Impact of phosphorus load reductions on eutrophication-related water quality of Roodeplaat Dam (Reservoir), Republic of South Africa

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Abstract

Roodeplaat Dam receives secondary treated domestic wastewater effluent and there is concern about its eutrophication-related water quality.

Various schemes have been adopted or proposed for controlling or mitigating the manifestations of eutrophication, such as phosphorus limitations for domestic wastewater effluents.

The OECD eutrophication modelling approach, which has been found to be applicable to South African dams in general and Roodeplaat Dam in particular, was used in conjunction with existing nutrient load and eutrophication response data for Roodeplaat Dam to evaluate the expected impact of several phosphorus management options. It was found that the enforcement of the 1 mg P/ℓ wastewater effluent standard would improve the usability of Roodeplaat Dam, especially if the second, proposed treatment plant were to discharge to the dam.

Introduction

Roodeplaat Dam (Reservoir) is a eutrophic impoundment located approximately 20 km from Pretoria, South Africa. Because it is an important recreational and water supply resource for the area (Pieterse and Bruwer, 1980), there is concern about its eutrophication-related water quality characteristics. This concern is accentuated by the fact that the effluent from a secondary wastewater treatment plant is currently being discharged to a tributary of the dam, and comprises about 75 % of the total phosphorus load. Further, another major domestic wastewater treatment plant is planned to be built to discharge its effluent to the dam in the near future.

As the demands on South Africa's fresh water resources are increasing with increasing population, greater attention is beginning to be directed toward managing the eutrophication-related quality to ensure the availability of readily treatable water for drinking and acceptable water for recreating. One eutrophication management option which has been adopted for certain sensitive areas of South Africa is a 1 mg/ℓ dissolved orthophosphate-P maximum limit for domestic wastewater treatment plant effluents. Others, such as detergent phosphate limitations, are being considered as well.

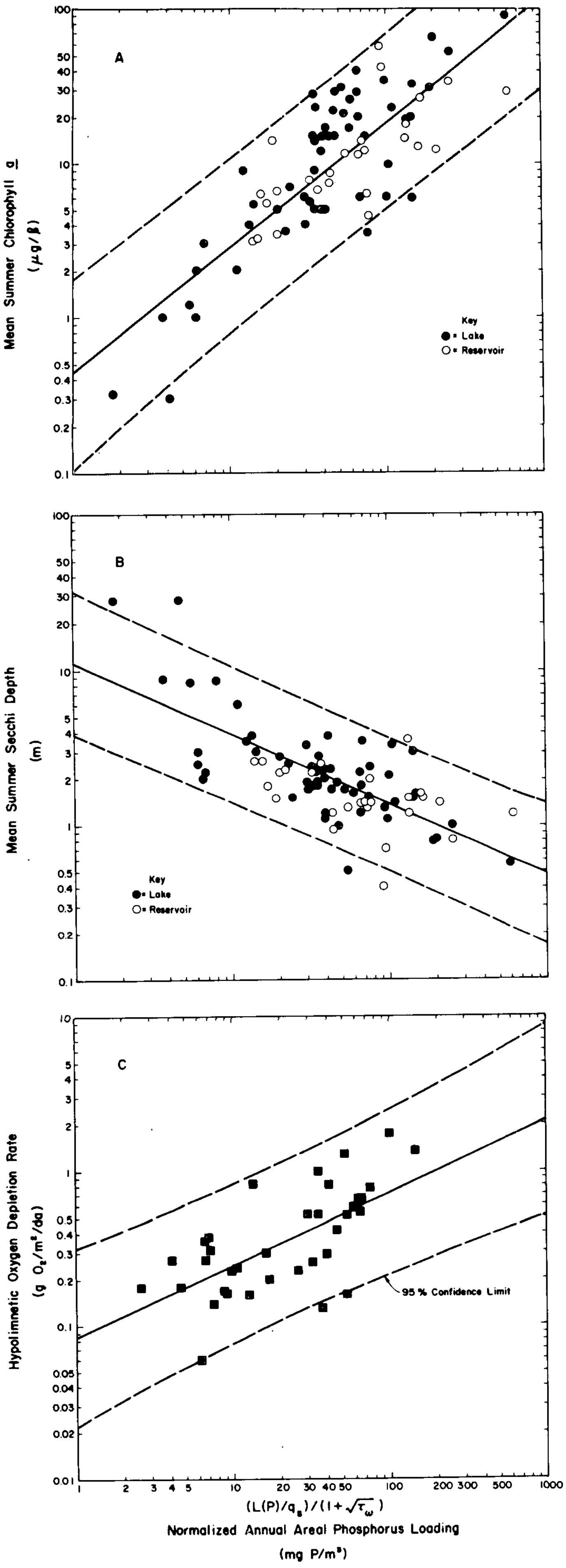
The limnological characteristics of Roodeplaat Dam have been studied by a number of individuals over the past decade. It was also included in an earlier study of 21 dams undertaken by the National Institute for Water Research (NIWR) of the Council for Scientific and Industrial Research (CSIR) on behalf of the Water Research Commission (WRC), (WRC and NIWR-CSIR, 1980), primarily to investigate eutrophication-related water quality. The study included bi-weekly collection of samples from the main body of the dam and from the three tributary rivers, as well as the determination of the general hydrological characteristics of Roodeplaat Dam. These data can be used to assess the potential impact of altering phosphorus loads to this waterbody on eutrophication-related water quality.

A method that has a demonstrated capability to predict the changes in eutrophication-related water quality characteristics that can result from changes in phosphorus load is the OECD (Organization for Economic Cooperation and Development) eutrophication modelling approach. This approach was developed out of a 5-year, 22-country, 200-waterbody study conducted under the direction of R.A. Vollenweider and advisers to quantify nutrient load-eutrophication response relationships for surface waters. Through this study, empirical relationships were developed between a waterbody's phosphorus loading (normalized by mean depth, hydraulic residence time and surface area) and the waterbody's eutrophication-related water quality characteristics (Rast and Lee, 1978; Lee *et al.*, 1978). The load-response relationships developed based on the results of the 34 US OECD waterbody studies, and the results of follow-on studies of about 40 additional US waterbodies conducted after completion of the US OECD study, are shown in Figure 1 (Jones and Lee, 1982a). The abscissa term, developed by Vollenweider (1976), is the normalized total P loading; the ordinate terms are mean summer chlorophyll (water greenness), mean summer Secchi depth (water clarity), and the rate of oxygen depletion in the hypolimnion of a waterbody. The lines of best fit, i.e., the relationships presented, are essentially the same as those developed for the entire OECD eutrophication study data base (OECD, 1982).

This paper presents a discussion of the application of the OECD eutrophication modelling approach to Roodeplaat Dam and of how this approach can be used to estimate the impact of nutrient load manipulations on the eutrophication-related water quality charcteristics of this waterbody. The data used for this assessment were the averaged data provided in Pieterse and Bruwer 1980). Because the original (unaveraged) data base was not available to the authors, the details of the sampling programme and the data produced have not been screened as recommended by Jones and Lee (1982a) for appropriateness for use in this modelling. The data were assumed appropriate as averaged.

Application of the OECD eutrophication modelling approach to Roodeplaat Dam

Doubts have been expressed whether the Vollenweider model, the approach which, as refined, served as the theoretical basis for the OECD load-response relationships, is applicable to South African waterbodies. However, Jones and Lee (1984) demonstrated that the relationships shown in Figure 1 do in fact hold true for the South African waterbodies evaluated. Figure 2



<u>KEY</u>

$L(P)$ = Areal Annual Phosphorus Load (mg P/m²/yr)

q_s = Mean Depth ÷ Hydraulic Residence Time = $\bar{z}/\tau_\omega$ (m/yr)

τ_ω = Hydraulic Residence Time (yr)

Figure 1.
Expanded US OECD normalized phosphorus load-eutrophication response relationships. After Jones and Lee (1982a)

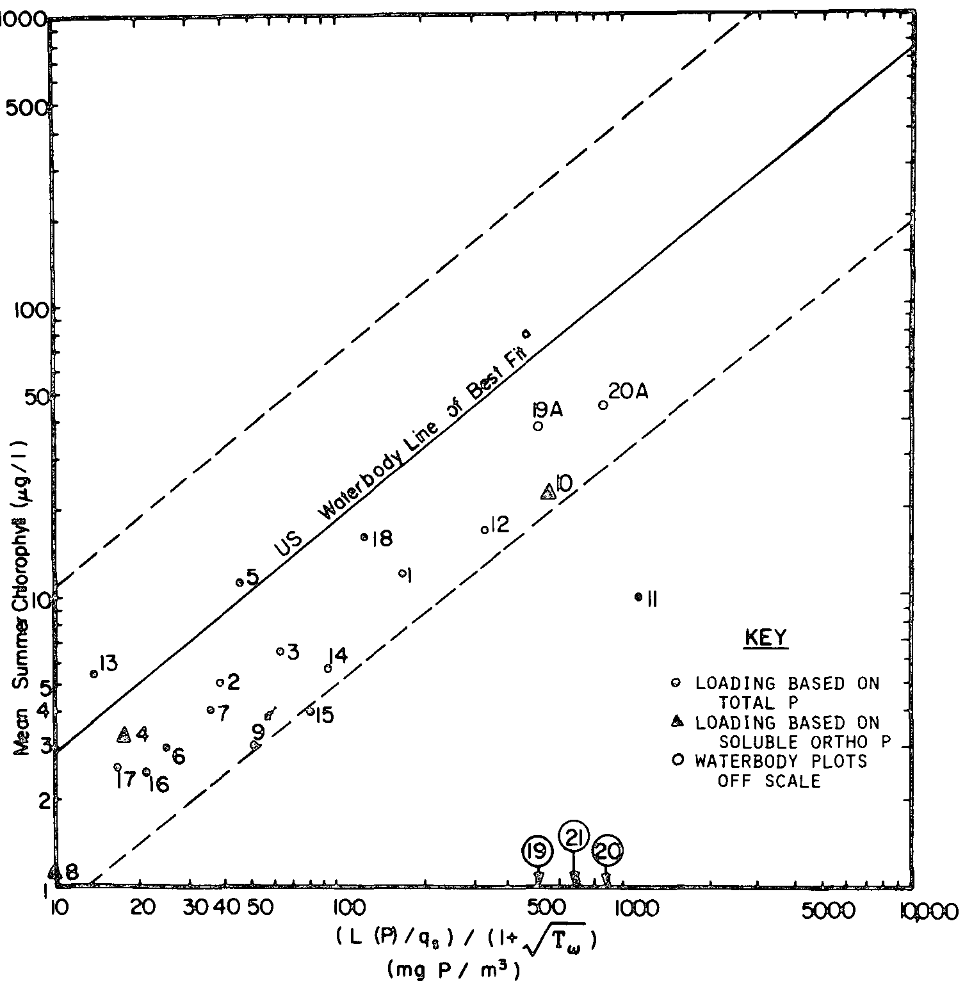


Figure 2.
Phosphorus load-annual average chorophyll relationships for South African dams (OECD Eutrophication Modelling Approach). [a]After Jones and Lee (1982a; 1984)

shows the position of the South African waterbodies evaluated relative to the US waterbody line of best fit for chlorophyll shown in Figure 1. As discussed by Jones and Lee (1984), it is expected that these waterbodies would consistently fall below the line of best fit owing to the fact that the chlorophyll data for the South African dams were mean annual concentrations; the line of best fit was developed for mean summer chlorophyll levels which would, for most waterbodies, be higher than annual averages.

Table 1 presents information on the characteristics of Roodeplaat Dam as presented by Pieterse and Bruwer (1980), which is pertinent to defining the normalized nutrient load-eutrophication response relationships for this waterbody. Point 12 on Figure 2 is the position of Roodeplaat Dam based on the information provided in Table 1. It falls within the family of load-response couplings for the more than 350 waterbodies evaluated to date. As discussed by Jones and Lee (1982a), this is important to establish before attempting to use this modelling approach for predicting changes in response that would result from a P load alteration.

TABLE 1
CHARACTERISTICS OF ROODEPLAAT DAM DURING 1977-78 STUDY[a]

Parameter	Value
Volume (x $10^6 m^3$) – full pool	41,9
– maximum	42,4
– mean	42,2
Area (km^2) – full pool	3,96
– maximum	3,97
– mean	3,95
Mean depth (m)	10,6
Hydraulic residence time (yr)	0,38
Total areal phosphorus loading (g P/m^2/yr)	14,97
Chlorophyll-*a* ($\mu g/\ell$) – annual mean	17
– annual maximum	52

[a]From Pieterse and Bruwer (1980)

Impact of phosphorus reduction strategies on eutrophication-related water quality characteristics

Impact on phosphorus loading

To use the OECD eutrophication modelling approach for estimating the impact of phosphorus reduction options on water quality, it is necessary to compute the expected normalized phosphorus loads under the altered conditions. Bruwer (1983) indicated that the current total P load from WWTP-1 (the existing wastewater treatment plant discharging to a tributary of Roodeplaat Dam) is 119 kg P/day and that this amount represents about 75 % of the total P load. The total P load under these assumptions would be about 57 900 kg P/yr or on an areal basis, 14,6 g P $m^{-2}yr^{-1}$ assuming full pool volume. This is about the same as the areal P loading reported for the 1977-78 study period by Pieterse and Bruwer (1980) of 14,97 g P $m^{-2}yr^{-1}$. It was therefore assumed for these calculations, that the P load from the WWTP-1 is 43 435 kg P/yr, and the current P load from all remaining sources is 15 725 kg P/yr, yielding a total current total P load to Roodeplaat Dam of 59 160 kg P/yr.

Achieving the 1 mg P/ℓ domestic wastewater treatment plant effluent limitation in South Africa, would be essentially the same as achieving 90 % removal of WWTP effluent P. Therefore, enacting this measure would reduce the WWTP-1 P load to Roodeplaat Dam to 4 344 kg P/yr, and the total load to 20 069 kg P/yr.

It is expected that the new wastewater treatment plant planned to be constructed (WWTP-2) will, with the aid of phosphorus removal to 1 mg/ℓ, discharge 85 kg P/day (Bruwer, 1983). Again assuming that the achieving of the effluent standard represents a 90 % P load reduction at the treatment plant, if P removal were not practised at WWTP-2, it would add 310 250 kg P/yr to Roodeplaat Dam. Thus, if both treatment plants were on-line and practising only secondary treatment, the total P load to the dam would be 369 410 kg P/yr. The addition of the effluent from WWTP-2 to Roodeplaat Dam will also increase the water input from the current 111 x 10^6 m^3/yr [based on Pieterse and Bruwer (1980) monthly average inflow] to 145 × 10^6 m^3/yr (Bruwer, 1983). This increase will result in a decrease in the hydraulic residence time (volume ÷ annual inflow) from 0,38 years (Pieterse and Bruwer, 1980) to 0,29 years.

If both WWTP-1 and WWTP-2 were to achieve the 1 mg P/ℓ effluent standard, a total P load to Roodeplaat Dam would be 51 095 kg P/yr.

Another P control strategy being considered in South Africa is the banning of the use of phosphates in household laundry detergents, since it is estimated that approximately 35 % to 55 % of the phosphorus in domestic wastewater treatment plant effluents in South Africa is from household laundry detergents (Heynike, 1983). If 35 % of the WWTP effluent is due to detergent P, and if detergent P was eliminated from the current WWTP-1 discharge, the total P load to Roodeplaat Dam would be 43 960 kg P/yr. This P control measure alone would result in a total P load to the dam after start-up of WWTP-2 of 245 620 kg P/yr.

Impact on waterbody quality

The change in phosphorus loading is not a measure of impact of a P control measure on water quality. Further, the conversion of the P load to an in-lake phosphorus concentration also does not quantify water quality or the change in water quality. Water quality must be evaluated in terms of desired beneficial uses for the water and therefore must be quantified in terms that the users can perceive as related to their uses of the waterbody. Chlorophyll, or water greenness, is a parameter that can often be used for assessing the "quality" of a waterbody for recreational use (Lee *et al.*, 1984) as well as for domestic water supply (Jones and Lee, 1982b). Using the OECD modelling approach and the US waterbody lines of best fit (Figure 1), the changes in P load and hydraulic residence times expected to result from the abovementioned phosphorus control strategies can be translated to expected changes in chlorophyll concentration (Jones and Lee 1982a); Rast *et al.*, 1983).

Table 2 presents the P loads to Roodeplaat Dam normalized, in accordance with the OECD modelling approach, by mean depth, hydraulic residence time, and waterbody surface area. According to Pieterse and Bruwer (1980), the volume and area of the reservoir were fairly uniform during the 1977-78 monitoring

TABLE 2
PREDICTED CHARACTERISTICS OF ROODEPLAAT DAM FOR VARIOUS PHOSPHORUS MANAGEMENT OPTIONS

Condition	Phosphorus Load to Reservoir (kg P/yr)	Hydraulic Residence Time (yr)	Normalized Areal Load $(L(P)/q_s)/(1+\sqrt{\tau_\omega})$ (mg P/m^3)	Predicted Mean Annual Chlorophyll (µg/ℓ)
A – Current	59 160	0,38	331	17**
B – P removal at WWTP-1* to 1 mg P/ℓ	20 070	0,38	112	7
C – Current P loading from WWTP-1 plus P loading expected from WWTP-2 without P removal	369 410	0,29	1 659	60
D – WWTP-1 and WWTP-2 achieving 1 mg P/ℓ effluent standard	51 095	0,29	229	13
E – Condition A with detergent P ban	43 960	0,38	246	13
F – Condition C with detergent P ban	245 620	0,29	1 103	45

*WWTP-1 is the wastewater treatment plant currently discharging to the tributary of Roodeplaat Dam; WWTP-2 is the wastewater treatment plant planned to be constructed to discharge into the Roodeplaat Dam system.
**Measured

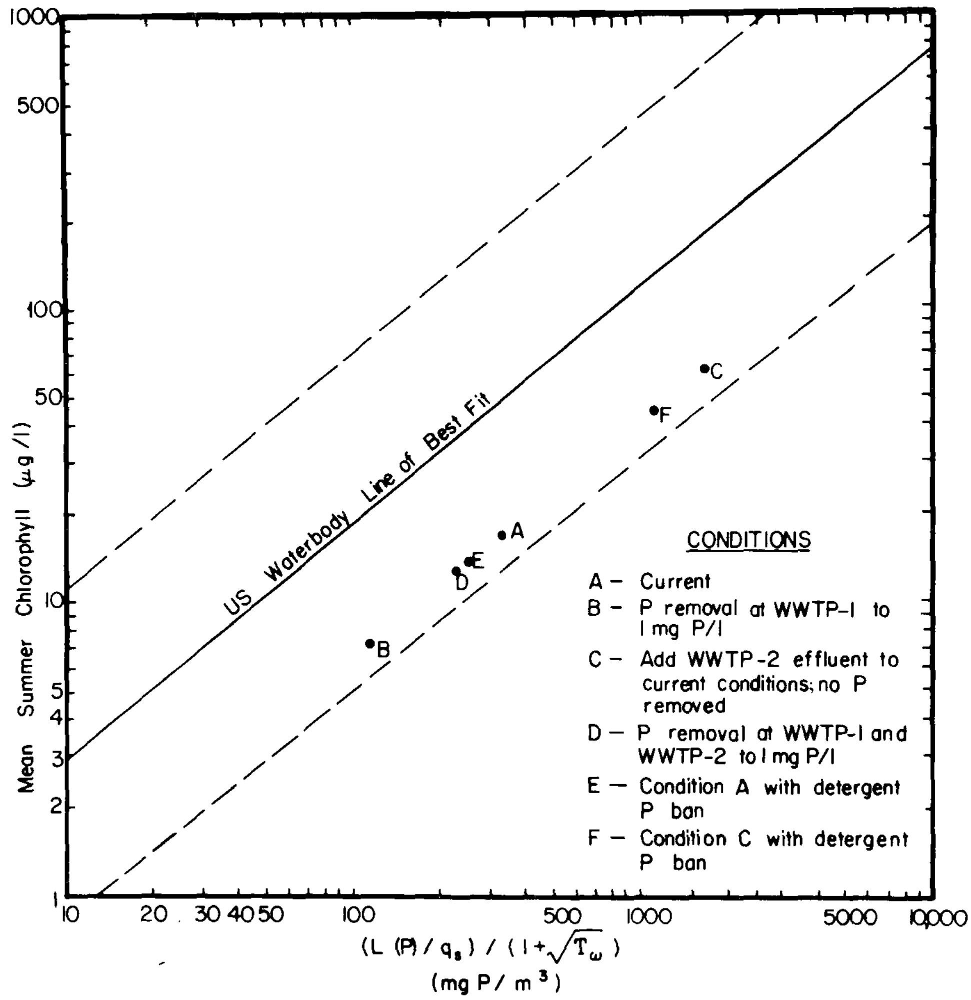


Figure 3.
Average annual chlorophyll levels in Roodeplaat Dam expected to result from selected phosphorus control strategies. After Jones and Lee (1982a)

period, with the mean values being within 1 % of the maximum values, and were essentially full pool (full supply level) values (Table 1). Therefore, full pool values were used for the morphological characteristics in the computations of normalized loading. It was also assumed that the additional water input to the dam from WWTP-2 would manifest itself as a decrease in hydraulic residence time, rather than as an increase in dam water volume; a mean depth of 10,6 m was assumed based on full pool volume and area.

The average annual chlorophyll level reported for Roodeplaat Dam for the 1977-78 study period by Pieterse and Bruwer (1980) was 17 $\mu g/\ell$ (Table 1). This chlorophyll level, together with the P load labeled in Table 2 as "current," positions Roodeplaat Dam under "current" conditions at position A in Figure 3. Moving through this point parallel to the line of best fit to a perpendicular line through one of the new normalized P loadings shown in Table 2, will provide an estimate of the chlorophyll concentration that will be found once the waterbody has come to an equilibrium with that new P load. According to the phosphorus residence time model of Sonzogni *et al.*, (1976), this recovery time can be approximated to be three times the phosphorus residence time of the waterbody. For Roodeplaat Dam, the authors estimate this recovery time to be less than 0,5 years based on data provided by Pieterse and Bruwer (1980) and the empirical relationship developed by Rast *et al.*, (1983) between the normalized P loading term and mean, in-lake P concentration.

As derived from Figure 3 and shown in Table 2, a noticeable change in mean annual chlorophyll concentration to 7 $\mu g/\ell$, would occur if the 1 mg P/ℓ effluent standard were met at the WWTP-1 (Condition B). Some improvements may even be seen with a detergent P ban (Condition E). However, with ever-increasing population pressures, the WWTP-2 may soon be on-line. Thus, it would be short-sighted of a manager to make evaluations based on the status quo. With neither WWTP-1 nor WWTP-2 treating for phosphorus removal (Condition C), the annual average chlorophyll concentration would increase to 60 $\mu g/\ell$. This level is characteristic of highly eutrophic, "pea soup" water; it is about the level of chlorophyll found in Hartbeespoort Dam near Pretoria. A detergent phosphate ban in the areas served by WWTP-1 and WWTP-2 could effect an improvement in the aesthetic quality of the water by reducing the annual average chlorophyll concentration to 45 $\mu g/\ell$. This level of chlorophyll is, however, still undesireable for a recreational and drinking water supply waterbody. By meeting the 1 mg P/ℓ effluent limitation at WWTP-1 and WWTP-2, the new wastewater treatment plant can discharge to Roodeplaat Dam without degrading the current water quality. Indeed, this P control strategy, even with the additional WWTP facility, will result in water quality characteristics which are improved over those which currently exist.

The question often arises of what improvement in eutrophication-related water quality would occur if both detergent P bans and 1 mg P/ℓ effluent limitations were imposed. While there would, in general, be some reduction in the cost of treatment and/or sludge disposal because of the reduction in the influent P level, the effluent P level which is discharged to the waterbody would likely be maintained at the 1 mg P/ℓ standard rather than below it. Thus, this combined strategy would not likely significantly improve eutrophication-related water quality beyond that achieved by a 1 mg P/ℓ effluent standard alone.

Summary and conclusions

The OECD eutrophication modelling approach is a proven tool available to the water quality manager to estimate the impact of phosphorus load reductions on eutrophication-related water quality for most waterbodies. Other approaches sometimes used for attempting to make such assessments, such as dynamic ecosystem models, or other empirical models (e.g., Larsen and Mercier, 1976; Dillon and Rigler, 1974) do not have demonstrated predictive capabilities and are based on a much narrower range of waterbody types. The OECD modelling approach appears to be applicable to South African waterbodies in general and Roodeplaat Dam in particular. Using this approach, it appears that the enforcement of the 1 mg P/ℓ effluent standard would improve the usability of Roodeplaat Dam. The importance of adopting this standard becomes even greater when the possible WWTP-2 effluent discharge is considered.

Because Roodeplaat Dam has a substantial P loading from domestic wastewater treatment plants, it is possible that a detergent P ban could effect a noticable improvement in its eutrophication-related water quality. However, since the 1 mg P/ℓ standard has already been established for this, one of the sensitive areas, the appropriateness of adopting a detergent P ban in parallel with this P limiting strategy should be critically evaluated.

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