Eutrophication control: a look into the future

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Abstract

Eutrophication causes serious water quality problems in some South African impoundments, and it is intended that the situation be alleviated by introducing a 1 mg P/ℓ effluent standard in sensitive catchments. An evaluation of the impact of this standard and other phosphate control measures, e.g. the restriction of the phosphate content of detergents, on the trophic status of 19 South African impoundments was made by using the OECD eutrophication modelling approach for predicting, over the next two decades, the trophic response of the water bodies to nutrient loads.

The predicted percentage time that severe nuisance conditions (chlorophyll concentrations exceeding 30 mg/m^3) can be expected, was used as criterion of the trophic status of impoundments. Predications showed that the trophic status of five impoundments is likely to remain acceptable until the year 2000 and no eutrophication control is required for them before that time. The trophic status of a further five impoundments was predicted to be marginal with the result that the effect of the phosphate standard on their trophic status can be expected to be only marginal. The trophic status of the remaining nine impoundments is either unacceptable, or is predicted to be unacceptable by the year 2 000. Although these impoundments are expected to respons to the phosphate standard, an even stricter standard than 1 mg P/ℓ might be necessary in some cases to ensure an acceptable trophic status. A ban on phosphate based detergents is unlikely to succeed in controlling eutrophication. Nevertheless, control of detergent phosphates may play a supporting role in a strategy to reduce phosphate loads on the water environment.

The limitations of the OECD eutrophication modelling approach, the data base used for the predictions and research priorities, are discussed.

Introduction

The enrichment of water bodies with plant nutrients, a process referred to as eutrophication, has developed into a serious water quality problem throughout the world (Jones and Lee, 1982; Vollenweider, 1981) and in South Africa (Toerien *et al.*, 1975; Toerien, 1977; Walmsley and Butty, 1980). The excessive growth of phytoplankton and/or macrophytes that occurs as a consequence of eutrophication, leads to many water quality problems e.g. increased water purification costs, interference with recreational uses of impoundments, loss of livestock, increased concentrations of trihalomethane precursors and possible sublethal effects of algal toxins on humans using eutrophic water supplies for drinking water (Toerien, 1977; Suess, 1981; Vollenweider, 1981; Jones and Lee, 1982; Falconer *et al.*, 1983; Walker, 1983).

Limiting water fertility, preferably by controlling phosphate, is generally regarded to be the most desirable eutrophication control strategy (Toerien, 1977). In cases of very large nutrient loads on impoundments sufficient nutrient reduction may not be feasible and additional control measures must then be considered (Benndorf *et al.*, 1981). The first step to control eutrophication of South African impoundments was taken recently. Legislation which limits the phosphate concentration in treated domestic and industrial wastewater discharged in specified sensitive catchments to 1 mg/ℓ dissolved ortho-phosphate (expressed as P), will be in effect by August 1985. Other ancillary phosphate control measures are now being considered, e.g. reducing the phosphorus content of synthetic detergents and introducing stricter phosphate standards for effluents. The 1 mg P/ℓ standard was selected after an assessment of the technical and economic feasibility of phosphate removal technology available at the time the standard was promulgated (Tayler *et al.*, 1984). The standard was predicted to result in 80 to 90 per cent reduction in the phosphate load from sewage works, which were estimated to contribute 60 to 80 per cent of the total phosphate load on the water environment. Considerable beneficial effects on the water quality of impoundments in catchments where the standard is to be introduced, were expected (Taylor *et al.*, 1984).

The decision to introduce a universal standard of 1 mg P/ℓ for all sensitive catchments, is being criticised on the grounds that the differences in phosphate-receiving capacity of impoundments have been ignored (Pretorius, 1983; Toerien, 1984) and that in some catchments the contribution from non-point sources has been so high that removal of phosphate from point sources would have negligible effects on the trophic status of impoundments (Pretorius, 1983). In such catchments, uncertainty about the benefits that would result from introducing the standard and the high cost of compliance with it, do not warrant its enforcement on small local authorities (Pretorius, 1983). However, personnel of the Department of Water Affairs responsible for water pollution control, have indicated that some of these criticisms may be considered when the standard is implemented, but that final decisions about the enforcement of the standard will be based on a quantitative assessment of the impact on the trophic status of individual impoundments (Claassens, 1984). To date no such estimates have been made.

This paper provides a summary of the findings of a research programme which was designed to assess the impact of various phosphate control measures on the trophic status of South African impoundments.

Methods

Data base

The data base consisted of river flow data provided by the Department of Water Affairs, as well as phosphate, nitrogen and chlorophyll concentrations in rivers and impoundments provided by the Department of Water Affairs and by various other research organisations and individuals. More information on the data base is available in a report by Grobler and Silberbauer (1984a).

The impact of eutrophication control on the trophic status was predicted for 19 impoundments (Fig. 1), selected on the basis

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Received 6 August 1984.

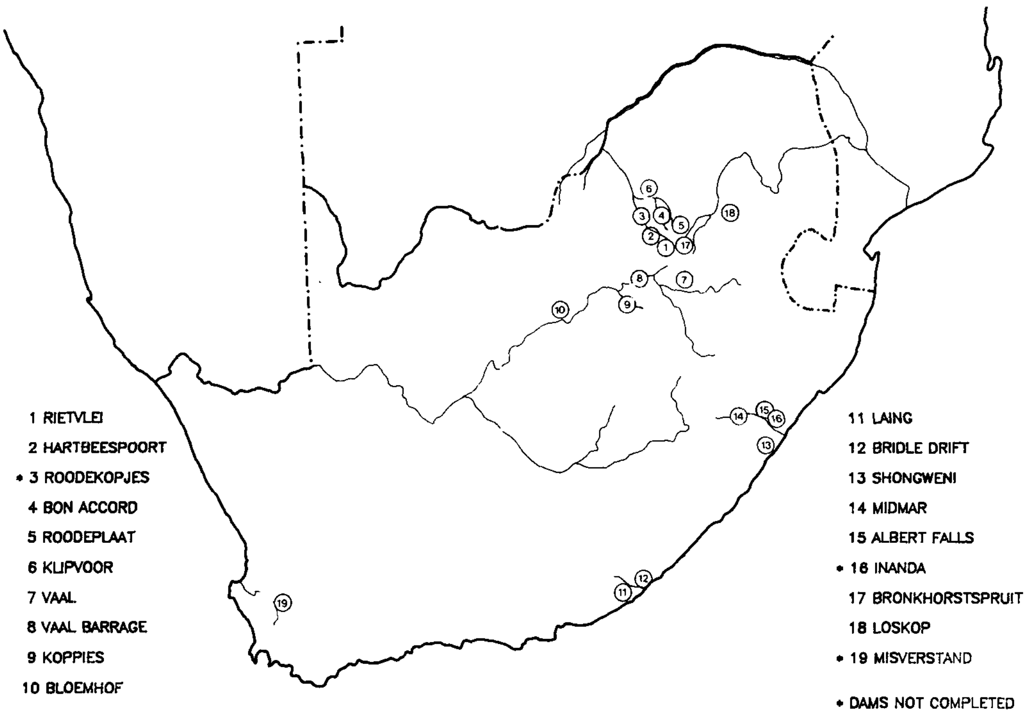

Figure 1
A map of South Africa showing the locality of the nineteen impoundments for which the impact of eutrophication control measures is predicted.

that sufficient data were available and that they were located in sensitive catchments.

Appropriate water quality variables

Reckhow and Chapra (1983) defined quality variables of concern (QVC's) as those variables that determine the usefulness of a water body for whatever purpose it is meant to be used. A QVC is therefore an appropriate variable to measure when considering the eutrophication response of a water body. Ideally a study of this nature should utilize a clearly defined QVC to evaluate the impact of different phosphate control strategies on the trophic status of impoundments. Most eutrophication-related water quality problems (and those potentially most serious e.g. blooms of toxic algae) result from the occurrence of undesirable quantities of phytoplankton in the water (Jones and Lee, 1982; Toerien, 1977).

It was decided to base the QVC for this study on chlorophyll-dependent variables because chlorophyll concentrations are the most commonly used measure of phytoplankton biomass. The following could equally as well have been chosen: total phosphate concentrations, rate of oxygen depletion in the hypolimnion, water clarity or fish yield (Jones and Lee, 1982). However, total phosphate *per se* does not adversely affect water quality, the usefulness in South African impoundments of the rate of oxygen depletion has been queried (Walmsley and Toerien, 1977), reduced water clarity in South African impoundments results also from suspended clay and not only from eutrophication (Noble and Hemens, 1978; Walmsley and Bruwer, 1980) and quantified fish yields for South African impoundments are available in only a few cases. For these reasons, none of these characteristics were considered as suitable QVC's.

QVC's related to chlorophyll concentrations can be defined in many ways depending on the specific management and planning objectives. Walmsley and Butty (1980) and Walmsley (1984) have emphasised the importance of providing an indication of how much of the time one can expect nuisance conditions in an impoundment. Walmsley (1984) developed a set of empirical equations for estimating the percentage of time that chlorophyll concentrations would fall into each of the following four chlorophyll concentration ranges with the indicated nuisance conditions:

0-10 mg Chl/m^3 – no problems encountered
10-20 mg Chl/m^3 – algal scums present
20-30 mg Chl/m^3 – nuisance conditions
$>$30 mg Chl/m^3 – severe nuisance conditions

The percentage time that chlorophyll concentrations exceed 30 mg/m^3 and consequently result in severe nuisance conditions (SNC), was selected for evaluating the consequences of the alternative phosphate control strategies. This was done because, firstly, it relates chlorophyll concentrations to the occurrence of problem conditions and, secondly, the concept is likely to be better understood by decision makers.

The mean annual phosphate concentration in impoundments was used for demonstrating the consequences of runoff extremes and the N:P mass ratio for determining whether nitrogen, rather than phosphate, was limiting the trophic response of impoundments.

Uncertainty associated with predictions

In the absence of formal error analysis it was assumed that the uncertainty associated with QVC is such that predicted QVC's had to differ by at least 20 units (% time SNC were expected) from the initial condition to ensure a reasonable chance that the predicted change would be realised. The following criteria were used to judge which predicted changes were likely to be perceptible: changes amounting to less than 20 units in the value of QVC were regarded as imperceptible; the perceptibility of changes from 21 to 40 units was regarded as marginal; and changes greater than 41 units were regarded as definitely perceptible.

The lower limit of QVC, which would suggest that no eutrophication control measures need to be introduced, was also set in an arbitrary manner. Taking into account that many of the assumptions were conservative (they represented the worst case), it was assumed that if the absence of phosphate control resulted in SNC being predicted for 20% or less of the year, then control would not be needed. If no phosphate control resulted in SNC being expected for 20 to 40% of the time, then control might be required, and if SNC were predicted to occur for more than 40% of the time, it would warrant the introduction of phophate control measures.

Eutrophication modelling approach

The OECD eutrophication modelling approach (Vollenweider *et al.*, 1980) was selected to simulate the impact of eutrophication control measures on impoundment trophic status, because for management purposes it is a proven and reliable approach to modelling eutrophication-related water quality (Jones and Lee, 1982; Lee and Jones, 1982; Reckhow and Chapra, 1983; Walmsley and Thornton, 1984). The OECD modelling approach was developed using an extensive data base covering a wide variety of impoundments in many parts of the world (Jones and Lee, 1982), it is easy to apply and has modest data requirements.

Total phosphate loads on impoundments were estimated as the sum of loads derived from point and non-point sources. Loads derived from point sources were predicted using information provided by the Division of Water Pollution Control of the Department of Water Affairs (Grobler and Silberbauer, 1984a). Loads derived from non-point sources were estimated using formulae which relate export to runoff (Grobler and Silberbauer, 1984b; Grobler, 1985).

Phosphate concentrations in impoundments were calculated with a phosphate budget model that was modified to reflect the higher phosphate sedimentation rates in South African impoundments (Grobler and Silberbauer, 1984a)

$$[P] = W_p/(Q + s_p.V) \quad (1)$$

where

$[P]$ = in-lake phosphate concentration
W_p = phosphate load on the impoundment
Q = inflow
V = volume
s_p = phosphate sedimentation rate (a value of 2,9 was used)

Nitrogen concentrations were simulated with a nitrogen budget model (Bachman, 1980):

$$[N] = W_n/(Q + S_n.V) \quad (2)$$

where

$[N]$ = in-lake nitrogen concentration
W_n = nitrogen load on the impoundment
S_n = nitrogen attenuation coefficient

Most South African impoundments respond in the same way as other water bodies with respect to chlorophyll-phosphate relationships (Grobler and Silberbauer, 1984a). Mean chlorophyll concentrations were estimated as a function of phosphate concentrations using the OECD chlorophyll:phosphate relationship (Jones and Lee, 1982; Rast *et al.*, 1983).

$$[Chl] = 0{,}45\,[P]^{0{,}79} \quad (3)$$

where

$[Chl]$ = mean chlorophyll concentration

The percentage time that chlorophyll concentrations were expected to exceed 30 mg/m³ and consequently result in severe nuisance conditions being experienced, was estimated as (Walmsley, 1984)

$$F = 1{,}19\,(\text{mean chlorophyll}) - 5{,}36 \quad (4)$$

where

F = the frequency of occurrence of severe nuisance conditions, expressed as a percentage of the year.

Scenarios simulated

Various scenarios were devised combining possible hydrological regimes with the phosphate control options likely to be exercised during the two decades from 1981 to 2000. The steady-state assumption of the OECD nutrient budget model requires that runoff and water levels are assumed to be constant. The mean annual runoff (MAR) for the catchment in which an impoundment is situated was chosen as standard runoff and the corresponding annual mean water level was set at 80% of the full supply volume of the impoundments.

No phosphate reduction measures applied

One of the options open to the water resources manager, faced with the problem of controlling eutrophication, is to not introduce any phosphate reduction measures. There may be valid reasons for selecting this option, e.g. either there may be so few sources of pollution that their combined effect is negligible or, there may be so many uncontrollable sources of pollution that restrictions would be ineffective.

Effluents complying with set phosphate standards

Complying to a 1 mg P/ℓ standard for 95 per cent of the time would require mean annual effluent concentrations to be much lower than 1 mg P/ℓ (Water Research Commission, 1984). It was therefore decided to select different effective point source effluent concentrations, e.g. 1,0; 0,5 and 0,1 mg P/ℓ to predict the effects of the promulgated and more stringent standards.

Detergent phosphate restriction

Phosphate derived from detergents is responsible for 30 to 50 per cent of the total phosphate load on sewage treatment works (Heynike and Wiechers, 1984), thus phosphate export from catchments can be controlled by limiting the amount of phosphate in detergents, rather than removing phosphate from sewage effluents (Pretorius, 1983). The effects of such a strategy were investigated by assuming that 50, 80 or 100% of the phosphates in detergents were removed and predicting the effect this had on the trophic response of selected impoundments.

Nitrogen limitation

Predictions of the trophic status of impoundments were based on the OECD chlorophyll-phosphate relationship, which assumes phosphate limitation. However, because nitrogen limited impoundments are unlikely to respond in the same manner to phosphate control than phosphate limited ones, the possibility of nitrogen limitation controlling the trophic response impoundments was investigated. Nitrogen and phosphate concentrations were simulated for three impoundments likely to be nitrogen limited, i.e. Rietvlei, Roodeplaat and Hartbeespoort Dams.

Extremes in runoff conditions

Grobler (1984) showed that runoff affects nutrient loads derived from non-point sources, water levels in reservoirs and their flushing rates (water retention times), which all determine the response of impoundments to phosphate control. Because South African hydrology is so variable (Schulze and McGee, 1978; Braune and Wessels, 1980; Braune and Visser, 1981) it was decided to evaluate the effect of extreme runoff conditions on the impact of phosphate control measures on the trophic status of reservoirs. The effect of runoff was demonstrated by assuming that a 1 mg P/ℓ standard is applied and that annual runoff varied from 10% to 200% of the MAR. Average water levels in the impoundments were assumed to be either a linear function of runoff, if runoff was lower than 120% of the MAR, or to be equal to the full supply capacity for greater runoff.

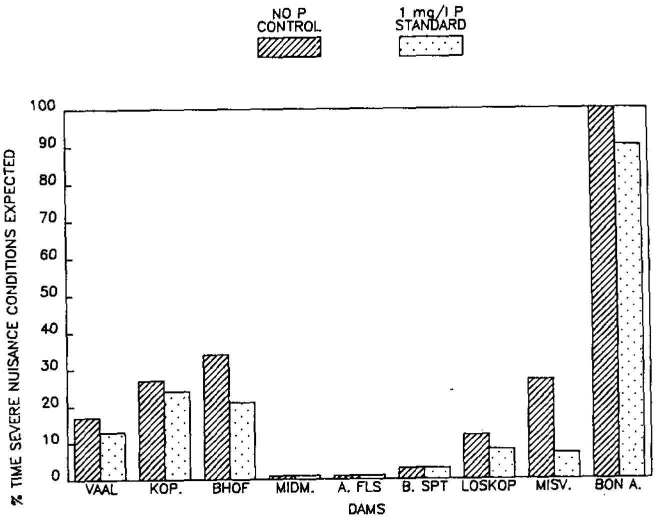

Figure 2
The predicted impact of no phosphate control and introducing a 1 mg P/ℓ standard on the percentage time severe nuisance conditions can be expected by the year 2000 in Vaal, Koppies, Bloemhof, Midmar, Albert Falls, Bronkhorst Spruit, Loskop, Misverstand and Bon Accord Dams.

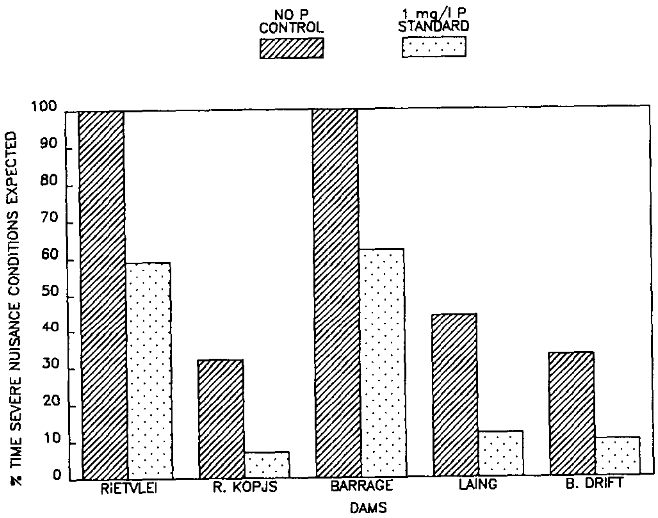

Figure 3
The predicted impact of no phosphate control and introducing a 1 mg P/ℓ standard on the percentage time severe nuisance conditions can be expected by the year 2000 in Rietvlei, Roodekopjes, Vaal Barrage, Laing and Bridle Drift Dams.

Results

No eutrophication control

Based on their predicted responses in the year 2000, assuming that no eutrophication control was applied, the impoundments were divided into the following three groups:

- Vaal, Midmar, Albert Falls, Bronkhorst Spruit and Loskop Dams. They would experience SNC for less than 21% of the year and therefore eutrophication control measures are not warranted in their catchments.

- Roodekopjes, Koppies, Bloemhof, Bridle Drift and Misverstand Dams. They would experience SNC for 21 to 40% of the time and the introduction of phosphate control measures in their catchments may, therefore, result in perceptible changes in trophic status but should be carefully considered in the light of the uncertainty associated with the predictions.

- Vaal Barrage, Rietvlei, Hartbeespoort, Bon Accord, Roodeplaat, Klipvoor, Laing, Shongweni and Inanda Dams. They were predicted to experience SNC for more than 40% of the time if no control is applied.

The impoundments with catchments in the Pretoria-Witwatersrand-Vereniging (PWV) area represented the worst cases. These highly eutrophic impoundments can be expected to respond favourably to the introduction of eutrophication control measures in their catchments, granted that these measures will result in sufficiently large reductions in nutrient loads.

Phosphate standards

The 1,0 mg P/ℓ standard

The impoundments were grouped according to the magnitude of their predicted response by the year 2000 to the introduction of a 1 mg P/ℓ standard. In nine impoundments a less than 21% reduction was predicted in the % time SNC can be expected (Fig. 2); in five impoundments a 21 to 40% reduction was predicted in the % time SNC can be expected (Fig. 3); and in a further five impoundments a greater than 40% reduction was predicted in the % time SNC can be expected (Fig. 4).

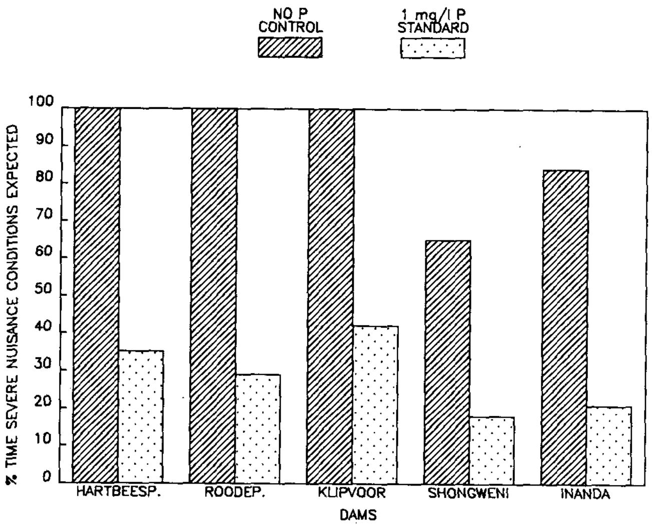

Figure 4
The predicted impact of no phosphate control and introducing a 1 mg P/ℓ standard on the percentage time severe nuisance conditions can be expected by the year 2000 in Hartbeespoort, Roodeplaat, Klipvoor, Shongweni and Inanda Dams.

The reasons for impoundments showing little or no response to the introduction of a phosphate standard were twofold. Firstly, they were not expected to experience SNC for a significant amount of time in the absence of control (e.g. Vaal, Koppies, Bloemhof, Midmar, Albert Falls, Bronkhorst Spruit, Loskop and Misverstand Dams; Fig. 2). Secondly, they were receiving such large phosphate loads that the load reductions, resulting from introduction of the standard, were insufficient to reduce the expected % time SNC by more than 21% (e.g. Bon Accord Dam; Fig. 2). No control is needed for impoundments for which the predicted responses were small, because their trophic status in the absence of phosphate control was low. However, in impoundments where the responses were small because the 1 mg P/ℓ standard was insufficient, either more stringent standards will have to be introduced, or additional eutrophication control measures must be considered.

Impoundments showed a moderate response to the introduction of the standard (Fig. 3), if their trophic status without control was not highly eutrophic (e.g. Roodekopjes, Laing and Bridle Drift Dams), or if they received such large phosphate loads that the control brought about by introducing a 1 mg P/ℓ standard was insufficient to cause a large reduction in their trophic status (e.g. Rietvlei Dam and Vaal Barrage). The % time SNC that could be expected in Roodekopjes, Laing and Bridle Drift Dams may not warrant the introduction of a standard, or, if a standard is introduced, the response of the impoundments may not be perceptible. Rietvlei Dam and Vaal Barrage require more stringent phosphate control measures to ensure a desired response.

Reductions greater than 40% in the % time SNC can be expected were predicted for Hartbeespoort, Roodeplaat, Klipvoor, Shongweni, and Inanda Dams (Fig. 4) and the enforcement of the standard in their catchments is recommended.

The 0,5 and 0,1 mg P/ℓ standards

Vaal Barrage, Hartbeespoort and Bloemhof Dams were selected to demonstrate the effect of more stringent standards on the trophic response of impoundments.

Hartbeespoort Dam represents those impoundments which showed a considerable response to phosphate standards lower than 1 mg P/ℓ as indicated by a greater than 30% reduction in the % time SNC can be expected, as a consequence of lowering effluent phosphate concentrations from 1,0 to 0,1 mg P/ℓ (Fig. 5).

Vaal Barrage (Fig. 5) represents those impoundments on which the phosphate loads are so large that the introduction of a very stringent phosphate standard would be required to reduce the % time SNC can be expected to acceptable levels. SNC were predicted for more than 30% of the time in Vaal Barrage assuming mean effluent concentrations as low as 0,1 mg P/ℓ. However, taking into account that with mean effluent concentrations at 1 mg P/ℓ SNC can be expected to occur for more than 60% of the time, the introduction of more stringent standards in the catchment of Vaal Barrage is warranted. The same conclusion would also apply to Rietvlei and Bon Accord Dams (Fig. 3).

Bloemhof Dam represents those impoundments that showed little response to the introduction of phosphate standards lower than 1 mg P/ℓ (Fig. 5). Mean effluent concentrations of 0,1 mg P/ℓ did not result in perceptible change in the predicted % time SNC can be expected in Bloemhof Dam (or Vaal, Koppies, Midmar, Albert Falls, Bronkhorst Spruit, Loskop and Misverstand Dams; Fig. 2).

In Roodekopjes, Laing and Bridle Drift Dams (Fig. 3) the introduction of more stringent effluent standards prior to the year 2000 would not be warranted because the 1 mg P/ℓ standard reduced the % time SNC to low levels.

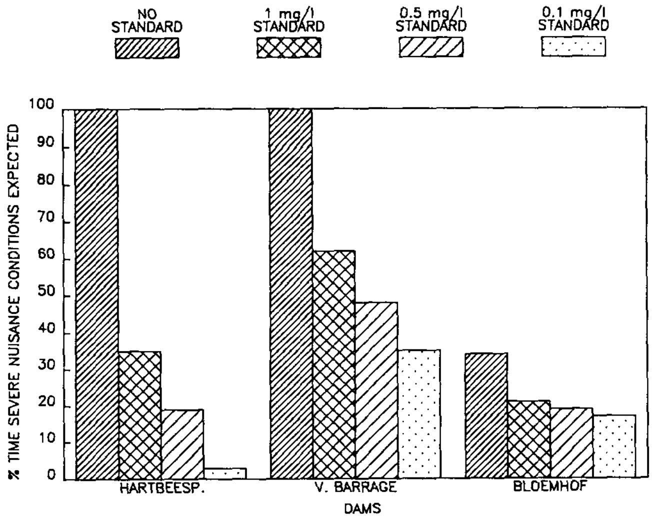

Figure 5
The predicted impact of no phosphate control and introducing 1,0; 0,5 and 0,1 mg P/ℓ standards on the percentage time severe nuisance conditions can be expected by the year 2000 in Hartbeespoort Dam, Vaal Barrage and Bloemhof Dam.

Detergent phosphate control

The effects of a eutrophication control strategy based on controlling detergent phosphate, rather than reducing the phosphate content of effluents, were demonstrated for Hartbeespoort Dam (which showed a marked response to the introduction of phosphate standards), Vaal Barrage (intermediate response to introduction of standards) and Vaal Dam (which showed little response to introduction of standards). The effects of different levels of detergent phosphate control, i.e. reducing the phosphate content of detergents by 50, 80 and 100%, were investigated. Comparison of detergent phosphate removal with no eutrophication control (Fig. 6) showed that even 100% detergent phosphate removal had no perceptible effect on the predicted trophic status of the impoundments. It is expected that this conclusion will apply to most impoundments and it is suggested that, in South Africa, eutrophication cannot be controlled by controlling detergent phosphates alone. Nonetheless, control of detergent phosphates could reduce the total phosphate load on the water environment and may play a supporting role in a strategy to control eutrophication.

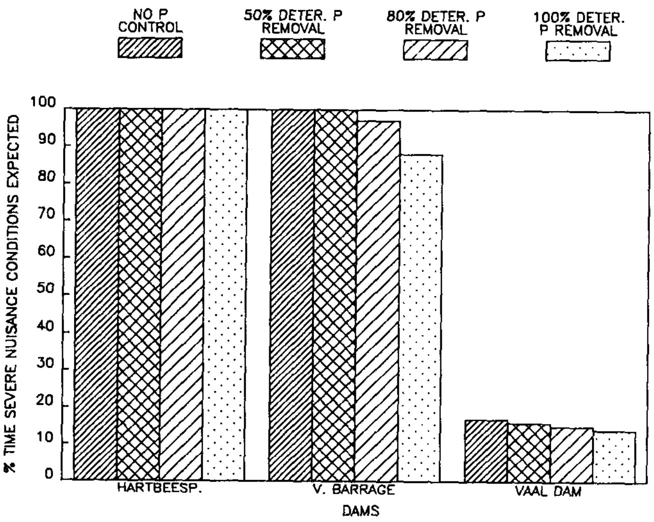

Figure 6
The predicted impact of no phosphate control and 50, 80 and 100% removal of detergent phosphate on the percentage time severe nuisance conditions are expected by the year 2000 in Hartbeespoort Dam, Vaal Barrage and Vaal Dam.

Nitrogen limitation

Nitrogen, and not phosphate, may sometimes control the trophic response of impoundments (Ashton, 1981). The three impoundments most likely to be N-limited namely Rietvlei, Hartbeespoort and Roodeplaat Dams, were selected for this investigation. N:P ratios before the introduction of phosphate control measures (1981) were considerably below the balanced ratio of 7:1 (Fig. 7). After the introduction of control measures (1990, 2000) the predicted N:P ratio in Hartbeespoort and Roodeplaat Dams was greater than 7:1, thus indicating that these impoundments can be expected to become phosphate limited. In Rietvlei Dam the N:P ratio would be only about 6:1 and 5:1 (by 1990 and 2000 respectively), which is close to the balanced ratio of 7:1.

The expected increase in effluent volumes from 1990 to 2000 resulted in the N:P ratios decreasing again (Fig. 7). It can, however, be expected that by the time phosphate loads have increased to levels where nitrogen may again become limiting, the trophic status of impoundments would be such that additional phosphate control measures would be required to prevent excessive eutrophication.

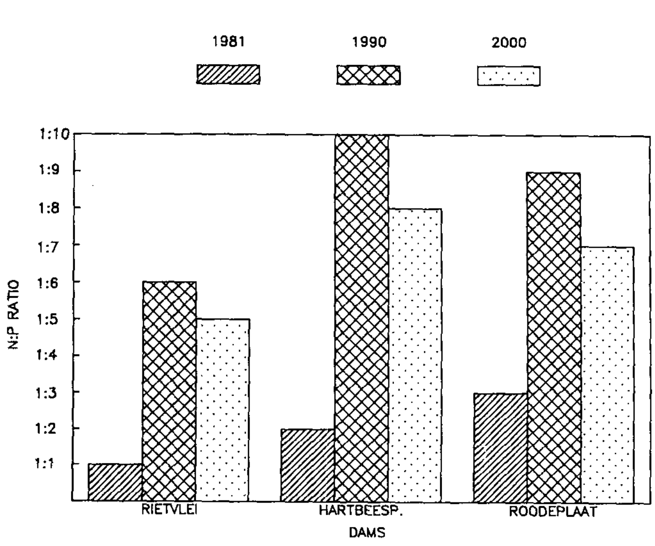

Figure 7
The predicted impact of introducing a 1 mg P/ℓ standard in 1985 on N:P ratios in Hartbeespoort, Roodeplaat and Rietvlei Dams.

It is concluded that the introduction of phosphate control measures resulting in mean effluent concentrations equal to or lower than 1 mg P/ℓ, will result in phosphate being the limiting nutrient in most impoundments, even in those which are now nitrogen limited. The authors are therefore fairly confident that the response of impoundments will adhere to the OECD chlorophyll-phosphate relationship used in this study.

Effect of runoff

Runoff affects phosphate loads derived from non-point sources, water levels in impoundments and their flushing rates (Grobler and Silberbauer, 1984b). The combined effects of runoff (expressed as a fraction of the MAR) and changing point source phosphate loads on phosphate concentrations in impoundments, are shown for Hartbeespoort Dam, Vaal Dam and Vaal Barrage (the effect of the standard coming into effect and increasing effluent volumes can be seen along the time axes) (Figs. 8 to 10).

Phosphate concentrations in Hartbeespoort Dam and Vaal Barrage, both dominated by very large point source loads, were predicted to respond in a similar manner to runoff. The effect of increased runoff was to lower (by dilution) the phosphate concentrations in these impoundments. This effect was more obvious if the point source loads were large, e.g. increased runoff from 0,1 to 2 MAR before the point source loads were reduced by introducing the standard (conditions in 1985) resulted in reductions of 21% (Hartbeespoort Dam) and 79% (Vaal Barrage) in the predicted phosphate concentrations. Compared to that, a similar increase in runoff, but with smaller point source loads, (conditions in the year 2000) reduced predicted phosphate concentrations only by 8% (Hartbeespoort Dam) and 67% (Vaal Barrage).

There was an inverse relationship between response and runoff and it was more obvious for Vaal Barrage (which has a high flushing rate) than for Hartbeespoort Dam. For example, if runoff was assumed to be low (0,1 MAR) predicted phosphate

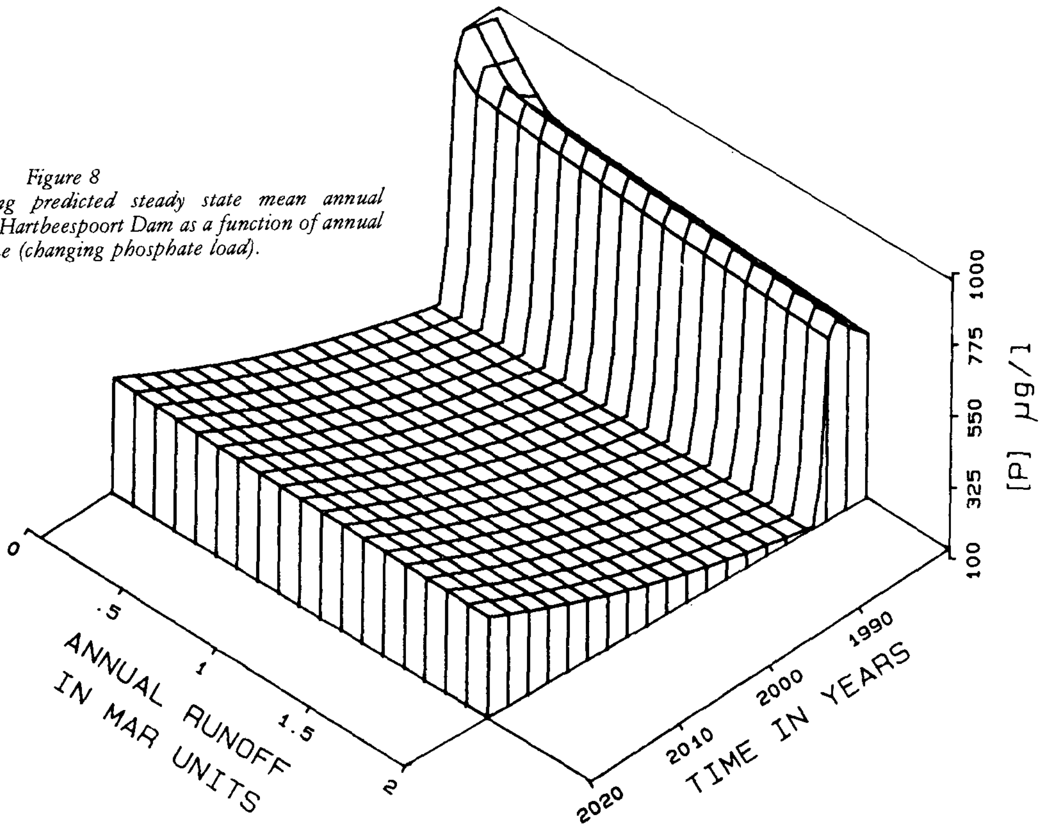

Figure 8
A response surface showing predicted steady state mean annual phosphate concentrations in Hartbeespoort Dam as a function of annual runoff and time (changing phosphate load).

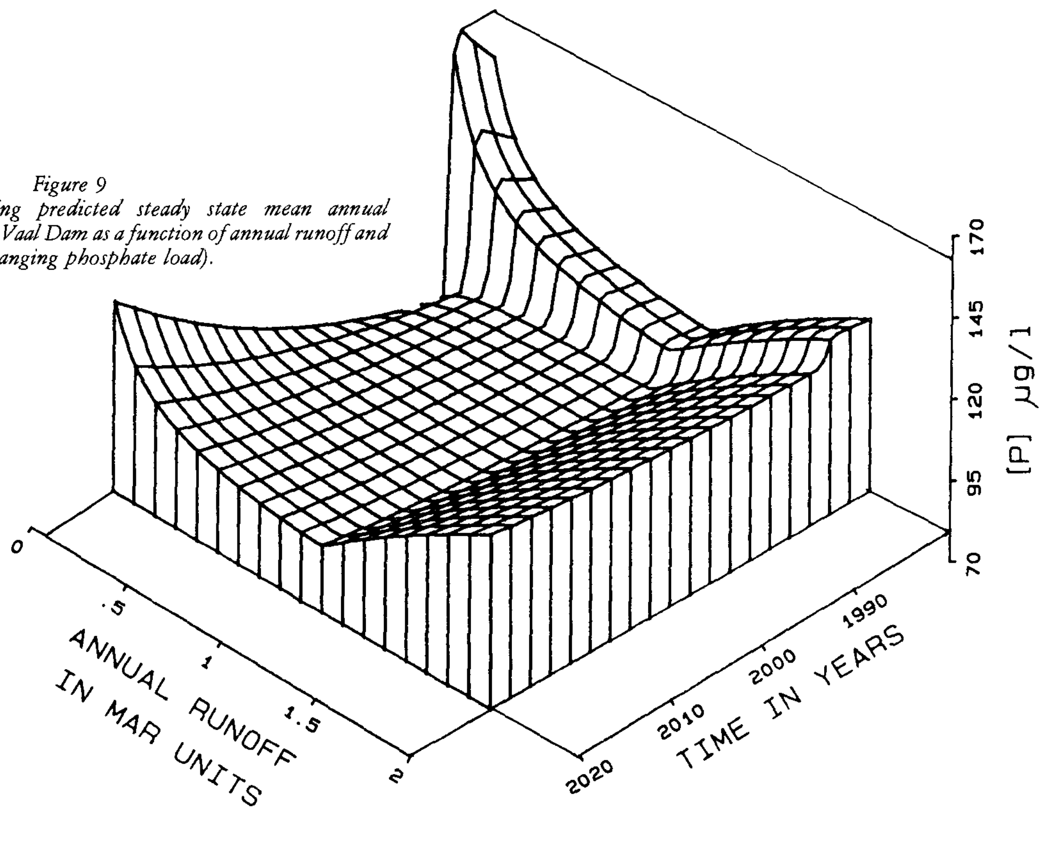

Figure 9
A response surface showing predicted steady state mean annual phosphate concentrations in Vaal Dam as a function of annual runoff and time (changing phosphate load).

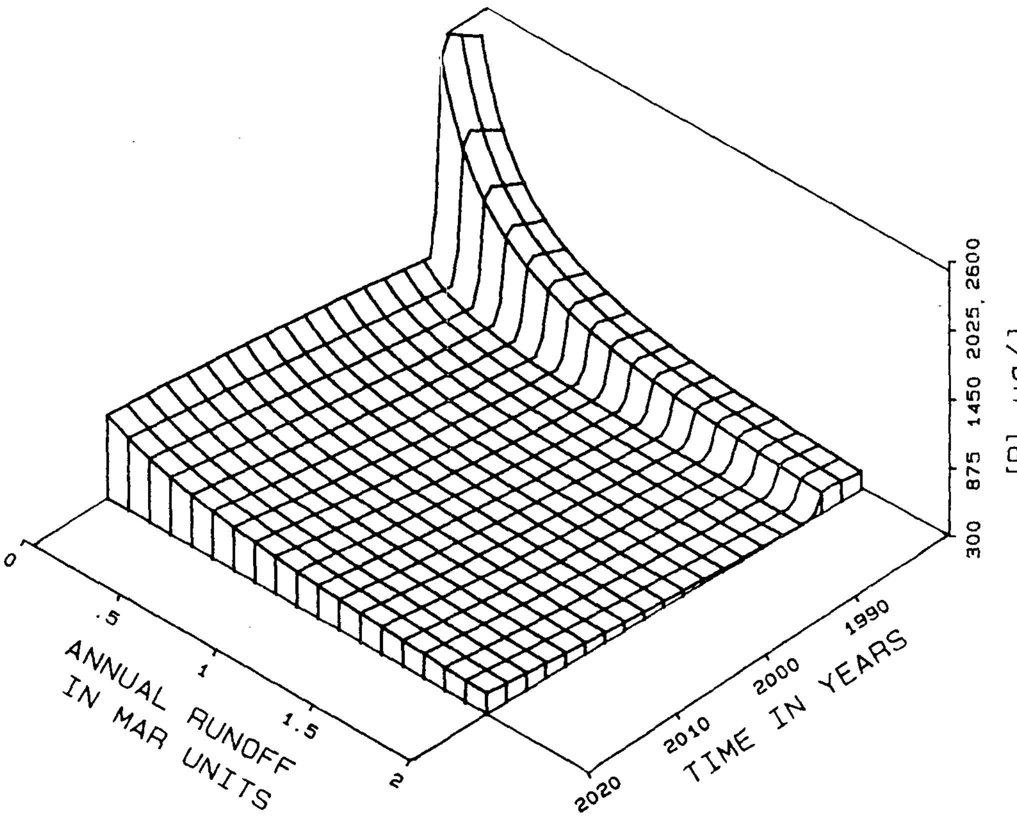

Figure 10
A response surface showing predicted steady state mean annual phosphate concentrations in Vaal Barrage as a function of annual runoff and time (changing phosphate load).

concentrations were lowered by 74% (Hartbeespoort Dam) and 65% (Vaal Barrage) as a result of introducing the standard (comparing 1985 with 2000) whereas, when runoff was assumed to be large (2 MAR), predicted phosphate concentrations were lowered by 70% in Hartbeespoort Dam and only by 25% in Vaal Barrage.

Vaal Dam (Fig. 10) represents systems in which phosphate loads derived from non-point sources play an important role and sometimes dominate the response of impoundments. At low runoff (0,1 MAR), point sources contributed significantly to the total load and consequently, the introduction of the phosphate standard resulted in a noticeable (43%) decrease in the predicted phosphate concentrations (comparing 1985 and 2000). However, as runoff increased the loads derived from non-point sources increased, thereby decreasing the proportional contributions from point sources to the total load, until, at runoff equal to 2 MAR, the introduction of the standard resulted in only a 5% reduction in predicted phosphate concentrations. An unusual feature of Vaal Dam's response to runoff was the minimum in the predicted phosphate concentrations observed when runoff was assumed equal to 1 MAR. This represented the point at which dilution of loads derived from point sources, as a result of larger runoff, was being cancelled by the increase in loads derived from non-point sources.

These results demonstrate that the steady state assumption for the OECD modelling approach imposes a serious limitation on the utility of the model as a management tool. Runoff in South Africa is highly seasonal and highly variable (Schulze and McGee, 1978; Braune and Wessels, 1980) and it is now demonstrated that it has an important effect on the impact of phosphate control measures on the trophic response of impoundments. Better predictions should be possible with a model avoiding the steady state assumption.

Discussion

The impact of the phosphate standard

The promulgation of a 1 mg P/ℓ standard was based on the assumption that implementation of the standard in the designated sensitive catchments will cause a considerable improvement in water quality. The results given here support this expectation for eight of the 19 impoundments studied. Rietvlei, Hartbeespoort, Bon Accord, Roodeplaat, Klipvoor, Vaal Barrage, Shongweni and Inanda Dams were predicted to be so eutrophic by the year 2000 that they would definitely require eutrophication control measures in their catchments. In two of these impoundments phosphate standards resulting in mean effluent concentrations as low as 0,5 (Vaal Barrage) and 0,1 mg P/ℓ (Bon Accord) would be required to have a noticeable effect on water quality. In the others mean effluent concentrations of 1 mg P/ℓ will bring about a considerable improvement in water quality.

In the rest of the impoundments the introduction of the phosphate standard was predicted to have only a marginal effect, or none at all, on eutrophication-related water quality. This is because one of the assumptions on which the standard was based, namely that 60% to 80% of the total phosphate load originates from point sources, was not valid in their cases. Five of the impoundments studied (Vaal, Midmar, Albert Falls, Bronkhorst Spruit, and Loskop Dams) received such small loads, that they require no eutrophication control measures. In the remainder (Roodekopjes, Koppies, Bloemhof, Laing, Bridle Drift and Misverstand Dams) a certain degree of eutrophication is expected by the year 2000. However, the proportion of the total phosphate load that is controllable at point sources is so small, that in three of them (Roodekopjes, Laing and Bridle Drift) the standard is expected to have only marginal effects and in the others (Koppies, Bloemhof and Misverstand Dams) it is expected to have no effect.

A uniform standard for sensitive catchments

Pretorius (1983) and Toerien (1984) doubt the wisdom of applying a uniform phosphate standard in all sensitive catchments. They argue that differences in the capacity of impoundments to absorb phosphate loads and the small contributions made by point sources to total loads in some of the sensitive catchments, have been ignored. Results in this paper support these arguments. In some systems the capacity of reservoirs to absorb phosphate will be exceeded many times by the expected phosphate loads and standards resulting in mean effluent concentrations of 0,5 mg P/ℓ, or less, would be required to bring about a perceptible change in the trophic status of such impoundments (e.g. Bon Accord and Vaal Barrage). In other systems the carrying capacity of the impoundments is such that a mean effluent concentration of 1 mg P/ℓ will bring about perceptible changes (e.g. Roodeplaat, Hartbeespoort and Shongweni Dams). Some systems, such as Bloemhof Dam, have a considerable reserve capacity to absorb phosphate and therefore it is unlikely that the introduction of a standard will bring about a perceptible change in their trophic status.

The introduction of a uniform standard is clearly not the best strategy for controlling eutrophication. It is therefore recommended that consideration should be given to imposing more stringent limits in some catchments and relaxing the present standard in others.

Detergent phosphate ban versus treatment of effluents

Different options for combining detergent phosphate removal and phosphate removal from effluents into a phosphate control strategy are available (Pretorius, 1983; Heynike and Wiechers, 1984). In this study only the ends of the scale were compared, i.e. detergent phosphate removal alone versus effluent treatment alone. The treatment of effluents was more effective because enforcing a 1 mg P/ℓ standard will bring about a 80 to 90% reduction in the phosphate load from sewage works. Detergents are responsible for only 30 to 50% of the phosphate reaching sewage works (Heynike and Wiechers, 1984) and consequently, even a total ban on detergent phosphate can reduce the phosphate load at most by 30 to 50%, which is not enough to bring about perceptible changes in the water quality of highly eutrophic systems. Of the two strategies, only effluent treatment is predicted to be a satisfactory phosphate control measure.

Application of the results

This study was a first attempt at quantifying the impact of phosphate control measures on impoundments in sensitive catchments. As such it may serve as a guide to water resources managers. However, users are cautioned to carefully scrutinise all the assumptions made (Grobler and Silberbauer, 1984a) and to make sure that they are valid for the specific application. It is therefore recommended, that for decisions about the application of the standard in individual cases, renewed efforts should be made to obtain all the relevant data and to use these to verify assumptions and to update predictions of the response of impoundments to the proposed control measures.

A phosphate budget model which avoids the steady state assumption and which employs a more realistic sedimentation submodel, has been developed (Grobler, 1985). From preliminary studies it is recommended that in future this model should be used for predicting the response of impoundments to phosphate control measures, because it allows the effect of variable runoff to be taken into account.

Research needs

A uniform QVC was used to assess the trophic response of impoundments whereas in reality different QVC's, depending on water use and present trophic status of the impound, should be used. Renewed efforts must be made to stimulate research directed at establishing quantitative relationships between eutrophication-related QVC's and eutrophication-related water quality problems associated with water purification (e.g. increased use of chemicals and reduced filter runs), health (e.g. occurrence of trihalomethanes and *Microcystis* toxins in drinking water) and aesthetics (e.g. the occurrence of hyperscums on impoundments).

The uncertainty associated with predictions was not quantified and because this is important for management, an error analysis procedure for the OECD modelling approach as applied to South African impoundments should be developed.

Several shortcomings of the OECD eutrophication modelling approach emerged during its application in this study (Grobler and Silberbauer, 1984a). The most important ones are those associated with the assumptions of steady state and a fixed sedimentation rate for the OECD phosphate budget model. There are clear indications that most South African impoundments are river-run systems, which typically have strong gradients in nutrient and chlorophyll concentrations between the inlet and the outlet. They also have fairly uniform, but short, water residence times and experience considerable variation in their water levels. These characteristics of South African reservoirs render the assumptions of steady state and a fixed sedimentation rate invalid. Investigation of ways to accommodate the effects of hydrological variability in the OECD phophate budget model, without doing away with its essential simplicity, should be encouraged.

Conclusions

- The impact of the phosphate standard for sensitive catchments on the trophic status of impoundments was predicted to be large in eight, marginal in three and imperceptible in eight of the 19 impoundments studied.

- There is no justification for a uniform phosphate standard for all sensitive catchments. In some cases (e.g. Bon Accord and Vaal Barrage) more stringent standards will be required whereas in other cases no eutrophication control will be required.

- A phosphate control strategy based on treatment of effluents to comply with a specified standard is expected to control eutrophication effectively, whereas a strategy based only on a ban of phosphate based detergents is not.

- It is predicted unlikely that, after the introduction of phosphate control measures, impoundments will be nitrogen limited.

- Hydrological regime (above or below average runoff, varying water levels and varying loads derived from non-point sources) has a marked effect on the predicted response of impoundments. This suggests that the steady state assumption of the OECD phosphate budget model may seriously limit its applicability to South African impoundments.

Acknowledgements

This research was funded by the Water Research Commission, the University of the Orange Free State and the Department of Water Affairs. Data were provided by the Department of Water Affairs, the National Institute for Water Research and the Institute of Freshwater Studies at Rhodes University.

The contributions of E. Braune, H. Best, C. Bruwer, G. Claassens, M. Oliveira, R. Walmsley and H. Wiechers, members of the Steering Committee for this research project, are gratefully acknowleged.

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