCIER, H.T. (1975) A six-year water, phosphorus and nitrogen budget for Shagawa Lake, Minnesota. *J. Environ. Qual.* 4 236—242.

MEIRING, P.G.J. (1978) Personal communication. Consultant Engineer.

NATIONAL INSTITUTE FOR WATER RESEARCH (1974) *Analytical Guide, Part II. Theoretical aspects and analytical methods.* Council for Scientific and Industrial Research, Pretoria.

SCOTT, W.E., SEAMAN, M.T., CONNELL, A.D., KOHLMEYER, S.I., and TOERIEN, D.F. (1977) The limnology of some South African impoundments. 1. The Physico-chemical limnology of Hartbeespoort Dam. *J. Limnol. Soc. Sth. Afr.* 3 43—58.

SCOTT, W.E. (1978) Personal communication.

SERRUYA, C., POLLINGHER, U. and GOPHEN, M. (1975) N and P distribution in Lake Kinneret (Israel) with emphasis on dissolved organic nitrogen. *Oikos* **26** 1—8.

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) *Specifications for water for domestic supplies.* South African Bureau of Standards Specification No. 241, Pretoria.

STEŸN, D.J., TOERIEN, D.F. and VISSER, J.H. (1976) Eutrophication levels of some South African impoundments. III. Roodeplaat Dam. *Water S.A.* 2(1) 1—6.

STUMM, W. and LECKIE, J.O. (1970) Phosphate exchange with sediments: its role in the productivity of surface waters. In "*Advances in Water Pollution Research*". Editor Jenkins, S.H., Pergamon Press, III/ 26 1—16.

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

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

VERWOERD, W.J. (1967) *The carbonatites of South Africa and South West Africa.* Government Printer, Pretoria.

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.* Organization for Economic Co-operation and Development, Paris.

WAGNER, G.H., STEELE, K.F., MACDONALD, H.C. and COUGHLIN, T.L. (1976) Water quality as related to linears, rock chemistry and rain water chemistry in a rural carbonate terrain. *J. Environ. Qual.* 5 444—450.

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

WALMSLEY, R.D., TOERIEN, D.F., and STEŸN, D.J. (1978b) An introduction to the limnology of Roodeplaat Dam. J. Limnol. Soc. Sth. Afr. 4(1) 35—52.

WOOD, R.B. and GIBSON, C.E. (1973) Eutrophication and Lough Neagh. *Wat. Res.,* 7, 173—187.