Phosphorus budget models for simulating the fate of phosphorus in South African reservoirs

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Abstract

Steady state and dynamic P budget models were compared for their ability to simulate the fate of P in three reservoirs for which good data bases are available. The dynamic P budget models were best able to simulate the fate of P in reservoirs experiencing highly variable hydrological conditions. The specific sedimentation submodel employed in the P budget models played an important role in the ability of the models to simulate the fate of P in reservoirs. The OECD P budget model in which the P sedimentation rate is estimated as a function of the water residence time was found to overestimate P concentrations in all the reservoirs and it is recommended that this model should not be used for South African reservoirs. If a steady state model has to be used, a P budget model employing a constant sedimentation rate of 3,5 a^{-1} should be used. If the available data allow it, a dynamic P budget model employing a variable P sedimentation rate, which is a function of the inlake P concentration, should be used for simulating the fate of P in South African reservoirs. It was shown that a major limitation of all the P budget models compared in this study is their inability to simulate the fate of P in reservoirs in which internal processes, rather than inflow, are largely responsible for the P in the reservoir.

Introduction

Eutrophication of reservoirs, which causes many water quality problems (Walker, 1983), is now accepted as a serious threat to water quality in South Africa. A 1 mg P/ℓ standard for wastewater effluents discharged to sensitive catchments will be enforced from August 1985 as a first step to control the eutrophication of South African reservoirs (Taylor *et al.*, 1984). Although a universal standard was promulgated to avoid the legal and administrative difficulties involved with enforcing a variable standard, the stated policy of the Division of Water Pollution Control of the Department of Water Affairs is to base their P control strategy on the carrying capacity of the water environment (Best, 1984). Implementation of this policy requires the ability to predict the trophic status of reservoirs in response to altered phosphorus loading rates.

South Africa has a semi-arid climate with the result that reservoirs are subjected to highly variable hydrological conditions. Both steady state and dynamic total phosphorus (P) budget models, each with different P sedimentation submodels, are currently being used to simulate the fate of P in South African reservoirs.

The OECD eutrophication model (Jones and Lee, 1982) and the reservoir eutrophication model (REM model) (Grobler, 1985) have been used for simulating the trophic status of South African reservoirs (Thornton and Walmsley, 1982; Grobler, 1984; Grobler and Silberbauer, 1984; Jones and Lee, 1984; Grobler, 1985). Both these models use a P budget submodel for simulating the fate of P in reservoirs. Grobler (1984; 1985) has shown that, as a result of the highly variable nature of hydrological variables in semi-arid regions, the P budget submodel employed in the OECD model (because it assumes catchment-receiving waterbodies to be in steady state) is not suitable for simulating the fate of P in South African reservoirs. He developed a dynamic P budget submodel for the REM model to simulate the fate of P in reservoirs and which can account for the hydrological variability.

In simple P budget models sedimentation is usually incorporated to simulate the non-conservative behaviour of P in waterbodies (Reckhow and Chapra, 1983; Kenney, 1983) and various submodels for simulating P losses, other than through the outlet, from a waterbody have been developed (Dillon and Rigler, 1974; Chapra, 1975; Vollenweider, 1976; Clasen, 1981; Frisk, 1981; Walker, 1982; Reckhow and Chapra, 1983; Grobler 1984; Grobler and Silberbauer, 1984). The sedimentation submodel employed in the OECD P budget model results in considerable underestimation of P concentrations in reservoirs (Jones and Bachman, 1976; Clasen, 1981; Higgens and Kim, 1981; Walker, 1982; Grobler and Silberbauer, 1984) and alternative sedimentation submodels for reservoirs have been suggested (Walker, 1982; Grobler, 1984; Grobler and Silberbauer, 1984).

The objective of this study is to compare the steady state P budget model employed in the OECD eutrophication model and the dynamic P budget model employed in the REM model, both using two alternative sedimentation submodels, for their ability to simulate the fate of P in three South African reservoirs.

Specification of the models

The steady state P budget model

The steady state P budget model was derived from the principle of conservation of mass (Vollenweider, 1969; 1975; 1976; Vollenweider *et al.*, 1980; Reckhow and Chapra, 1983) to state the changes in the amount of P stored in a waterbody with time (t) as

$$dP/dt = W - P_{out} - P_{sed} \quad (1)$$

where P is the mass of total phosphorus in the waterbody above the sediments, W the P load (mass/time) entering the waterbody, P_{out} the P lost (mass/time) through the lake outlet and P_{sed} all other losses of P (mass/time), such as irreversible fixation in bottom sediments, which are conve-

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niently described as sedimentation. The steady state P budget model was originally developed for large lakes in the north temperate climatic zone and therefore the following assumptions could be made about the waterbodies involved (Vollenweider, 1975; 1976; Reckhow and Chapra, 1983):

- The catchment-receiving waterbody systems were assumed to be in steady state. Consequently, the inflow to, and outflow from the waterbody could be assumed to be equal and constant in the long term. The mass of P stored in the waterbody above the sediments could also be assumed to be constant with the result that

$$dP/dt = 0 \qquad (2)$$

$$V = \text{constant} \qquad (3)$$

$$Q_{in} = Q_{out} = Q = \text{constant} \qquad (4)$$

where V is the volume of water stored in the waterbody, Q_{in} the inflow (volume/time) to, Q_{out} the outflow (volume/time) from the waterbody and Q the throughflow.

- Waterbodies were assumed to be completely mixed (no large P concentration gradients existed) and consequently the P concentration in the outflow from a waterbody could be assumed to be the same as that in the main waterbody so that

$$P_{out} = (Q/V)P \qquad (5)$$

- Sedimentation losses of P were assumed to be governed by a first-order reaction and to be proportional to the amount of P stored above the sediments in the waterbody, therefore

$$P_{sed} = s.P \qquad (6)$$

where s is the P loss rate (time^{-1}).

An expression for the steady state P concentration, [P], in a waterbody can be derived firstly, by substituting equations 2, 5 and 6 into equation 1 which results in

$$dP/dt = 0 = W - (Q/V)P - s.P \qquad (7)$$

and secondly, by rearranging the terms and dividing by the volume, so that the steady state mean P concentration can be calculated as

$$[P] = W/(Q + s.V) \qquad (8)$$

Before equation 8 can be used to estimate the mean P concentration in a waterbody the value of s (the only parameter in the model) has to be estimated. Because s (as it is defined above) does not correspond to a process rate which can be directly measured, other sedimentation submodels, with parameters which did correspond to process rates that could be measured, were developed. For example, Dillon and Rigler (1974) developed a sub-model based on the concept of a P retention coefficient which they defined as the amount of P remaining in a waterbody expressed as a fraction of the amount of P that entered a waterbody. Chapra (1975) calculated sedimentation losses as a function of the area of waterbody in which case the sedimentation rate had units of length per time. However, these modifications did not overcome the fundamental problem, namely, that the sedimentation rate in the P budget model is a lumped parameter which therefore cannot be estimated by directly measuring any single process rate (Golterman, 1980). Two sedimentation submodels, one developed by Vollenweider (1976) and one proposed by Grobler and Silberbauer (1984) are currently employed in steady state P budget models applied in South Africa (Grobler and Silberbauer, 1984; Jones and Lee, 1984; Walmsley and Thornton, 1984) and only these sedimentation submodels are discussed here.

Vollenweider (1976) calibrated s on data for 21 lakes in which the water retention time T_w ($T_w = V/Q$) varied from 1 to about 50 years (median = 4 years). He found that s could be related to the square root of the water retention times of the lakes and simplified the relationship to

$$s = T_w^{-0,5} \qquad (9)$$

Although Kenney (1982) later showed that this relationship was partly the result of a spurious correlation, equation 9 is widely used to estimate the sedimentation rates in lakes and reservoirs throughout the world (Jones and Lee, 1982) and has recently also been used in South Africa (Walmsley and Thornton, 1984; Jones and Lee, 1984).

The standard OECD phosphate budget model was derived by substituting $T_w^{-0,5}$ for s in equation 8 so that

$$[P] = W/(Q + V.T_w^{-0,5}) \qquad (10)$$

Alternatively the P load can also be expressed as an areal loading rate (L, g $m^{-2}a^{-1}$) which is defined as

$$L = W/A \qquad (11)$$

where A is the surface area of the waterbody. If the areal water (hydraulic) loading rate, q_s, is defined as

$$q_s = Q/A \qquad (12)$$

the most frequently quoted form of the standard OECD P budget model can be derived by substituting equations 11 and 12 into equation 10 so that

$$[P] = L/[q_s(1 + T_w^{-0,5})] \qquad (13)$$

In the rest of this paper the steady state P budget model with s estimated as $T_w^{-0,5}$ is referred to as the OECD P budget model.

The OECD P budget model (equation 10) was assumed to be precalibrated (Vollenweider, 1976) and was therefore only verified on the reservoirs.

Grobler and Silberbauer (1984) used equation 6 as sedimentation submodel for the steady state P budget model applied to South African reservoirs. They assumed the sedimentation rate in a reservoir to be constant so that the parameter s could be estimated after rearranging equation 8 so that

$$s = (W/[P] - Q)/V \qquad (14)$$

and s the only unknown. From here on the steady state P

TABLE 1
DATA USED FOR CALIBRATION AND RESULTS OF VERIFICATION OF THE STEADY STATE P BUDGET MODELS. THE OECD P BUDGET MODEL WAS ASSUMED TO BE PRECALIBRATED, THEREFORE P CONCENTRATIONS IN THE RESERVOIRS COULD BE SIMULATED FOR BOTH YEARS. THE SA P BUDGET MODEL WAS CALIBRATED ON THE FIRST YEAR'S DATA, THEREFORE THE MODEL WAS VERIFIED ONLY ON THE SECOND YEAR'S DATA.

Reservoir + year	Mean volume of water stored m^3x10^6	Annual P load $t\ a^{-1}$	Annual inflow $m^3x10^6a^{-1}$	Observed annual mean P concentration $mg\ m^{-3}$	Annual mean P concentration simulated during model verification $mg\ m^{-3}$ SA model	OECD model
ROODEPLAAT						
Year 1	40,6	43,3	36,4	241	—	577
Year 2	40,2	33,8	19,1	228	211	724
HARTBEESPOORT						
Year 1	174	268	194	338	—	709
Year 2	175	329	212	408	403	812
BLOEMHOF						
Year 1	1137	791	800	57,0	—	451
Year 2	687	21*	126*	66,5	2,6	41

* On Bloemhof Dam the record for the second year consisted of data for 208 days only. Annual P loads and inflow were estimated as 365/208 times the P load and inflow measured during the 208 day record.

budget model employing a constant sedimentation rate, estimated as in equation 14, is referred to as the South African (SA) P budget model.

Because only one value for s could be estimated for each reservoir formal objective functions were not used to express the results of parameter estimation and verification of the steady state P budget models.

Dynamic P budget model

If appropriate input data are available the steady state assumption required for the specification of the steady state P budget model can be avoided and a *dynamic* P budget model for simulating P concentrations in reservoirs can be derived from a statement of the principle of conservation of mass (equation 1). If it is assumed that a waterbody can be treated as a completely mixed reactor, the principle of the conservation of mass can be used to state the change in P storage as

$$dP/dt = W - (Q_{out}/V)P - s.P \qquad (15)$$

If the amount of P in the waterbody has to be stated as a concentration the changes in the volume of water stored also have to be simulated and in a similar manner so that

$$dV/dt = Q_{in} + Q_r - Q_{out} - Q_e \qquad (16)$$

where the subscripts *in* and *out* refer to inflow and outflow and *r* and *e* refer to rainfall on and evaporation from the reservoir. Note that in equation 16 gains from or losses to groundwater are not included because they are assumed to be negligible for South African reservoirs (Braune, 1983) but the same assumption will not necessarily apply to other waterbodies (e.g. as shown by LaBaugh and Winter, 1984). The volume of water stored in a reservoir was calculated as

$$V_{t+1} = V_t + Q_{in,t} + Q_{r,t} - Q_{out,t} - Q_{e,t} \qquad (17)$$

where the subscript t indicates a time step of one day.

The trapesium rule was applied to solve equation 15 for the amount of P stored in a reservoir as

$$\begin{aligned} P_{t+1} = {} & P_t + (W_t + W_{t+1})\,\Delta t/2 \\ & - (P_t\,.\,Q_{out,t}/V_t + P_{t+1}\,.Q_{out,t+1}/V_{t+1})\Delta t/2 \\ & - (s_t\,.\,P_t + s_{t+1}\,.\,P_{t+1})\,\Delta t/2 \end{aligned} \qquad (18)$$

which after rearranging becomes

$$\begin{aligned} P_{t+1} = {} & [P_t(1 - (Q_{out,t}/V_t + s_t)\,\Delta t/2) + (W_t + W_{t+1})\,\Delta t/2]/ \\ & [1 + (Q_{out,t+1}/V_{t+1} + s_{t+1})\,\Delta t/2] \end{aligned} \qquad (19)$$

TABLE 2
ESTIMATED PARAMETER VALUES AND RESULTS OF CALIBRATION AND VERIFICATION OF A DYNAMIC P BUDGET MODEL EMPLOYING A CONSTANT OR A VARIABLE SEDIMENTATION RATE. THE STANDARD ERRORS OF THE ESTIMATE (SE), EXPRESSED AS PERCENTAGE OF THE MEAN P CONCENTRATIONS, WERE USED AS OBJECTIVE CRITERIA.

Reservoir and model	calibrated parameter values $s\ (a^{-1})$	$k\ [a^{-1}/(mg\ m^{-3})^2]$	calibration SE (%)	verification SE(%)
ROODEPLAAT DAM				
Model with constant sedimentation rate	2,88	—	18	14
Model with variable sedimentation rate	—	$4,75 \times 10^{-5}$	20	13
HARTBEESPOORT DAM				
Model with constant sedimentation rate	2,81	—	12	12
Model with variable sedimentation rate	—	$2,3 \times 10^{-5}$	16	14
BLOEMHOF DAM				
Model with constant sedimentation rate	2,19	—	38	73
Model with variable sedimentation rate	—	$65,7 \times 10^{-5}$	22	53

Mean P concentrations in the reservoir were calculated as

$$[P]_t = P_t/V_t \quad (20)$$

The assumption that phosphate losses (other than through the outlet) in a waterbody can be visualised as a constant sedimentation rate has been found to be false for many waterbodies (Prepas, 1979; Clasen, 1981; Frisk, 1981). Clasen (1981) observed that sedimentation rates were generally proportional to the P concentration in the inflow to a waterbody and Walker (1982) found that the OECD phosphate budget model could be calibrated best (lowest standard error of the estimate) on a data set consisting of reservoirs in the United States of America, if the sedimentation rate was assumed to be a function of the P concentration in the inflow to the reservoirs. Frisk (1981) derived a submodel for simulating the sedimentation rate in phosphate budget models by assuming that the sedimentation rate was proportional to both the P concentration in the waterbody and the P concentration in the inflow. Because the P concentration in the waterbody is functionally related to the P concentration in the inflow, he simplified the submodel by assuming that the sedimentation rate was a function of the square of the P concentration in the waterbody so that

$$s = k[P]^2 \quad (21)$$

where k then becomes the model parameter, s becomes a variable and [P] is the ambient P concentration in the waterbody. Grobler (1984) proposed a submodel with a concentration-dependent sedimentation rate in which

$$s = k/([P]^* - [P]) \quad (22)$$

where k and $[P]^*$ (the equilibrium P concentration) are parameters and [P] is the P concentration in the reservoir. In preliminary studies it was found that dynamic P budget models which incorporated any one of these submodels (equations 21 and 22) could be calibrated and verified equally well with the available data. However, if equation 22 was used as sedimentation submodel, special care had to be taken to avoid the sedimentation rate from becoming negative by choosing $[P]^*$ such that it will always be greater than [P], the ambient P concentration. The sedimentation submodel (equation 21) proposed by Frisk (1981) is robust and has only one parameter. It, rather than the submodel (equation 22) proposed by Grobler (1984), was therefore selected as an alternative to the constant sedimentation rate submodel for the dynamic P budget model.

One of the implications of using a concentration-dependent sedimentation rate is that sedimentation is assumed to be a third-order (instead of a first-order) reaction. This can be shown by noting that the P concentration in a reservoir is equal to the P mass divided by the volume and therefore equation 21 can also be written as

$$s = k(P/V)^2 \quad (23)$$

and substituting equation 23 for the sedimentation term in equation 15 so that it becomes

$$dP/dt = W - (Q_{out}/V)P - kP^3/V^2 \quad (24)$$

The dynamic P budget model was evaluated with a constant and with a variable sedimentation rate to determine which of the two submodels were the best for simulating P concentrations in the reservoirs studied.

The parameter s (when a constant sedimentation rate was assumed) or k (when a variable sedimentation rate was assumed) was estimated by minimizing the standard error of the estimate (SE) expressed as a percentage of the mean during calibration.

$$SE = 100\Sigma([P]_{o,i} - [P]_{s,i})^2\Big)^{0,5}(N - 2)^{-0,5}[\hat{P}]_o^{-1} \quad (25)$$

where $[P]_o$ and $[P]_s$ were observed and simulated daily mean P concentrations in the reservoirs on day i, N the number of days in the record used for calibration and $[\hat{P}]_o$ the average daily mean P concentrations. The dynamic P budget model was verified on independent data sets.

Data base

The data used for the calibration and verification of the phosphate budget models were obtained from the Department of Water Affairs which collected the data as part of a research project on the eutrophication of Roodeplaat, Hartbeespoort and Bloemhof Dams.

Roodeplaat Dam has a mean depth of 10,6 m and a surface area of 3,96 km². The water in the dam is clear compared to most South African reservoirs (mean Secchi depth of about 3 m; Walmsley and Bruwer, 1980). It is highly eutrophic (Toerien *et al.*, 1975; Walmsley and Butty, 1980; Grobler and Silberbauer, 1984) because it receives large P loads in the form of the effluent from the Baviaanspoort Sewage Works situated, about 5 km upstream of the reservoir, on the Pienaars River.

Hartbeespoort Dam, which has a mean depth of 9,0 m and a surface area of 20,3 km², in 1980 had a mean Secchi depth of 1,0 m (Walmsley and Bruwer, 1980) and was classified as hypertrophic (Scott *et al.*, 1977). It receives large P loads in the form of effluents from several sewage works in its catchment (Grobler and Silberbauer, 1984).

Bloemhof Dam, situated on the Vaal River, is large (surface area = 220 km²), shallow (mean depth = 5 m) and, because of clays suspended in the water, it is turbid (mean Secchi depth = 0,66 m) Weaver, 1981). It was classified as eutrophic (Walmsley and Butty, 1980). P loads on Bloemhof Dam are dominated by non-point sources (Grobler and Silberbauer, 1984).

All the inflows and outflows of the reservoirs (with the exception of the Magalies River, a minor river flowing into Hartbeespoort Dam, which was sampled at weekly intervals) were sampled daily from 1980 to 1981 for chemical analysis. On Roodeplaat Dam 5 sampling stations were sampled 3 times per week, on Hartbeespoort Dam 3 stations were sampled once a week and on Bloemhof Dam 4 stations were sampled twice a week. On each visit to the reservoir sampling stations the temperature and oxygen concentrations in the water column were measured and 5 m integrated samples were taken from the surface and, if the water column was stratified, also below the thermocline. All water samples were preserved by adding enough mercuric chloride to give a final concentration of 20 mg Hg/ℓ in the samples.

The inflows, outflows and reservoir levels were monitored continuously with stage recorders at weirs immediately upstream and downstream of the reservoirs and at the dam. The data were digitised by the Division of

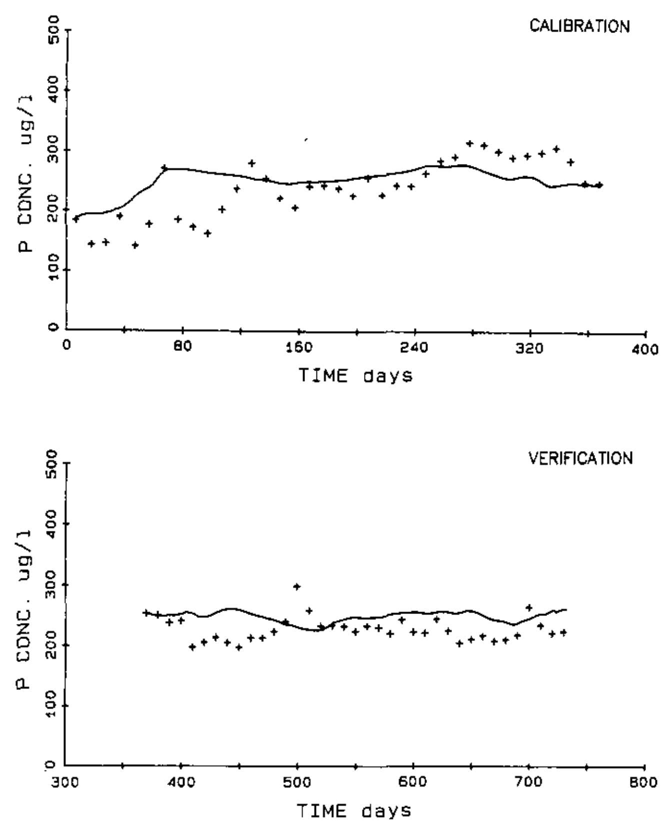

Figure 1
Observed (+) total phosphorus (P) concentrations in Roodeplaat Dam and concentrations simulated (————) during calibration and verification of the dynamic P budget model that used a constant sedimentation rate.

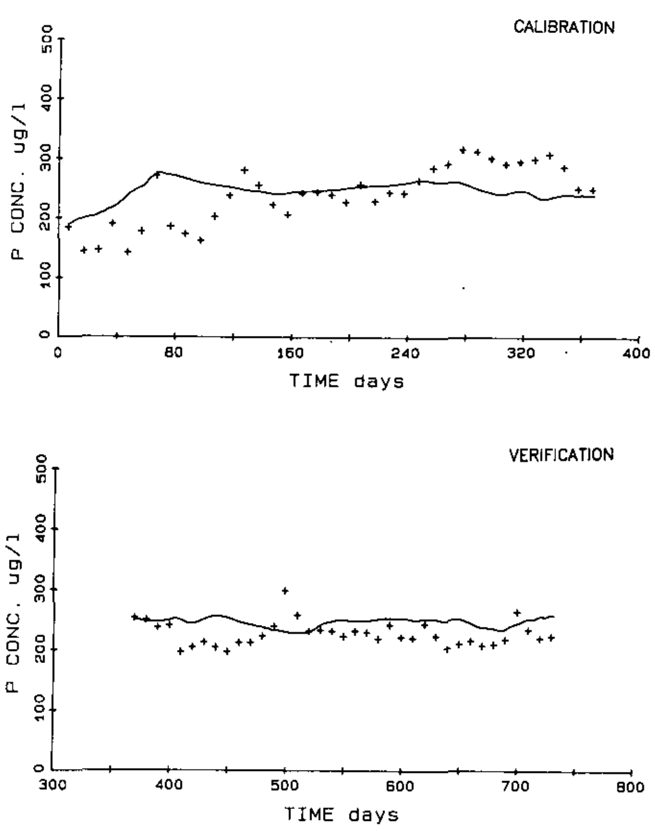

Figure 2
Observed (+) total phosphorus (P) concentrations in Roodeplaat Dam and concentrations simulated (————) during calibration and verification of the dynamic P budget model that used a variable (concentration dependent) sedimentation rate.

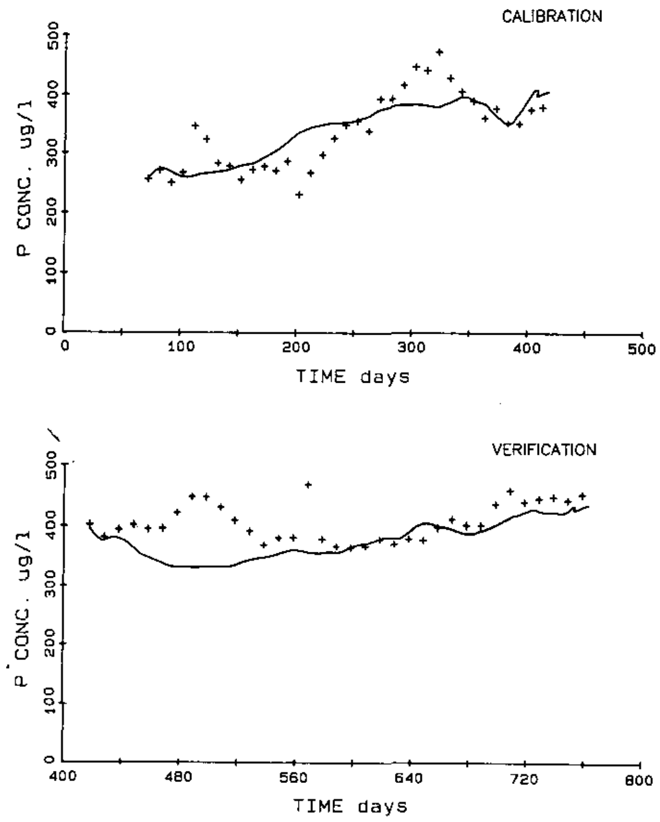

Figure 3
Observed (+) total phosphorus (P) concentrations in Hartbeespoort Dam and concentrations simulated (————) during calibration and verification of the dynamic P budget model that used a constant sedimentation rate.

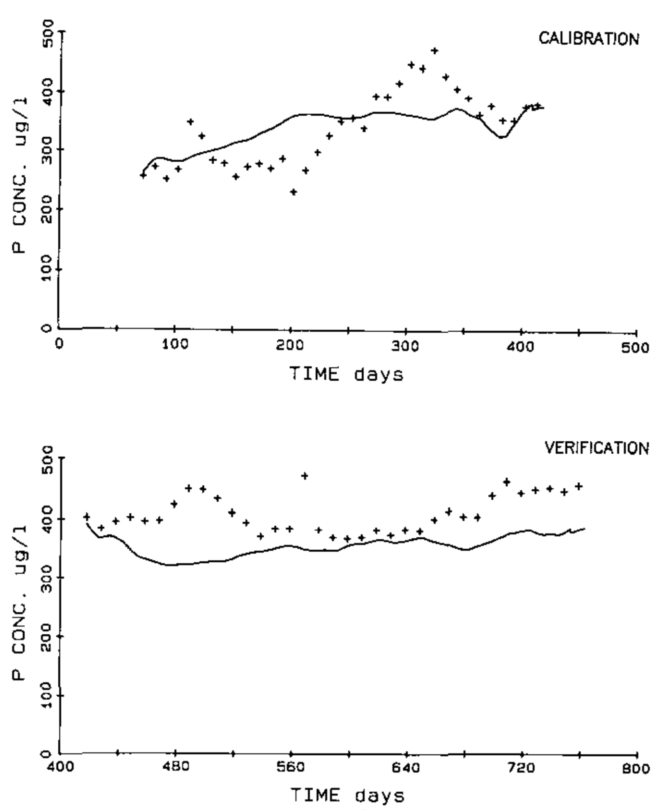

Figure 4
Observed (+) total phosphorus (P) concentrations in Hartbeespoort Dam and concentrations simulated (————) during calibration and verification of the dynamic P budget model that used a variable (concentration dependent) sedimentation rate.

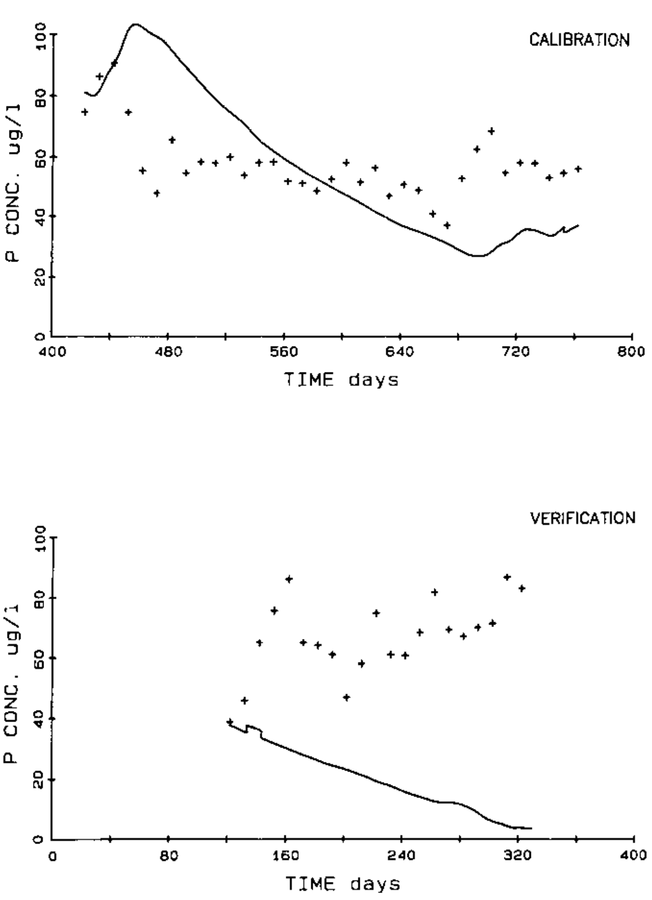

Figure 5
Observed (+) total phosphorus (P) concentrations in Bloemhof Dam and concentrations simulated (————) during calibration and verification of the dynamic P budget model that used a constant sedimentation rate.

Hydrology of the Department of Water Affairs and made available as daily mean flows for the inflows and outflows and as daily reservoir levels. Rainfall and evaporation data were provided by the Division of Hydrology as monthly totals from which daily rates were estimated by dividing monthly totals by the number of days in a month.

Daily P loads entering and leaving the reservoirs (except the Magalies River) were calculated as

$$L_i = C_iQ_i \tag{26}$$

where L was the P load, C the P concentration measured in the inflow or outflow and Q the measured total flow on day i. P loads in the Magalies River, in which P concentrations were measured at weekly intervals, were estimated with a regression method (Grobler, 1985).

In P budget models waterbodies are assumed to be completely mixed and therefore only the mean P concentration in the waterbody is simulated. The mean P concentrations, on the days the reservoirs were sampled, were calculated as

$$[P]_i = (C_{ijk})/N_i \tag{27}$$

where $[P]_i$ is the mean P concentration on day i, C_{ijk} is the P concentration in the sample taken on sampling day i at station j and position k in the water column and N_i is the total number of samples taken on the reservoir on sampling day i. Smoothed mean P concentrations in the reservoirs were estimated for every day of the year by calculating 10 day running means and these were used as the observed data for each reservoir.

A two-year time series of observed data was available of which one year's data were used for calibration and the other for verification of the models. To avoid having to use day, month and year for indicating the date when displaying daily data, the first of January 1980 was assigned as day 1 and all subsequent days were numbered accordingly.

Results

Steady state P budget model

Calibration

The sedimentation rates estimated for the SA P budget model were higher (for Roodeplaat Dam s = 3,53 a^{-1}; for Hartbeespoort Dam s = 3,49 a^{-1} and for Bloemhof Dam s = 11,42 a^{-1}) than the sedimentation rates estimated (as s = $T_w^{-0,5}$) for the OECD P budget model (s = 0,95 and 0,69 a^{-1} for Roodeplaat Dam; s = 1,06 and 1,10 a^{-1} for Hartbeespoort Dam and s = 0,84 and 0,43 a^{-1} for Bloemhof Dam).

Verification

Mean P concentrations simulated during verification of the SA P budget model were about equal to the observed concentrations for Roodeplaat and Hartbeespoort Dams, but in Bloemhof Dam the simulated mean P concentration was about 26 times lower than the observed concentration (Table 1). The OECD P budget model overestimated annual mean P concentrations for Roodeplaat and Hartbeespoort Dams by 2 to 4 times, but for Bloemhof Dam, overestimated them by about 8 times in one, and underestimated them in the next year. The P concentrations simulated with the OECD P budget model were much higher than those simulated with the SA P budget model because the sedimentation rates used in the SA model were about 3 times (Roodeplaat and Hartbeespoort Dams) and 14 to 26 times (Bloemhof Dam) higher than the sedimentation rates estimated as $T_w^{-0,5}$ for the OECD model.

Dynamic P budget model

Calibration

The sedimentation submodel used (variable or constant sedimentation rate) did not affect the success with which the dynamic P budget model could be calibrated on Roodeplaat and Hartbeespoort Dams (Table 2, Figs. 1 to 4). However, on Bloemhof Dam (Table 2, Figs. 5 and 6) the model with variable sedimentation rate could be calibrated with greater success (SE = 22%) than the model with constant sedimentation rate (SE = 38%).

Bloemhof Dam received a series of large floods during the initial few weeks of the period used for calibrating the model and consequently, the incoming P loads were high during that period. A large sedimentation rate was therefore required to adequately simulate P concentrations in the reservoir. During the rest of that period incoming P loads were low and consequently a low sedimentation rate was required to simulate P concentrations. The model which used a constant sedimentation rate could not adequately simulate these events in Bloemhof Dam and the estimated value of the constant sedimentation rate had to be a compromise between overestimating the P concentrations somewhat when floods were experienced and underestimating the P concentrations during the low-flow period (Fig. 5). The model which used a variable sedimentation rate could be better calibrated to simulate P concentrations both when floods were experienced and during the low-flow period (Fig. 6)

The estimated k values, at a given P concentration, were lower in Roodeplaat and Hartbeespoort Dams (Fig. 7) than in Bloemhof Dam. The higher sedimentation rates estimated for Bloemhof Dam were probably the result of it receiving a greater proportion of its P load in the particulate form, both because sediment concentrations in the rivers flowing into Bloemhof Dam are generally higher than in the rivers flowing into the other reservoirs and because P loads into Bloemhof Dam are not dominated by point sources (which result in an increased ratio of dissolved:particulate P) (Grobler and Silberbauer, 1984; 1985).

Verification

The dynamic P budget model was verified successfully on Hartbeespoort and Roodeplaat Dams and SE values were lower than those obtained during calibration (Table 2). The success with which the dynamic P budget model could be verified on these reservoirs was not affected by whether a constant or a concentration dependent sedimentation rate was used (Figs. 1 to 4, Table 2).

In constrast the results of model verification on Bloemhof Dam were poor (Table 2, Figs. 5 and 6) both when a constant and a variable sedimentation rate was employed (SE = 73% and 53%). The time series of observed data against which the model was verified, consisted of data representing the low-flow part of the year (May to November) during which the water level in Bloemhof Dam was only at 54% of its full supply capacity (Table 1). It was demonstrated, by simulating P concentrations with the sedimentation rate set at zero, that even if no nett loss of P to the sediments was assumed there was more P in the reservoir than what could be accounted for by the measured P loads entering and leaving it during this period (Fig. 8).

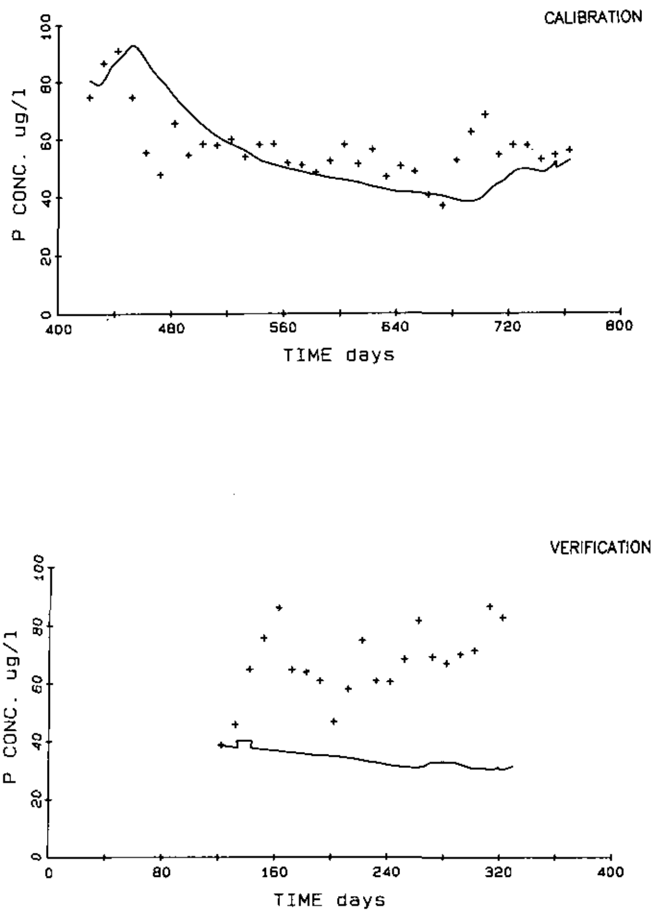

Figure 6

Observed (+) total phosphorus (P) concentrations in Bloemhof Dam and concentrations simulated (————) during calibration and verification of the dynamic P budget model that used a variable (concentration dependent) sedimentation rate.

Discussion

Sedimentation submodels

The sedimentation rates for the SA P budget model were higher than those, estimated as $T_w^{-0.5}$, for the OECD model and their estimated values (3,49 and 3,53 a^{-1}) for Hartbeespoort and Roodeplaat Dams closely correspond to the mean sedimentation rate (3,6 a^{-1}) estimated for a similar P budget model from data for reservoirs in the United States of America (Walker, 1982). These results support the conclusion that the OECD phosphate budget model generally underestimates annual mean P concentrations in reservoirs (Jones and Bachman, 1976; Clasen, 1981; Higgins and Kim, 1981; Walker, 1982; Grobler and Silberbauer, 1984). The factors responsible for the larger sedimentation rates required to simulate P concentrations for reservoirs, compared to natural lakes, can be any combination of the following:

- Reservoirs often receive P loads of which a large proportion consists of particulate P, which is lost at a faster rate than dissolved P (Canfield *et al.*, 1982; Chapra, 1982). The exceptionally high sedimentation rate ($S = 11{,}4\ a^{-1}$)

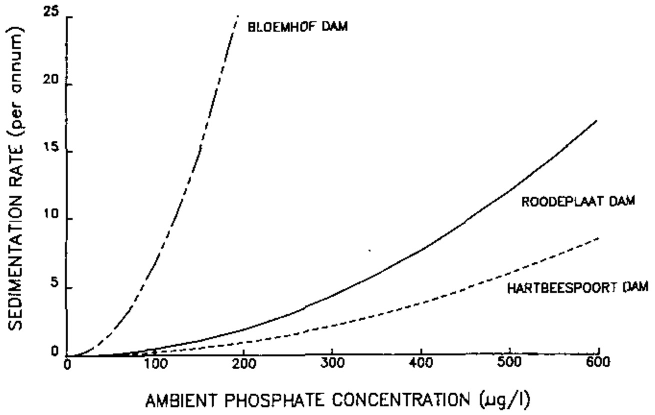

Figure 7
Sedimentation rates (which varied as functions of the total phosphorus concentration) of Roodeplaat, Hartbeespoort and Bloemhof Dams that were estimated by calibrating the dynamic P budget model on each reservoir.

estimated for Bloemhof Dam was probably the result of it receiving a large particulate P load as a consequence of several floods occurring in the Vaal River during that year.

- Reservoirs are usually constructed by building a dam in a river with the result that they are characteristically long and narrow with the inflow at one end and the outflow at the other end. Consequently, they often behave as plug-flow systems which are characterized by pronounced concentration gradients (e.g. Roodeplaat Dam; Fig. 9). For a given sedimentation rate, P losses by means of sedimentation are greater in plug-flow systems than in completely mixed systems (Sonzogni *et al.*, 1976; Chapra, 1981; Higgens and Kim, 1981). Therefore, if a plug-flow system is assumed to be completely mixed, it will require a higher sedimentation rate than a similar but mixed system, to simulate its mean P concentration.
- Because P concentrations are often higher in the bottom water than in the surface water of stratified systems, bottom withdrawal of water from them can result in larger quantities of P being removed through the outlet, than what would be calculated from the product of the outflow and the mean inlake P concentration. In natural lakes, surface water is usually lost through the lake outlet so that less P may actually leave a stratified lake than what would be estimated from the product of outflow and mean inlake P concentration (Vollenweider, 1975; Sonzogni *et al.*, 1976). To compensate for underestimating (from reservoirs) and overestimating P losses (from lakes) through the outlets of waterbodies, estimated sedimentation rates have to be higher for reservoirs and lower for lakes.

The application of the OECD P budget model (equations 10 or 13) to waterbodies, other than the 21 lakes used by Vollenweider (1976) to estimate s as equal to $T_w^{-0,5}$, implies that all waterbodies can be assumed to behave essentially the same as those 21 lakes. This assumption was shown to be false in this and in other studies; particularly for reservoirs, in which P concentrations were overestimated if the sedimentation rate was assumed to be equal to $T_w^{-0,5}$ (Jones and Bachman, 1976; Prepas, 1979; Clasen, 1981; Frisk, 1981; Higgins and Kim, 1981; Canfield *et al.*, 1982; Walker, 1982; Grobler and Silberbauer, 1984). One of the consequences of estimating the P sedimentation rate in reservoirs as a function of the water residence time, as in the OECD model, is that in the same river small reservoirs are predicted to have much higher sedimentation rates than large reservoirs. For example, for Vaal Barrage ($V = 57$ million m^3) and Bloemhof Dam ($V = 1\ 270$ million m^3) both in the Vaal River (mean annual runoff $= 2\ 200$ million m^3a^{-1}), the sedimentation rates predicted as $T_w^{-0,5}$ are 6,2 a^{-1} for Vaal Barrage and 1,3 a^{-1} for Bloemhof Dam. However, there is no evidence supporting this conclusion. The OECD P budget model should therefore not be used for estimating P concentrations in South African reservoirs. Instead, if a steady-state P budget model has to be used, the SA P budget model, with its sedimentation rate estimated by calibrating the model on time-series data for the reservoir it will be applied to, should preferably be used. If the required data for calibrating the SA P budget model are not available, a sedimentation rate of about 3,5 a^{-} should be used, but users must realise that it could mean that sedimentation rates in systems receiving a large proportion of their P loads in particulate form might be underestimated.

The use of a variable sedimentation rate which depends on the inlake P concentrations in reservoirs is supported by the fact that the dynamic P budget model employing a variable sedimentation rate was best able to simulate P concentrations in Bloemhof Dam, which experienced large fluctuations in P concentrations. Support for using a variable sedimentation rate in P budget models also comes from the modifications made to the OECD P budget model to correct for its tendency to underestimate P concentrations in waterbodies. These corrections are of the form

$$[P] \text{ corrrected} = a\ [P]^b \text{predicted} \qquad (28)$$

where a and b have values of 0,77 and 0,85 (Clasen, 1981) or 1,8 and 0,805 (Lee and Jones, 1983). The correction becomes proportionally larger as the predicted P concentrations increase (for the parameter values estimated by Lee and Jones (1983) this only applies when predicted P concentrations exceed 20,4 mg m^{-3}) and can be interpreted as correcting for increased sedimentation rates as the inlake P concentrations rise Further support for using a variable and P concentration dependent sedimentation rate in P budget models was provided by Canfield *et al.* (1982) who measured actual sedimentation rates in lakes and reservoirs and showed that these were positively correlated with inorganic sediment concentrations and the trophic status of the waterbodies.

Verification of P budget models

The SA and dynamic P budget models were successfully verified on Roodeplaat and Hartbeespoort dams. However, because the data used for calibration and verification did not represent these reservoirs in different states, this verification should be regarded as tentative and it should be repeated as soon as data representing these systems in different states (e.g. before and after they have experienced major floods) become available. The data used for calibration and verification of the models on Bloemhof Dam represented the reservoir in different states and therefore verification on Bloemhof Dam amounted to severe tests of the models.

Verification of the P budget models on Bloemhof Dam identified one of their important limitations, namely an inability to simulate the response of reservoirs in which P concentrations are controlled by internal processes. When the verification data were collected, P concentrations were probably primarily controlled by internal processes in Bloemhof Dam which then was only 54% full (and therefore shallow compared to when it is full). Since Weaver (1981) measured considerable increases in suspended sediment concentrations during high-wind events, it can be assumed that periodic resuspension of bottom sediments was responsible for the higher than expected P concentrations in Bloemhof Dam.

Comparison of the P budget models

Because the steady state P budget models can only simulate the annual mean P concentration in a reservoir the models could be directly compared only on the basis of their ability to simulate annual mean P concentrations (Table 3). In Roodeplaat and Hartbeespoort Dams the annual mean P concentrations simulated with the SA P budget model and both dynamic P budget models were essentially the same. However, in Bloemhof Dam the annual mean P concentrations simulated with the dynamic models were considerably better than that simulated with either of the steady state models (with the exception of the OECD model in year 2).

Comparing the models which employed a constant sedimentation rate, the estimated sedimentation rates for the dynamic P budget model (2,8; 2,9 and 2,2 a^{-1} for Roodeplaat, Hartbeespoort and Bloemhof Dams) were lower than the estimated sedimentation rates for the SA P budget model (3,5; 3,5 and 11,4 a^{-1} for Roodeplaat, Hartbeespoort and Bloemhof Dams). The differences in estimated parameter values reflect the differences in model assumptions (e.g. in the SA P budget model the reservoirs are assumed to be in steady state whereas in the dynamic model they are not) and the objectives of model calibration. Although both models were derived from the same equation stating the conservation of mass, the estimated parameter values were not interchangeable. Therefore, when models are applied with

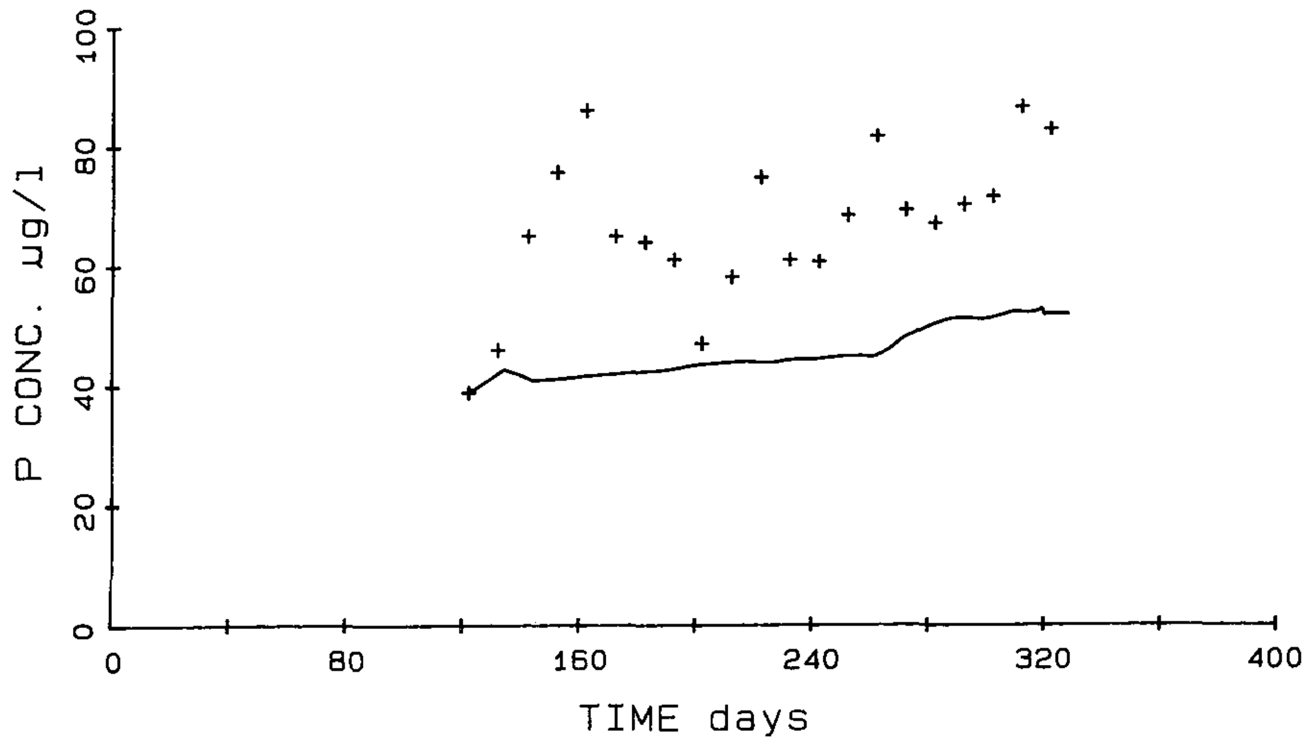

Figure 8
Observed (+) total phosphorus (P) concentrations in Bloemhof Dam and P concentrations simulated (————) with the dynamic P budget model with its sedimentation rate set at zero.

parameter values obtained from sources other than calibration, great care should be exercised to ensure that the model specification and the objectives of its calibration (when the parameter values were estimated) are the same as those of the model used in the application. For example, Walker (1982) showed that the parameter values required for the same P budget model were different when it was calibrated to simulate the annual mean inlake P concentrations compared to when it was calibrated to simulate the mean P concentrations in the outlets of the same reservoirs. Different parameter values were required despite a fundamental assumption of the model that the reservoirs are completely mixed reactors, for which the inlake P concentrations and P concentrations in the outlets should be identical.

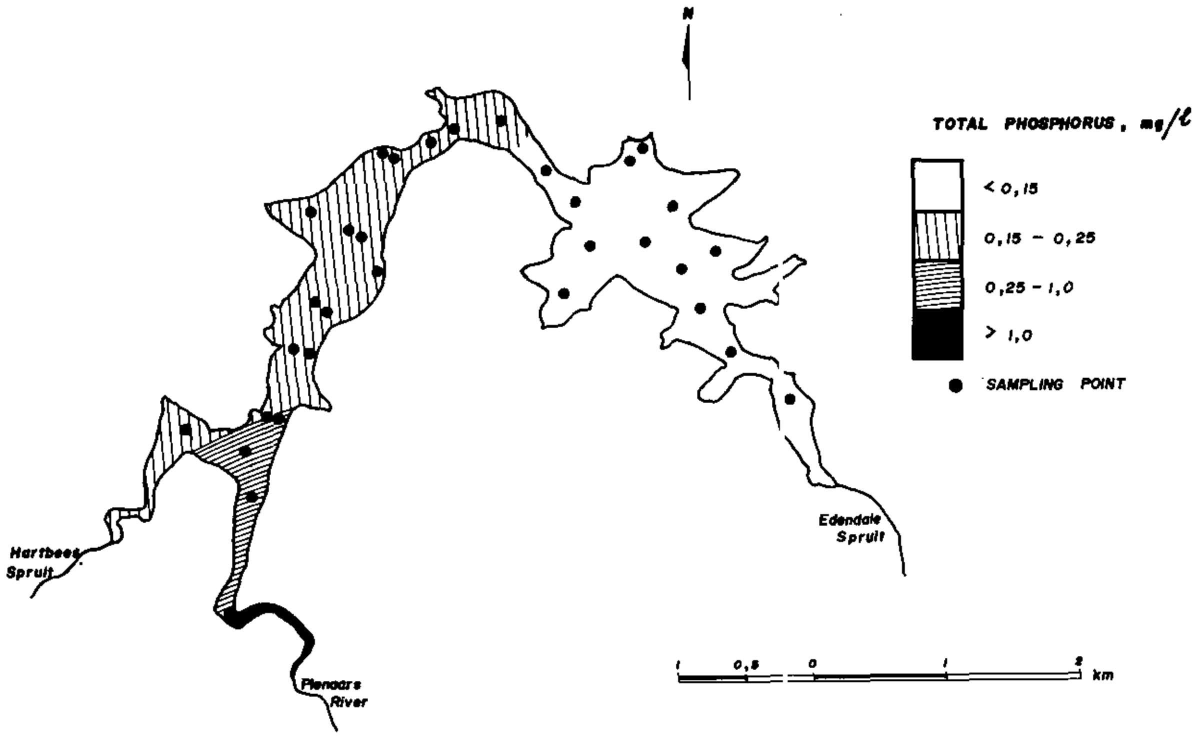

Figure 9
Total phosphorus concentration gradient in the 0 to 5 m layer in Roodeplaat Dam on 30/9/82 (A. Howman, Hydrological Research Institute, Private Bag X313, Pretoria; Unpublished M.Sc. thesis).

Of the models employing a constant sedimentation rate the dynamic P budget model performed much better than the SA P budget model during verification. The only difference between these models was that the dynamic model did not assume the system to be in a steady state whereas the SA model did. Consequently, the greater success with which the dynamic model could be verified can be regarded as being a result of it avoiding the steady state assumption. Verification of the dynamic P budget model on Bloemhof Dam was further improved by employing a variable, instead of a constant, sedimentation rate in the model.

The dynamic P budget model using a concentration-dependent sedimentation rate was judged to be the best model for simulating P concentrations in reservoirs because of its better ability than the steady state models to simulate the fate of P in reservoirs experiencing highly variable hydrological conditions. However, further research aimed at extending the model so that it can also account for recirculation of P in reservoirs is required.

Acknowledgements

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TABLE 3
ANNUAL MEAN P CONCENTRATIONS (mg m^{-3}) OBSERVED AND SIMULATED WITH STEADY STATE AND DYNAMIC P BUDGET MODELS

Reservoir and Period	observed P concentrations	simulated P concentrations			
		steady state P budget models		dynamic P budget models	
		OECD	SA	constant sedimentation rate	variable sedimentation rate
ROODEPLAAT DAM					
Year 1	241	577	*	254	248
Year 2	228	724	211	248	247
HARTBEESPOORT DAM					
Year 1	338	709	*	338	347
Year 2	408	812	403	376	361
BLOEMHOF DAM					
Year 1	57,0	451	*	64,6	55,1
Year 2	66,5	41	2.6	22,3	34,5

* The model calibrated to give exactly the observed annual mean P concentration for year 1.

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