# A Comparison of the Summer Phosphorus Loadings to Three Zimbabwean Water-Supply Reservoirs of Varying Trophic States

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## Abstract

Three water-supply reservoirs located in north central Zimbabwe were sampled extensively during the 1977/78 summer wet season in order to calculate phosphorus mass-balances for the impoundments. The three dams shared a number of physico-chemical characteristics although they differed markedly in trophic state and morphology. The results of the phosphorus mass-balances are expressed in terms of both areal and volumetric loading as well as in tonnage loading. It was found that trophic state compared favourably with phosphorus loading, but was influenced by water retention times. It was suggested that the Vollenweider-type graphic models might require modification if used in tropical conditions. The nutrient-filter effect of an upstream lake was also demonstrated.

## Introduction

Most calculations of phosphorus loadings to lakes have been made for temperate lakes in North America and Europe. This data has been used to derive various types of models for use in lake management. Such models would be desirable for use in an African context, but until recently little data has been available with which to test the applicability of the temperate lake models (Schindler, 1978). With this in mind, it was considered particularly desirable to evaluate the relationship between phosphorus loading and lake trophic state.

To this end, an intensive study of the reactive phosphorus loads to three Zimbabwean water-supply reservoirs was made during the 1977/78 summer rainy season. The data from the three reservoirs, Lakes McIlwaine and Robertson and John Mack Lake, provides a range of morphological and trophic state characteristics with which to make a preliminary assessment of the applicability of the Vollenweider-type phosphorus loading-trophic state graphic model. Phosphorus mass-balances for the three reservoirs for the 1977/78 summer season are presented, and some of the responses of the lakes to that loading will be discussed and contrasted. In addition, the relationship between a eutrophic impoundment (Lake McIlwaine) and a downstream, oligotrophic dam (Lake Robertson) will be considered.

## Materials and Methods

### Study Area

All three impoundments lie in north central Zimbabwe on rivers flowing northward into the Zambesi River (Hydrological Zone "C"; Figure 1). Lakes McIlwaine and Robertson, formed by Hunyanipoort and Darwendale Dams respectively, are located on the Hunyani River and provide potable water to the City of Salisbury. Lake John Mack was created by Claw Dam on the Umsweswe River and supplies water for the Town of Gatooma. Selected hydrographical data for each of the three impoundments are presented in Table 1.

Numerous hydrobiological investigations carried out on Lake McIlwaine have shown that lake to be eutrophic with the eutrophication of the impoundment being caused by the rapid chemical changes arising from the input of treated sewage effluent to the lake by the City of Salisbury (Munro, 1966; Marshall and Falconer, 1973a, 1973b; Mitchell and Marshall, 1974; Thornton, 1979a,b). The hydrobiology of Lake Robertson and John Mack Lake is less well known. The work of Cotterill (1980) suggests that the former may be considered to be oligotrophic, and the latter has been assessed as being meso-oligotrophic (Robarts and Southall, 1977).

### Hydrographical Investigations

Fortnightly sampling cruises were made between mid-December 1977 and mid-April 1978 on Lakes McIlwaine and Robertson, and were designed to provide data on the distribution of phosphorus in the system. Sampling cruises on John Mack Lake were less regular and were made in March and April 1978. All sampling sites were selected primarily on the basis that they would allow inter-comparison of the data gathered during the present study with historical data. In all cases these sites were in the lower lake basins near the dam walls and coincided with the area of maximum depth of the lake. Previous work by the Hydrobiology Research Unit, University of Zimbabwe (unpublished data), has shown these stations to be representative of the impoundments concerned. Samples were collected using a 2 ℓ Friedinger sampler at 5 m vertical intervals. The stations are shown in Figure 1.

In addition to the fortnightly sampling programme, daily sampling of the major riverine inflows and outflows of the lakes was carried out over the same period as the lake sampling at stations 5 and 9 on the Hunyani River, station 6 on the Umzuzuru River, station 7 on the Gwebi River, and stations 10 and 12 on the Umsweswe River. Daily sampling was also done at the Morton Jaffrey Water Works at Lake McIlwaine during March and the results of this sampling are combined with those from station 5. Three samples per day were obtained from the Hunyani River at station 1, and hourly samples were taken from the Makabusi and Marimba Rivers, stations 2 and 3 respectively, during the period from December to April. With the exception of the samples from the Hunyani River at station 1, all sampling was done by the Ministry of Water Development and the Salisbury Municipality. Samples at station 1 were taken by automatic water sampler by the Department of Civil Engineering, University of Zimbabwe.

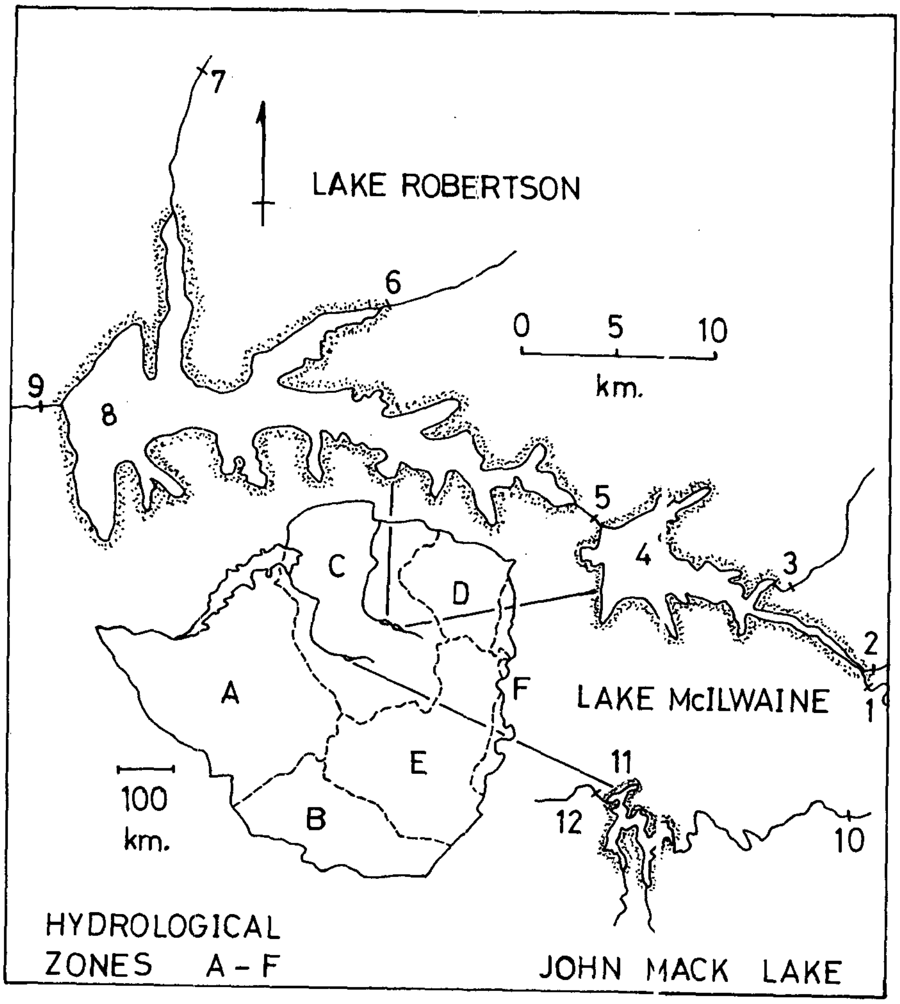


*Figure 1*
*Hydrological map of Zimbabwe showing the locations of the three reservoirs and the sampling sites used in this study*

**TABLE 1**
**SELECTED HYDROGRAPHICAL DATA FOR LAKE McILWAINE, JOHN MACK LAKE, AND LAKE ROBERTSON, ZIMBABWE, BASED ON LONG-TERM MEANS**

| Parameter | L. McIlwaine | J. Mack L. | L. Robertson |
|---|---|---|---|
| Location (lat.) | 17° 54' S | 18° 28' S | 17° 48' S |
| (long.) | 30° 48' E | 29° 53' E | 30° 34' E |
| Year built | 1952 | 1973 | 1976 |
| Catchment geology | granite | granite sandstone | granite |
| Catchment land use | urban | rural | rural |
| Lake area ($10^6 m^2$) | 26,3 | 4,85 | 81,0 |
| Lake volume ($10^6 m^3$) | 250 | 21 | 490 |
| Mean annual run-off ($10^6 m^3$) | 267 | 106 | 457 |
| Replacement rate (yr) | 0,9 | 0,2 | 1,1 |
| Maximum depth (m) | 27,4 | 17,5 | 22,6 |
| Mean depth (m) | 9,4 | 4,3 | 6,0 |
| Catchment area ($10^6 m^2$) | 2 227 | 2 300 | 3 800 |
| Full supply level (m above mean sea level) | 1 368,5 | 1 090,0 | 1 341,0 |

## Analytical Methods

Soluble and particulate reactive phosphorus (SRP and PRP respectively) and their sum, total reactive phosphorus (TRP), were determined on a Pye-Unicam SP 1800 spectro-photometer using a modified ascorbic acid-molybdate method (Murphy and Riley, 1962; Golterman, 1970; Strickland and Parsons, 1972). Water samples were preserved with a saturated mercuric chloride solution and were stored in aged 500 mℓ PVC bottles. Analyses were carried out on both filtered and unfiltered samples to allow determination of the three phosphorus fractions; Whatman GF/B glass fibre filters were used for filtration of the filtered samples. All analyses were completed within one week of sample collection.

Total suspended solids (TSS) were measured gravimetrically by filtration through tared Whatman GF/B glass fibre filters at stations 2 and 3, and 6 and 7, and coulorimetetrically by using a Corning 252 Colourimeter at the other riverine stations (Strickland and Parsons, 1972; Ward, 1977). Conductivity and pH were measured at each station and temperature was recorded daily at each station on the rivers. Phytopigment (chlorophyll *a* and phaeophytin) concentrations were determined after the acetone extraction method of Golterman (1970). Dissolved oxygen and secchi disc light penetration measurements were made at the lake stations; the oxygen determination was modified Winkler titration (Strickland and Parsons, 1972).

River flow data was made available by the Ministry of Water Development, and additional physico-chemical data was provided by the Ministry of Water Development through the Salisbury City Chemist. Phosphorus loads were calculated using the method described in Thornton (1979a).

## Results and Discussion

### Physico-chemistry

The summer rainy season is a transitional phase for most Zimbabwean lakes. Prior to the rains the lakes are stratified in terms of both an oxycline and a thermocline; the hypolimnion is usually deoxygenated and several degrees cooler than the surface waters (Mitchell and Marshall, 1974; Walmsley and Toerien, 1977). This stratification breaks down during the summer and the lakes remain homogeneous through the winter dry season, re-stratifying in the spring dry season when air temperature increase. Lake McIlwaine was stratified at the outset of the study in December and remained so through to the end of March (Figure 2). Lake Robertson was only briefly stratified between mid-January and mid-March (Figure 3). John Mack Lake was weakly stratified throughout the study period (Figure 4). The hypolimnion of John Mack Lake was not deoxygenated at any time during the study although it is likely that the lake was stratified during December. Table 2 gives a resume of the average physico-chemical characteristics of the three lakes during the summer season.

Although the three impoundments share a number of common features, there are notable differences in their physico-chemical regimes. Some similarities would be expected as all

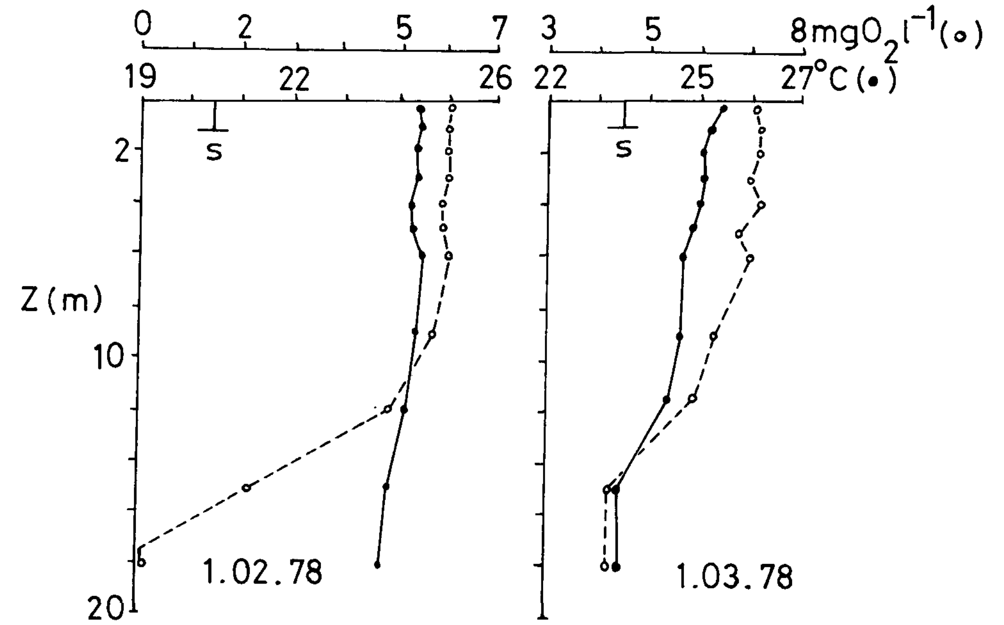


*Figure 2*
*Temperature (●) and oxygen (o) profiles of Lake McIlwaine (Station 4) showing the breakdown of stratification during the summer wet season; S, secchi disc measurement*

three dams fall within the same hydrological zone. Conductivity and pH values for the three impoundments overlap considerably in range, and all three lakes are slightly alkaline on average. The greatest similarities occur between Lakes McIlwaine and Robertson due to the common catchment and river system. These lakes also have similar secchi disc light penetration distances.

The obvious differences between the impoundments stem largely from the different trophic states of the three lakes (Table 2). Reactive phosphorus concentrations follow the order of the trophic states of the lakes as defined from previous studies. Lake

**TABLE 2**
**PHYSICO-CHEMICAL CHARACTERISTICS OF LAKES McILWAINE AND ROBERTSON AND JOHN MACK LAKE DURING THE 1977/78 SUMMER SEASON INTEGRATED OVER DEPTH AND TIME. RANGES IN CONCENTRATIONS ARE PRESENTED FOR STATIONS 4, 8 AND 11 RESPECTIVELY, AND WATER COLUMN AVERAGES ARE SHOWN IN BRACKETS IMMEDIATELY BELOW THE RANGES OF CONCENTRATIONS. UNITS ARE mg $\ell^{-1}$ UNLESS OTHERWISE SPECIFIED**

| Parameter | L McIlwaine | J. Mack L. | L. Robertson |
|---|---|---|---|
| SRP | 0,004–0,134 (0,045) | 0,012–0,052 (0,028) | 0,002–0,033 (0,014) |
| TRP | 0,011–0,206 (0,082) | 0,013–0,174 (0,058) | – |
| Chlo *a* | tr–0,076 (0,019) | tr–0,018 (0,009) | tr–0,025 (0,009) |
| pH | 6,9–8,9 (7,4) | 7,2–7,5 (7,4) | 6,4–9,1 (7,6) |
| Cond. (mS/m) | 7,4–10,8 (9,2) | 4,6–9,5 (7,4) | 7,1–13,2 (10,1) |
| TSS | 0,7–120,0 (18,7) | 12,8–484,4 (94,5) | – |
| TDS[1] | 51,8–75,6 (64,4) | 32,3–66,5 (51,8) | 49,7–9,24 (70,7) |
| Avg. secchi disc (m) | (1,2) | (0,4) | (1,2) |

[1]Total Dissolved Solids (TDS) were derived by the relationship: Cond. (mS/m) x 7 (Cotterill, 1980).
tr = trace quantity

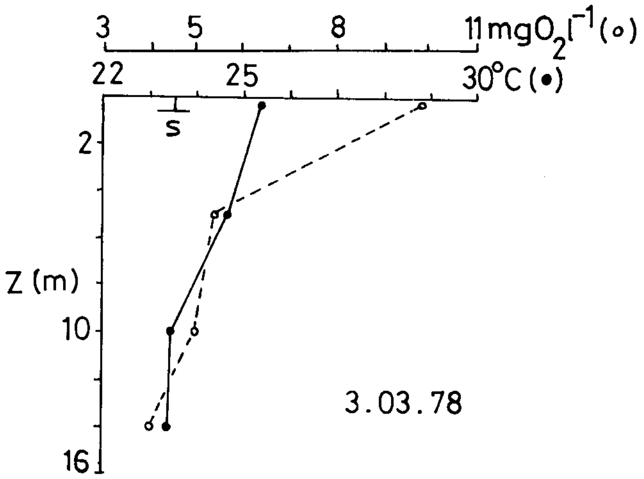


*Figure 3*
*Temperature (●) and oxygen (o) profile of John Mack Lake (Station 11) showing the homogenous nature of the impoundment during the summer wet season; S, secchi disc measurement*

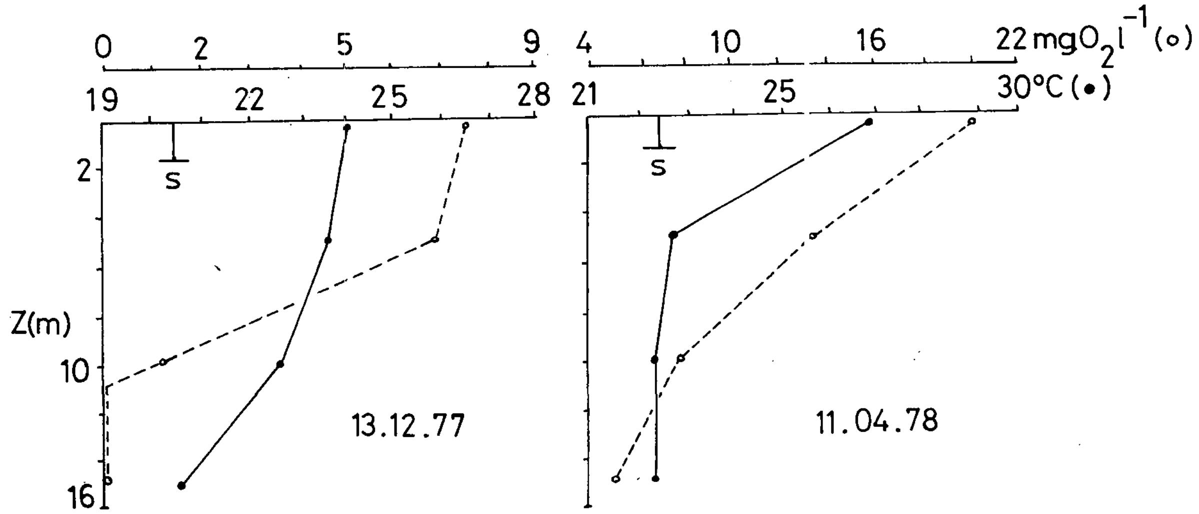


*Figure 4*
*Temperature (●) and oxygen (o) profiles of Lake Robertson (Station 8) showing the breakdown of stratification during the summer wet season; S, secchi disc measurement*

McIlwaine, which has been shown to be a eutrophic impoundment (Marshall and Falconer, 1973a, 1973b), has the highest phosphorus concentrations and supports the highest phytoplankton standing crop as indicated by the relatively high chlorophyll *a* concentrations. John Mack Lake has the second highest phosphorus concentration and is followed by Lake Robertson with the lowest. Both John Mack Lake and Lake Robertson support similar phytoplankton standing crops. This is most likely due to the extremely turbid nature of John Mack Lake. This impoundment has the highest concentration of total suspended solids and the lowest secchi disc light penetration measurements. The high pH values for Lakes McIlwaine and Robertson are due to periodic algal blooms which occur in these impoundments, and which coincide with high levels of chlorophyll *a*.

**Phosphorus Loading**

Phosphorus mass-balance calculations were made for the three reservoirs for the summer rainy season. As far as possible total reactive phosphorus (TRP) was used in the calculation of the mass-balances, although TRP data was not available for the Lake Robertson station (station 8). TRP was used because this fraction was thought to incorporate a majority of the biologically available phosphorus (Schaffner and Oglesby, 1978) and corresponded closely to "total" phosphorus (Thornton, 1980). Riverine inflows and outflows were based on at least one sample per day, and lake concentrations were based on at least monthly samples. Table 3 presents the mass-balance calculations.

Previous work by Thornton (1979a, 1979b) has shown that the summer phosphorus loads to Lake McIlwaine account for over 80% of the annual phosphorus loading to the lake. Thus, the values obtained during this study may be considered to represent the major part of the loading to the impoundments during the 1977/78 hydrological year.

Comparison of the phosphorus mass-balances for the three dams (Table 3) shows that there is a net accumulation of phosphorus in both Lake McIlwaine and Lake Robertson. Work on Lake McIlwaine by Nduku (1976) and Thornton (1979b) suggests that much of the phosphorus entering the lake is lost to the sediments. This is most likely the case in Lake Robertson as well. The amount of phosphorus retained in the impoundments in both cases agrees well with published figures; 46% of the phosphorus entering Lake McIlwaine is retained whilst some 82% of the phosphorus entering Lake Robertson is retained. Dillon and Rigler (1974a) and Schaffner and Oglesby (1978) have previously reported the retention of between 30 and 40% of the phosphorus entering temperate lakes with water residence times of less than one year, and of between 75 and 90% of the phosphorus in lakes with water residence times exceeding one year.

Dillon and Rigler (1974a) and Dillon (1975) further report that lakes with residence times of less than 0,5 years do not conform to this model due to the "wash-out" of phosphorus. This is, in fact, the case with John Mack Lake which shows a retention of only 11% of the phosphorus entering the lake. This "wash-out" of phosphorus may be supported by the work of Ward (1977) who has shown that there is relatively little depo-

TABLE 3
PHOSPHORUS MASS-BALANCES FOR LAKE McILWAINE, JOHN MACK LAKE AND LAKE ROBERTSON FOR SUMMER 1977/78, IN t P

| Component | L. McIlwaine | J. Mack L. | L. Robertson |
|---|---|---|---|
| Riverine P inflows | | | |
| Sta. 1 | 25,9 | – | – |
| 2 | 22,8 | – | – |
| 3 | 25,5 | – | – |
| 5 | – | – | 33,3 |
| 6 | – | – | 5,1 |
| 7 | – | – | 11,7 |
| 10 | – | 13,3 | – |
| Totals | 74,2 | 13,3 | 50,1 |
| Riverine P outflows | | | |
| Sta. 5 | 33,6 | – | – |
| 9 | – | – | 13,2 |
| 12 | – | 11,1 | – |
| Totals | 33,6 | 11,1 | 13,2 |
| Mass-balance | +41,0 | +2,2 | +36,8 |
| Change of P in soln. in lake | +6,8 | −0,7 | −4,4 |
| P loss (means unspecified) | 34,2 | 1,5 | 41,2 |
| Avg. amt. of P in soln. in lake | 20,5 | 0,8 | 6,9 |

sition of sediment in the impoundment despite a high TSS loading due to the fine particle size of the sediment (approximately 70% of the sediment has a particle size of less than 1 μm). The high concentrations of PRP (trace – 0,166 mg P $\ell^{-1}$) would seem to indicate that much of the phosphorus entering the impoundment is washed through with the sediment, and that little of this PRP fraction is ever released into the water column.

In order to further compare the phosphorus loadings to the three impoundments, it is necessary to utilize some other expression of loading than a simple mass-balance. Whilst this expression of phosphorus loading to the total volume of a lake is useful in assessing the effects of phosphorus inputs to a particular lake over time (Edmondson, 1961), it fails to take into account differences in lake morphology (Toerien, 1977). Therefore, phosphorus loading per unit of lake surface area has been widely employed (Vollenweider and Dillon, 1974), and phosphorus loading per unit of lake volume has been proposed (Schaffner and Oglesby, 1978). All three expressions of phosphorus loading are given in Table 4. Pre-diversion phosphorus loadings for Lake McIlwaine have been adapted from Marshall and Falconer (1973b) and are also presented in Table 4; diversion of municipal wastewater from the Lake McIlwaine catchment to pasture irrigation schemes was accomplished between 1970 and 1975.

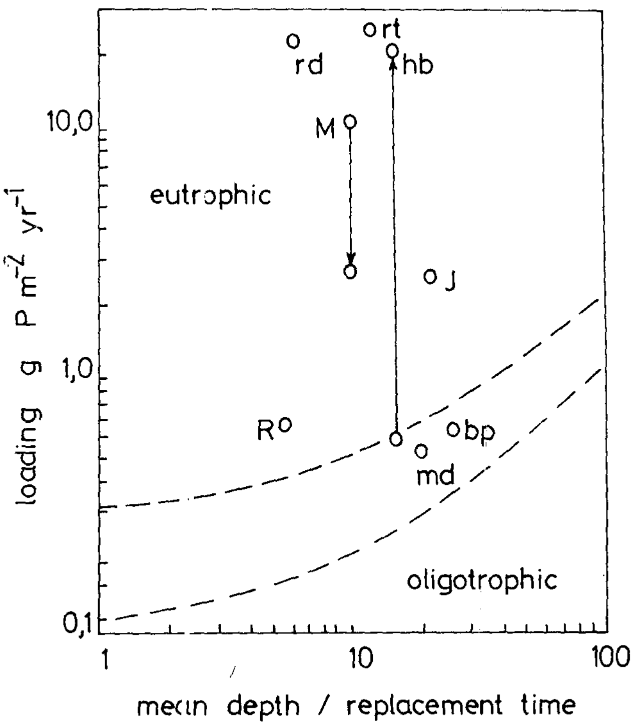


*Figure 5*
*A modified Vollenweider graphic presentation of phosphorus loadings to several southern African impoundments (after Toerien, 1977). R, Lake Robertson; J, John Mack Lake; M, Lake McIlwaine; md, Midmar Dam (Natal); bp, Buffelspoort Dam (Transvaal); hb, Hartbeespoort Dam (Transvaal); rt, Rietvlei Dam (Transvaal), rd; Roodeplaat Dam (Transvaal). Arrows indicate current trends in phosphorus loading where previous data is available*

**TABLE 4**
**PHOSPHORUS LOADINGS TO THE THREE IMPOUNDMENTS EXPRESSED AS AREAL AND VOLUMETRIC LOADINGS PER SEASON IN ADDITION TO THE LOADING RATE PER LAKE VOLUME**

| Lake | t/lake | g/m² | g/m³ |
|---|---|---|---|
| L. McIlwaine (pre-diversion) | 288,1 | 11,0 | 1,2 |
| L. McIlwaine (present study) | 74,6 | 2,8 | 0,3 |
| John Mack Lake | 13,3 | 2,8 | 0,6 |
| L. Robertson | 50,0 | 0,6 | 0,1 |

Lake McIlwaine has the highest tonnage loading of phosphorus of the three reservoirs and is the only one of the three to receive municipal wastewater and urban run-off. This high tonnage loading is reflected in the areal loading which is also relatively high. John Mack Lake has a similar areal phosphorus loading to Lake McIlwaine. Figure 5 shows a modified Vollenweider graphic presentation of the areal phosphorus loadings to several southern African impoundments. It is interesting to note that all three impoundments of the present study show eutrophic tendencies according to the plot. John Mack Lake has the highest phosphorus loading using the volumetric notation of Schaffner and Oglesby (1978) and is followed by Lake McIlwaine. Lake Robertson has the lowest areal and volumetric phosphorus loadings.

## Trophic States

The use of phosphorus loading expressions as a criteria for defining the trophic state of a lake is well documented (Oglesby and Schaffner, 1978; Toerien, 1977; Dillon, 1975; Vollenweider and Dillon, 1974; Dillon and Rigler, 1974a, 1974b; Edmondson, 1961). It is reasonable, therefore, to make an assessment of the trophic states of the three reservoirs included in the present study on this basis. Lake McIlwaine is the obvious starting point for such an assessment. This lake has been shown to be eutrophic (Marshall and Falconer, 1973a, 1973b) and has been favourably compared to the eutrophic Hartbeespoort Dam in the Republic of South Africa (Scott, *et al.*, 1977; Toerien and Steyn, 1975). Pre-diversion phosphorus loading to the impoundment (calculated from Marshall and Falconer, 1973b) is extremely high and well within the eutrophic area of Figure 5. The present, post-diversion study, however, has shown a marked reduction in the phosphorus loading to the impoundment. Based on present concentrations of SRP and chlorophyll *a* it can be seen that the lake is approaching a meso-eutrophic state (Wetzel, 1975). This trend is shown on Figure 5 by the arrow. At the present time, though, the lake may still be classed as slightly eutrophic.

John Mack Lake has been previously assessed as meso-oligotrophic (Robarts and Southall, 1977). This classification would appear to be incorrect when phosphorus loadings are considered, as the impoundment is well within the eutrophic zone in Figure 5. However, this reservoir has been shown to have relatively low chlorophyll *a* concentrations and moderate SRP concentrations; both of which would indicate a mesotrophic state. The possible influences of the high turbidity on phytoplankton standing crop and on the "wash-out" of phosphorus, and of the low water residence times on the retention of phosphorus in the impoundment have already been considered. These facts would seem to support the work of Dillon (1975) on Cameron Lake, Canada, where he was able to show that despite high phosphorus loadings the lake did not become eutrophic. It is therefore reasonable to classify John Mack Lake as mesotrophic despite the high phosphorus loadings.

It would appear from the areal phosphorus loading data in Figure 5 that Lake Robertson is also a eutrophic lake. However, previous studies by Cotterill (1980) have shown the lake to be oligotrophic, and this is largely supported by the low SRP and chlorophyll *a* concentrations found during the present study. This classification is further supported by comparison of this impoundment with Midmar Dam, Republic of South Africa, which has a similar areal phosphorus loading and water residence time (Hemens, *et al.*, 1977). Thus, on this basis, it is reasonable to suggest, if tentatively, that the upper line in Vollenweider's model (Figure 5) depicting the transition from mesotrophy to eutrophy might be low when used in a tropical African context. This study, therefore, supports the findings of Toerien and Walmsley (1979) who reached a similar conclusion from their study of man-made lakes in the Republic of South Africa.

The special relationship which exists between Lakes McIlwaine and Robertson due to their close proximity affords a unique opportunity to assess the effects of a eutrophic impoundment on an oligotrophic dam. Thornton and Cotterill (1977) have suggested that Lake McIlwaine acts as a phosphorus sink and removes large quantities of the nutrient prior to the water passing into Lake Robertson. Mitchell, *et al.* (1975), on the other hand, have postulated that Lake McIlwaine might act as a nutrient source to Lake Robertson; thus causing the rapid eutrophication of that lake. To clarify this relationship, the phosphorus mass-balance calculations for the two lakes are given in Table 3.

It is readily apparent from the data in Table 3 that Lake McIlwaine (station 5) is the major source of phosphorus to Lake Robertson. However, it can also be seen that there has been a significant reduction in the amount of phosphorus carried by the Hunyani River (including its tributaries) during the passage of the river through Lake McIlwaine. Of the 74,6 t of phosphorus entering Lake McIlwaine, only 33,3 t are allowed through the impoundment into Lake Robertson; some 34,2 t are lost to the sediments and/or retained in the water column of Lake McIlwaine. This retention of phosphorus by Lake McIlwaine has been dealt with above. In other terms, Lake Robertson receives 75% of its water load from Lake McIlwaine but only 65% of its phosphorus load from that lake. Thus, it can be concluded that Lake McIlwaine is primarily a sink for phosphorus and only secondarily a source of phosphorus to Lake Robertson.

## Conclusions

1. Trophic state was found to compare favourably with phosphorus loading in two of the three impoundments studied.

2. Low water residence times in the third impoundment studied were shown to result in a low trophic state despite high phosphorus loadings.

3. The Vollenweider-type graphic model might require modification if it is to be used to assess eutrophication problems under tropical conditions.

4. Upstream lakes act as nutrient sinks thereby reducing the nutrient loading to lakes further downstream.


## Acknowledgements

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