A comparison of phosphorus concentrations in Hartbeespoort Dam predicted from phosphorus loads derived near the impoundment and in the upper catchment area

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Abstract

Two estimates of the annual total phosphorus load entering Hartbeespoort Dam between September 1980 and October 1984 were made using direct measurements of flow and total phosphorus concentration in the Crocodile River at weir A2M12 near the dam (weir estimates) and using estimates of total point source loads plus diffuse loads in the catchment (catchment estimates). Catchment load estimates were at least 1,8 times greater than weir load estimates. Both types of load estimates were used to predict annual in-lake total phosphorus concentrations using several published empirical models. Comparisons of predicted in-lake total phosphorus concentrations with measured in-lake concentrations showed that predicted in-lake concentrations exceeded observed values when catchment loads were used. Predictions based on weir load estimates deviated far less from observed values than predictions based on catchment estimates. It was concluded that in-stream phosphorus losses were substantial and that catchment load estimates are not appropriate when predicting total phosphorus concentrations in Hartbeespoort Dam with the models used in this study.

Introduction

Hartbeespoort Dam is an important multi-use water supply reservoir. Its excessive eutrophication, due almost entirely to nutrients from the Crocodile River, which drains an industrially developed area of the Transvaal Highveld (Scott *et al.*, 1980), has been extensively studied (Toerien and Walmsley, 1976; Scott *et al.*, 1977, 1980; Steyn *et al.*, 1975; Robarts *et al.*, 1982; NIWR, 1985). Recently, simple empirical models such as those resulting from the OECD studies (OECD, 1982), have been applied to eutrophication management in Hartbeespoort Dam (Thornton and Walmsley, 1982; Grobler and Silberbauer, 1984; NIWR, 1985). The applicability of some of these models to South African impoundments has been shown to be adequate for certain management purposes (Thornton and Walmsley, 1982; Walmsley and Thornton, 1984; Jones and Lee, 1984). However, a recent study suggests that the commonly used Vollenweider nutrient budget model has severe limitations in its use for South African impoundments (Grobler and Silberbauer, 1984).

Clearly, the reliability of load/response models, such as the OECD suite of models, is heavily dependent on the use of accurate estimates of the phosphorus load that actually enters the receiving water body (OECD, 1982; Jones and Lee, 1984). At best, load calculations, such as those used in the OECD study, are characterized by errors of $\cong 35\%$ and this is regarded as the major source of data scatter in the OECD relationships (OECD, 1982).

Estimates of external phosphorus loading on Hartbeespoort Dam have been made using daily data from a gauging weir close to the dam (NIWR, 1985) and in the catchment area using measured and projected point source inputs and export coefficients for diffuse sources (Grobler and Silberbauer, 1984). Whilst the former method may provide more accurate loading estimates (Grobler *et al.*, 1982), the lack of adequate gauging facilities precludes its use at many sites. The second approach, using catchment data, may therefore be the only alternative in many instances. This paper assesses the use of both methods of load estimate in predicting total phosphorus concentrations in Hartbeespoort Dam. Selected load-response models were used and some of the implications of the discrepancies between predictions using the different load estimates are discussed.

Materials and methods

Data for three hydrological years (1 October to 30 September), beginning on 1 October 1980, were used in this study. Mean annual volumes and surface areas in Hartbeespoort Dam during this period were calculated as the means of weekly values. Mean annual phosphorus concentrations in the impoundment were calculated from weekly values for volume-weighted total phosphorus (TP) concentrations in Hartbeespoort Dam according to equations given in NIWR (1985). Annual loads of TP entering the impoundment were calculated as the sum of the products of daily flow and daily TP concentrations at the Department of Water Affairs gauging weirs on the Crocodile River (A2M12) and on the Magalies River (A2M13).

Grobler *et al.* (1982) indicate that this method provides adequate estimates of phosphorus load. Values for annual total phosphorus loads were also converted to areal loading rates by using the mean annual surface area of the lake for each successive hydrological year. During the study period the Magalies River contributed less than 10% of the total water inflow and less than 1,5% of the phosphorus input, into the dam (NIWR, 1985).

Alternative phosphorus load estimates for 1981 have been presented by Grobler and Silberbauer (1984). These are based on measured point source emissions and diffuse source loads calculated from catchment export coefficients (Grobler and Silberbauer, 1984). The catchment load estimates for the period 1982 to 1984 are based on projected 5% per annum increases in treated sewage outputs and a constant diffuse source load from the remainder of the catchment (Grobler and Silberbauer, 1984).

Predictions of In-Lake Total Phosphorus Concentrations

With the load data for Hartbeespoort Dam for the period 1 October 1980 to 30 September 1984, predictions of mean in-lake total phosphorus concentrations were made using the following four different models:

The Vollenweider nutrient budget model (Vollenweider, 1976; OECD, 1982):

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$(P_p) = L/q_s(1+\sqrt{Tw})$ .... (1)

where:

(P_p) = predicted mean annual total phosphorus concentration ($g\ m^{-3}$)
L = areal phosphorus loading rate ($g\ m^{-2}\ a^{-1}$)
Tw = water residence time (a)
q_s = areal hydraulic loading, $= z/Tw$ ($m\ a^{-1}$)
z = mean depth (m).

This nutrient budget model has a tendency to overestimate in-lake total phosphorus concentrations (or underestimate phosphorus sedimentation losses) and an essential prerequisite for its use to predict mean annual in-lake total phosphorus concentrations is the incorporation of an appropriate correction factor, specified in the OECD Manual (OECD, 1982: p. 66). Predictions arising from the correction factor generated for the combined OECD data set (OECD, 1982), were found to deviate less than those for the individual OECD Projects. Therefore the former was used:

$OECD = 1{,}55(P_p)^{0{,}82}$ .... (2)

where:

OECD = modified prediction of mean annual phosphorus concentration ($mg\ m^{-3}$) using the OECD modification.

Similarly, Thornton and Walmsley (1982) analysed 31 Southern African impoundments and derived a correction factor, based on linear regression analysis of predicted and observed phosphorus concentrations, to account for significant overestimates of in-lake total phosphorus concentration using the Vollenweider nutrient budget model:

$T\&W = ((P_p) - 0{,}09)/1{,}39$ .... (3)

where:

T&W = modified predictions of mean annual total phosphorus concentrations ($g\ m^{-3}$) using the Thornton and Walmsley modification.

A further modification of the Vollenweider nutrient budget model for use in South African impoundments was made by Grobler and Silberbauer (1984) who incorporated a larger sedimentation factor:

$G\&S = W/(Q + s\,V)$ .... (4)

where:

G&S = predicted mean annual phosphorus concentration ($mg\ m^{-3}$)
W = annual phosphorus load (kg)
Q = water inflow ($10^6\ m^3$)
V = volume of lake ($10^6\ m^3$)
s = phosphorus sedimentation coefficient (a value of 3,5 was used in place of the 2,9 shown in Grobler and Silberbauer; Grobler 1984).

Results

Morphometric characteristics and phosphorus load data for Hartbeespoort Dam during the study period are shown in Table 1. The impoundment volume and surface area decreased in each successive year. Water residence time first rose by 40% and then declined to below its 1980/81 value, due to excessive drawdown during the prolonged drought of 1982 to 1984 when water levels dropped to 22% of full supply capacity.

Estimates of the amount of phosphorus entering the impoundment annually during the study period showed wide fluctuations (Table 1) due to annual variations in hydrological conditions and differences in the method used to estimate inflow loads. Annual load estimates made from point and diffuse source loads (catchment loads) were generally about twice as high (mean 581 t) as those made at the gauging weir (mean 262 t). However, the projected increase in catchment loads during the 1981/82, 1982/83 and 1983/84 hydrological years were not reflected in the weir load estimates. These weir load estimates did not follow changes in total annual inflow, except that they were lowest in the year with the distinctly lowest inflow. Nevertheless, phosphorus concentrations in the dam rose steadily from year to year.

Predictions of in-lake total phosphorus concentration using these load estimates, and comparisons between these and measured in-lake total phosphorus, are presented in Table 2. Predictions using all models with both load estimates showed considerable deviation from the measured values. Based on loading rates at weir A2M12, the Vollenweider nutrient budget model overestimated in-lake concentrations by an average of 58%. The OECD modification and the Grobler and Silberbauer model showed average deviations from observed concentrations of 28% and 21% respectively (consistent underestimates), while the Thornton and Walmsley modification underestimated in 1980/81 (−24%) and overestimated in the following three years (+21%, +13% and +1%).

Using the catchment loads all of the models substantially

TABLE 1
MORPHOMETRIC AND PHOSPHORUS LOADING DATA FOR HARTBEESPOORT DAM DURING THE PERIOD 1 OCTOBER 1980 TO 30 SEPTEMBER 1984
(Tw = V/Q; P-conc (lake) = annual volume-weighted mean concentration of total phosphorus in the lake)

Parameter	Units	Symbol	Hydrological year			
			1980/81	1981/82	1982/83	1983/84
Lake volume	$10^6\ m^3$	V	184,2	170,4	85,0	67,5
Lake area	km^2	A	19,5	18,1	10,3	8,9
Mean depth	m	$\bar{z}$	9,5	9,4	8,2	7,6
Water residence time	years	Tw	0,75	1,08	0,86	0,56
Inflow	$10^6\ m^3$	Q	245,6	157,8	98,8	119,5
Hydraulic load	$m\ a^{-1}$	q_s	12,67	8,70	9,53	13,43
Catchment load	t	–	539	566	594	624
Catchment loading rate	$g\ m^{-2}\ a^{-1}$	Lc	27,7	31,2	57,6	70,1
Weir load	t	–	283	323	206	237
Weir loading rate	$g\ m^{-2}\ a^{-1}$	Lw	14,5	17,8	20,0	26,6
P-conc (lake)	$mg\ m^{-3}$	–	493	543	634	743

TABLE 2
COMPARISON OF PREDICTED AND OBSERVED TOTAL PHOSPHORUS CONCENTRATIONS (mg m^{-3}) IN HARTBEESPOORT DAM, USING A) WEIR LOADING DATA AND B) CATCHMENT LOADING DATA. (Voll. = VOLLENWEIDER NUTRIENT BUDGET MODEL; OECD = OECD MODIFICATION; T&W = THORNTON AND WALMSLEY MODIFICATION; G&S = GROBLER AND SILBERBAUER MODIFICATION; % = PERCENTAGE DEVIATION OF PREDICTED CONCENTRATION FROM OBSERVED CONCENTRATION)

Year	Obs.	Voll.	%	OECD	%	T&W	%	G&S	%
A) Weir									
80/81	493	613	+ 24	299	− 39	376	− 24	318	− 35
81/82	543	1 003	+ 85	448	− 17	657	+ 21	428	− 21
82/83	634	1 089	+ 72	479	− 24	719	+ 13	520	− 18
83/84	743	1 133	+ 52	495	− 33	750	+ 1	666	− 10
Mean Dev.			58		28		15		21
B) Catchment									
80/81	493	1 172	+ 138	509	+ 3	778	+ 58	605	+ 23
81/82	543	1 759	+ 224	710	+ 31	1 201	+ 121	750	+ 38
82/83	634	3 136	+ 395	1 141	+ 80	2 191	+ 246	1 499	+ 136
83/84	743	2 986	+ 302	1 096	+ 48	2 083	+ 180	1 754	+ 136
Mean Dev.			252		38		154		66

overestimated in-lake concentrations; the extent of the discrepancy increasing progressively with the projected increases in loading rates during 1981 to 1984. Based on the average deviation between measured and predicted values the OECD modification gave the best, albeit poor, predictions (+ 41% deviation) followed by the Grobler and Silberbauer model (+ 83% deviation) and the Thornton and Walmsley modification (+ 151% deviation).

Regardless of the model used the average deviations between predicted and measured concentrations were proportionately far higher when the catchment loads were used, suggesting that the weir loads are generally more appropriate for use in all the models.

Discussion

This study stresses the need to clarify the applicability of different phosphorus load estimates to load/response modelling in eutrophication management. Since the reliability of these models is dependent on the use of accurate phosphorus load estimates (Jones and Lee, 1984) the choice of appropriate loading data, when more than one option is available, becomes critical for sound management decisions and for meaningful assessment of the applicability of general models, such as the OECD models (OECD, 1982), to specific water bodies. Catchment load estimates made during the 4-year study period consistently exceeded weir load estimates by a factor of approximately two. Clearly, the use of these contrasting estimates in load/response models results in differing in-lake predictions, as shown in Table 2, both of which cannot be appropriate for eutrophication management decisions.

The discrepancy between catchment and weir loads could reflect consistent errors in estimating loads, or, alternatively, it could indicate significant phosphorus losses (approximately 50% of the catchment load) in the drainage basin. For various reasons load estimates are characterised by wide margins of error (OECD, 1982) and the possibility that differences between catchment and weir loads result from consistent errors in their estimation must be considered. An independent assessment of catchment loads during the study period was made by Pitman (1985), who used the product of daily flow and mean phosphate concentration in effluents from sewage works in the catchment to calculate loads. These estimates were 4%, 6% and 19% lower than those of Grobler and Silberbauer (1984) for the first three years of this study, respectively. Within the range of error generally associated with such estimates, these differences, with the possible exception of the third year, are negligible. It is therefore assumed that the catchment loads are reasonable estimates of the actual loads entering the drainage basin. This assumption should be verified.

The weir load estimates could be subject to substantial errors due to the flow characteristics of the Crocodile River. Since the flow varies widely in response to short-term events, daily sampling intervals may not be adequate for accurate monitoring of loads during periods of high river flow and phosphorus loading. Grobler (1985) has shown that up to 68% of the annual phosphorus load carried by some South African rivers can be transported during short periods of high flow which may occur for only 3% of the time. He did, however, point out that the dependence of phosphorus load on river flow was not as strong in point source dominated rivers, such as those occurring in the Hartbeespoort Dam drainage basin. The extent to which weir loads based on daily sampling may underestimate phosphorus loads to Hartbeespoort Dam, thereby accounting for some of the discrepancy between catchment and weir loads, is thus not clear.

The alternative explanation for the discrepancy between catchment and weir load estimates is that a large proportion of the phosphorus inputs to the catchment is retained, at least temporarily, within the drainage basin. Phosphorus transport in surface waters is subject to abiotic and biotic influences and efficient retention of soluble and particulate phosphorus has been reported in rivers, reservoirs and wetlands (e.g. Fiala and Vasata, 1982; Hill, 1982; Nichols, 1983). In the Hartbeespoort Dam drainage basin there is evidence of considerable phosphorus loss. Toerien and Walmsley (1979) noted that in 1973/74 about 64% of the phosphorus entering the Hennops River upstream of Rietvlei Dam, from the Kempton Park sewage treatment plant, was retained in the river and associated wetlands. They also noted that a further 27% of the point source load was lost in Rietvlei Dam, resulting in a total loss of approximately 90% of the point source load entering the upper Hennops River. Similar phosphorus retention efficiencies in Rietvlei Dam were reported by Ashton (1981). Less information is available regarding phosphorus retention in the Jukskei/Crocodile River sector of the drainage basin, which receives the larger proportion of total phosphorus inputs. Twinch (1984) estimated that up to 40% of the phosphorus load measured at weir A2M12 could be removed by sediments in the Crocodile River arm of Hartbeespoort Dam during periods of low flow, but this loss would not contribute to the losses apparent when comparing catchment and weir loads. A recent assessment of phosphorus transport in the Hartbeespoort Dam drainage basin (Pitman, 1985) showed that about 50% of the total point source phosphorus input into the drainage basin was retained upstream of weir A2M12, 13% through irrigation draw-off and 37% through natural losses in rivers, wetlands and Rietvlei Dam.

All of the models used in this study grossly overestimated in-lake phosphorus concentrations based on catchment loads, but gave more realistic predictions using weir loads. Assuming that the most appropriate load estimates for use in these models are those that result in the least deviation between predicted and observed in-lake concentrations, we therefore conclude that the weir loads are more reliable estimates of the actual amount of phosphorus entering Hartbeespoort Dam, than the catchment loads. This supports the view that loss processes in the catchment may effectively reduce phosphorus loads to Hartbeespoort Dam. Although Grobler and Silberbauer (1984) reported phosphorus losses between point source inputs and impoundments, these were not quantified in modelling the responses of impoundments to reduced phosphorus loading and a 'worst possible' condition was assumed, whereby no phosphorus retention in river systems occurred. This is a safe approach to the problem but in view of the magnitude of the 'apparent' losses in the Hartbeespoort Dam catchment ($\cong 50\%$) it may be over-cautious. If natural river systems generally retain phosphorus at this level of efficiency it would be useful to incorporate natural river retention of phosphorus into water quality management planning.

The advantage of estimating catchment loads, as was done by Grobler and Silberbauer (1984), is that it eliminates the laborious and costly process of monitoring loads to impoundments in the conventional manner and facilitates use of load/response models at sites where no alternative load data are available. Furthermore, it provides the only means of predicting responses to future conditions and therefore presents an important tool for eutrophication managers. However, as shown for Hartbeespoort Dam, these estimates can be much higher than the actual loads entering impoundments due to losses in the drainage basin, resulting in unrealistic predictions when using load/response models for predicting in-lake phosphorus concentrations. On the basis of the findings in the Hartbeespoort Dam catchment it is felt that before catchment loads are used in load/response models, the phosphorus retention capacity of the drainage basin in question should be assessed and, if required, the loads should be adjusted to account for losses which occur between the sources in the catchment and the receiving water body. Direct water draw-off for agricultural/domestic supplies should be measured or estimated since, in the Hartbeespoort Dam catchment, about 13% of the point source phosphorus input is lost to irrigation alone (Pitman, 1985).

Many factors are likely to influence the efficiency of phosphorus retention in a drainage basin: for example, distance between source and receiving water body; hydrological characteristics in the drainage basin; nature of the river (deep meandering versus shallow fast-flowing); presence of wetlands, weirs and impoundments between the source and the receiving water body; nature and extent of the phosphorus source (point versus diffuse source). At present it is not possible to adequately combine these interacting variables in simple predictive models that would be compatible with the load/response modelling approach, since the mechanisms that contribute to efficient phosphorus retention in aquatic systems are not well understood.

Since nutrient load/eutrophication response models are essential eutrophication management tools, it is a matter of urgency to clarify some of the problems raised in this paper. The suitability of different load estimates, for use in load/response models, should be examined further and the in-stream processes, with their influence on nutrient loads to downstream water bodies, should be quantified and incorporated into management models for use when only catchment load estimates are available. Until these problems are resolved, predictions using catchment loads will be unreliable, complicating the choice and implementation of eutrophication control strategies and obscuring the assessment of their effectiveness.

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