Development of the reservoir eutrophication model (REM) for South African reservoirs

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Abstract

The reservoir eutrophication model (REM) is commonly used to simulate the trophic status of South African reservoirs. Uncertainty analysis is usually not included in such modelling. This is unfortunate because a false sense of model accuracy may result. Uncertainty analyses conducted in this study suggest that the conventional REM model is too simple and too inflexible to accurately characterise the behaviour of individual South African reservoirs. A more accurate reservoir specific eutrophication model (RSEM) has therefore been developed. The RSEM model is more complicated in that it takes account of more variables and has to be calibrated individually for each reservoir. But the improvement in model accuracy, for predicting both historical and future data justifies this complication. In the case of Hartbeespoort Dam the newly developed RSEM model has been compared to the conventional REM model using Monte Carlo simulation. This simulation was designed to test the effect of a 20% decline in the inflow of point source phosphorus. The RSEM model predicts that the effect of this management strategy is an average reduction in chlorophyll of 25%. The REM model predicts only an average 7% reduction in chlorophyll.

Introduction

Eutrophication is the enrichment of water bodies with plant nutrients, mainly phosphorus and nitrogen, which leads to excessive growth of aquatic plants to such levels that it interferes with the desirable uses of the water. Over the last ten years, the word "eutrophication" has been used more and more to denote the artificial and undesirable addition of nutrients and the effect this has on a water body. The effect of eutrophication is visible in excessive growth of algae and aquatic plants. Consequences of such increased growths include taste and odour problems in treated drinking water from eutrophied sources, reduced oxygen which is detrimental to fish and impairment of recreational use of the water.

In this paper we develop empirical models in order to estimate eutrophication. These empirical models can be used to simulate the eutrophication levels that can be expected as the result of different water quality management strategies for the control of point source phosphorus. In this paper we consider the effect of a 20% reduction in the inflow of point source phosphorus for Hartbeespoort Dam. The empirical models derived in this study indicate that the effect of this management strategy would be an average reduction in chlorophyll of 25%. This suggests that large-scale point source removal of phosphorus would have a substantial effect on eutrophication at Hartbeespoort Dam.

The reservoir eutrophication model (REM)(Grobler 1985a; 1985b; 1986) was used to assess the future trophic status of South African reservoirs (Grobler, 1988). This model assumes that only phosphorus limits eutrophication and that chlorophyll concentration is a suitable measure for assessing trophic status of a water body. Three submodels are used in the REM model: a phosphorus export model, a phosphorus budget model and a chlorophyll concentration model. The REM model simulates the export of non-point source and point source phosphorus from catchments, the phosphorus mass balance for the reservoir and resulting chlorophyll concentrations in the reservoir. The REM model is illustrated by the schematic in Fig. 1.

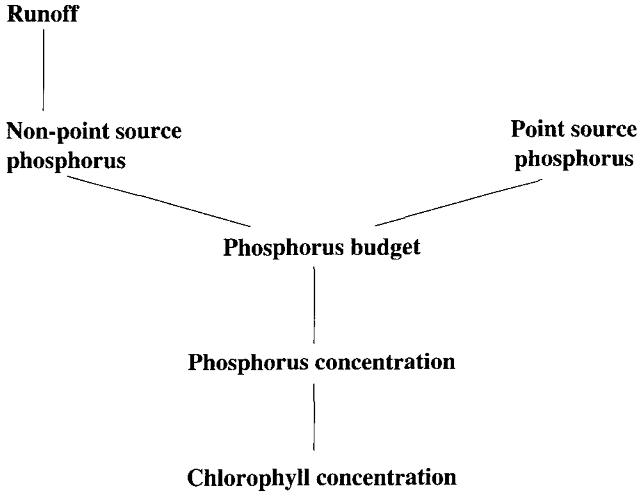

Figure 1
Schematic for the REM Model

This paper describes how each of the three REM submodels was evaluated using South African data. The high degree of uncertainty found to be associated with the REM models for individual reservoirs suggests that the application of the REM procedure may lead to incorrect conclusions regarding the impact of proposed water management strategies for phosphorus control. New models have therefore been developed which address the characteristics of South African reservoirs more closely and hence simulate their behaviour more accurately.

Model evaluation

In this study models are evaluated according to bias, R^2 and error standard deviation. Bias measures the mean prediction error and

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is expressed as a percentage of the observed mean. Ideally the bias should be zero. The R^2 values provide a measure of the explanatory power of the model. Ideally the R^2 should be close to one. Finally the error standard deviation, which is also expressed as a percentage of the observed mean, is used. The errors, e_t, are defined as the difference between the observed and predicted values of the response variable(y) in period t.

$$e_t = y_t - \hat{y}_t, \ t = 1,2, \dots n$$

The error standard deviation is simply the standard deviation of these errors. Ideally the error standard deviation should lie close to zero.

However, when the errors exhibit significant serial correlation the R^2 and error standard deviation measures are unreliable. The R^2 values tend to be over-estimated and the error standard deviations tend to be under-estimated. More accurate estimates for the R^2 and error standard deviations can be obtained as follows. Let us assume that the errors are serially correlated and can be described by the model

$$e_t - \phi e_{t-1} = a_t$$

with the a_t denoting an independent (noise) series or process. Then when the equation

$$y_t - \phi y_{t-1} = b_0 + b_1 (\hat{y}_t - \phi \hat{y}_{t-1})$$

is fitted to the data, the R^2 and error standard deviation obtained will approximate the true R^2 and error standard deviation for the model (Neter et al., 1988).

Model development

There are usually five stages in model development: conceptualisation, formulation, calibration, verification and application. In this study these stages have been used to fit statistical models to South African time series data, resulting in reservoir specific eutrophication models(RSEM). In theory, the complexity of these models is limited only by the extent of the available data base. However, in practice it is found that the reliability of prediction deteriorates with increasing complexity (Constanza and Sklar, 1985). Consequently one of the aims in this study has been to keep the models as simple as possible.

The model conceptualisation stage is usually achieved with the help of "word-models" and flow diagrams (Rossouw, 1986). "Word-models" are used to obtain an accurate verbal description of the system. The system is broken up into modules or compartments in which the controlling processes and interrelationships can be identified. Flow charts are then used to clarify these "word-models".

Linear regression models have been used to formulate the models for individual reservoirs. There are many advantages in these relatively simple models. They are easily calibrated and uncertainty or error analysis, used as a test of model appropriateness, is straightforward. In addition, regression models are easily extended to introduce more water quality variables which are of importance in the system under investigation. By allowing only variables which make a statistically significant contribution (to the predictive information available) to enter and stay in the model, one ensures that models are kept simple and reliable for predictive purposes.

Uncertainty or error analysis has been used as the verification tool. If the errors obtained from a calibrated model do not satisfy the assumptions of the linear regression model this means that the model is either not complete or inappropriate. Regression models assume that the errors are not serially correlated and that both the mean level and variance of the residuals are constant, independent of the value of any variable. If one or more of these assumptions are not supported by the residuals it means that the regression model in its present form is inappropriate and must be changed.

For time series data the Durbin-Watson statistic is a useful measure of independence for successive errors. For values of this statistic close to two, error independence between successive errors can be assumed. For values of this statistic close to zero, successive errors are positively correlated and for values of this statistic close to four, successive errors are negatively correlated. Critical values for this statistic are readily available (Durbin and Watson, 1951).

When the errors are not independent, in all respects, a return to the "conceptualisation stage" is required in order to reformulate the models. The criteria used for successful verification of the models are a Durbin-Watson statistic value close to two and a random error pattern (i.e. horizontal band) when errors are plotted against predicted values or predictor values.

After successful model verification and the fitting of a statistical distribution to the errors, the models have been applied using Monte Carlo simulation. A final check of the newly developed RSEM model for Hartbeespoort Dam involved the comparison of observed (measured) chlorophyll concentrations with chlorophyll concentrations simulated using the newly developed phosphorus export, phosphorus budget and chlorophyll concentration models.

Unfortunately, no split-sample verifications of the final calibrated models were implemented with independent data sets. In time-series simulation in the hydrological and water quality fields the independent verification test has become a crucial criterion for model acceptability. The relative shortness of the time series available in this study made this final test impossible.

The conventional REM phosphorus export model

The REM model for phosphorus export has the form

$$P_t = aR_t^b \qquad (1)$$

where P_t denotes the period t phosphorus load (mass·time^{-1}) derived from non-point sources and R_t (m^3·time^{-1}) denotes the corresponding volume of runoff. This model has been evaluated by Meyer and Harris(1991) using a minimum of six years of monthly data, collected at six flow gauging stations situated in the summer rainfall region of South Africa. Their findings are detailed below.

For each gauging station Model 1 was fitted using non-linear regression procedures (Table 1). For the sample sizes considered a Durbin-Watson statistic value of less than 1,59 indicated, at a 5% significance level, a positive serial correlation between successive errors. This meant that the R^2 values and the error standard deviations had to be corrected for some rivers using the method described previously.

Meyer and Harris (1991) found that the mean level of the errors obtained when Model 1 was fitted to their data was not always independent of runoff. For four of the six rivers they

TABLE 1
CONVENTIONAL REM PHSOPHORUS EXPORT MODEL PERFORMANCE

Gauge	Bias (%)	Durbin-Watson	R^2(%)	Error std. dev. (%)
U2M06 Karkloof	-0,3	2,03	99,4	13,7
U2M12 Sterk	1,7	2,04	97,1	35,8
U2M13 Umgeni	-0,1	1,02	82,2	89,9
A2M13 Magalies	2,4	1,15	96,6	27,5
C4M04 Vet	-9,8	1,65	93,9	56,0
C1M07 Vaal	18,6	1,43	77,0	163,3

TABLE 2
PERFORMANCE OF RSEM PHOSPHORUS EXPORT MODEL

Gauge	U2M06 Karkl.	U2M12 Sterk	U2M13 Umgeni	A2M13 Magal.	C4M04 Vet	C1M07 Vaal
R2 (%)	99,9	99,4	88,6	99,1	94,0	95,7
Error std. dev. (%)	5,4	15,8	72,1	14,5	55,4	70,2

considered, Model 1 under-estimated phosphorus export at both very low and very high runoff volumes. This meant that Model 1 was not sufficiently flexible to model the realities of phosphorus export for South African catchments in the summer rainfall region. Furthermore the values for the Durbin-Watson statistic suggested that Model 1 was not sufficiently flexible to explain the lagged behaviour of phosphorus export systems in all South African catchments. Their data indicated that the effect of runoff is often delayed in the sense that this month's phosphorus export is often affected by runoff in both the current and the previous month.

The improved RSEM phosphorus export model

After considering these deficiencies in Model 1, Meyer and Harris(1991) were able to produce a model which could be used to more accurately simulate phosphorus export in South African catchments. This model is defined as follows:

$$\begin{aligned} &P_t = k \exp(y_t) \; for\; t = 2, 3, ..., n \\ &y_t - cy_{t-1} = b_0 + b_1 (\ln R_t - c\ln R_{t-1}) \\ &\qquad + b_2((\ln R_t)^2 - c(\ln R_{t-1})^2) \qquad (2) \\ &with\; y_t = \ln\,(observed\; P_t) \end{aligned}$$

The k-parameter serves to eliminate bias, the c-parameter serves to eliminate serial correlation in the errors and the b_2 parameter ensures that phosphorus export will not be underestimated at very low and very high runoffs. For two or the rivers considered, the Karkloof and Vet, the quadratic b_2 term was not required. As indicated in Table 2 the improvement in predictive and hence simulative accuracy was often highly significant. Bias is not reported in this table because the k-parameter was calibrated individually for each time series to eliminate the bias completely.

The conventional REM phosphorus budget model

The REM model assumes that the mass of phosphorus in a reservoir at the end of month t, P_t(mass), can be described by the equation:

$$P_t = P_{t-1} + PIN_t - POUT_t - s_t \left(\frac{P_t + P_{t-1}}{2}\right) \qquad (3)$$

where PIN_t(mass) denotes the phosphorus mass entering the reservoir in month t, $POUT_t$(mass) denotes the phosphorus load leaving the reservoir through the outflow in month t, and s_t denotes the sedimentation rate for month t. If it is assumed that the reservoir is completely mixed, $POUT_t$ can be estimated as the product of average in-lake phosphorus concentration and outflow volume. Sas(1989) indicates that this is a reasonable assumption for shallow reservoirs, into which category most of South Africa's reservoirs fall. Under these conditions Model 3 simplifies to the following form:

$$P_t = \frac{P_{t-1}\left(1 - \dfrac{s_t}{2} - \dfrac{WOUT_t}{2W_{t-1}}\right) + PIN_t}{1 + \dfrac{s_t}{2} + \dfrac{WOUT_t}{2W_t}} \qquad (4)$$

where $W_t(10^6 m^3)$ denotes the volume of water in the reservoir at the end of month t and $WOUT_t(10^6 m^3)$ denotes the outflow for

TABLE 3
CHARACTERISTICS FOR HARTBEESPOORT AND WITBANK DAMS

Average monthly values	Hartbeespoort: Mean depth = 9,6 m		Witbank: Mean depth = 10,6 m	
	Mean	Standard dev.	Mean	Standard dev.
Volume ($10^6 m^3$)	118,9	50,6	82,9	19,1
P conc (mg/ℓ)	0,440	0,165	0,041	0,030
Inflow ($10^6 m^3$)	12,78	8,30	9,26	16,13
Outflow ($10^6 m^3$)	12,18	6,58	9,57	18,92

TABLE 4
CONVENTIONAL REM PHOSPHORUS BUDGET MODEL PERFORMANCE

Model	Hartbeespoort Dam		Witbank Dam	
	s = 0,27	k = $4{,}6 \times 10^{-7}$	s = 0,51	k = $3{,}7 \times 10^{-5}$
Bias (%)	1,7	18,0	0,2	-31,3
Durb. Wats.	1,45	1,82	2,19	1,90
R^2 (%)	64	60	74,4	57,1
Error std.dev. (%)	16,6	17,5	42,9	55,5

TABLE 5
PERFORMANCE IMPROVED RSEM PHOSPHORUS BUDGET MODELS

	Hartbeespoort Dam	Witbank Dam
s_1 (in-lake)	0,043	0,275
s_2 (inflow)	0,635	0,334
Durbin-Watson	1,81	2,61
R^2 (%)	86	87
Error std.dev. (%)	15,7	39,2

month t. Either a constant sedimentation rate (s_t=s) or a third-order concentration dependent sedimentation reaction ($s_t=k[P]_t^3$) are assumed throughout the reservoir. Both these models have been tested for the Hartbeespoort and Witbank Dams using monthly data for the periods October 1980 to January 1989 and October 1986 to December 1989 respectively. As indicated in Table 3 these two reservoirs differ markedly in their physical and chemical characteristics.

Using non-linear regression the sedimentation parameters, s for a constant sedimentation rate and k for a third-order sedimentation reaction, were estimated and the performance of the corresponding models was assessed in Table 4. Clearly the constant sedimentation rate s-models fitted the data better for these reservoirs than the third-order reaction k-models.

The improved RSEM phosphorus budget model

Grobler (1985a) explains that South African reservoirs often receive inflows rich in particulate phosphate which is lost through sedimentation at a faster rate than dissolved phosphorus. It seems therefore that a higher sedimentation rate for the inflow is called for as a result of the form of the incoming phosphorus.

This suggests an unbiased constant sedimentation rate phosphorus budget model of the form:

$$P_t = (1 - s_1)\, P_{t-1} + (1 - s_2)\, PIN_t - POUT_t \qquad (5)$$

$$i.e.\ P_t = \frac{\left(1 - s_1 - \dfrac{WOUT_t}{2W_{t-1}}\right) P_{t-1} + (1 - s_2)\, PIN_t}{1 + \dfrac{WOUT_t}{2\, W_t}}$$

where s_1 is the general in-lake sedimentation rate and s_2 is the sedimentation rate for the inflow only. Calibration results for Hartbeespoort and Witbank Dam appear in Table 5. A general in-lake sedimentation rate of 4,3% per month and 27,5% per month are suggested for Hartbeespoort Dam and Witbank Dam respectively. The sedimentation rate predicted for the inflow is 63,5% per month for Hartbeespoort Dam and 33,4% per month for Witbank Dam. The differences in the sedimentation rates of these two dams are, to some extent, the result of differences in reservoir morphometry. The R^2 values and error standard deviations in Table 5 indicate that Model 5 describes the data better than the constant sedimentation rate s-Model 4.

This is not the first study in which in-lake and inflow sedimentation rates have been allowed to differ. Prairie(1988) found this approach appropriate in a cross-sectional study for 122 Northern Hemisphere lakes. In such cross-sectional studies

TABLE 6
THE CONVENTIONAL REM CHLOROPHYLL MODEL 7 RECALIBRATED

	Hartbeespoort	Witbank
Durbin-Watson	1,38	2,02
R^2 (%)	2	7
Error std.dev. (%)	28,8	43,0
a	7,786	13,037
b (std. error)	0,23 (0,15)	0,34 (0,19)

TABLE 7
NUTRIENT CONCENTRATIONS : HARTBEESPOORT AND WITBANK DAMS

	Hartbeespoort		Witbank	
	Mean	Std. dev.	Mean	Std. dev.
Total phosphorus (mg/ℓ)	0,460	0,271	0,035	0,025
Kjeldahl nitrogen (mg/ℓ)	0,998	0,403	0,611	0,184
Ratio TN : TP	6,08	4,45	29,89	14,95
Ammonia (mg/ℓ)	0,217	0,170	0,089	0,089
Nitrites (mg/ℓ)	2,231	1,145	na	na
Nitrates (mg/ℓ)	0,179	0,109	0,201	0,118
Orthophosphate (mg/ℓ)	0,291	0,198	0,007	0,008
Total dissolved salts (mg/ℓ)	na	na	271	23
Secchi depth (m)	1,32	0,72	1,46	0,46
Chlorophyll (µg/ℓ)	47,2	41,8	4,61	3,38

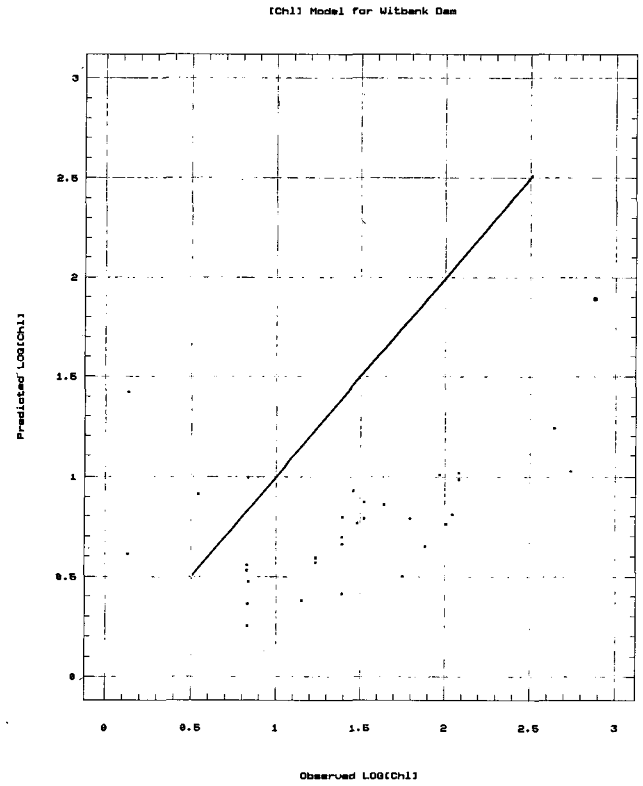

Figure 2
Jones and Lee (1982)
[Chl] model for Witbank Dam

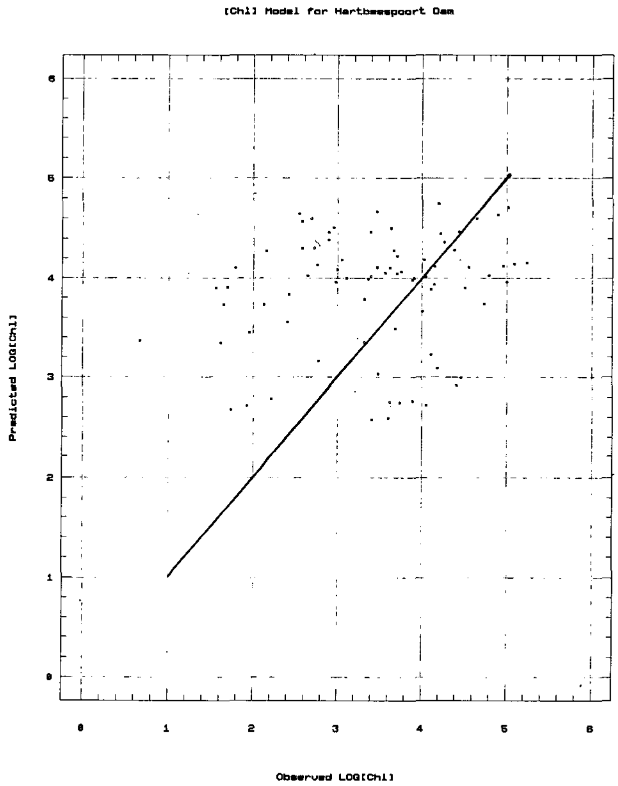

Figure 3
Jones and Lee (1982)
[Chl] model for Hartbeespoort Dam

data for many reservoirs are analysed, usually with only one observation per reservoir instead of a time series for each reservoir (Time series usually consist of a set of observations collected regularly over a period of time).

The conventional REM chlorophyll concentration model

The OECD eutrophication study involved the examination of phosphorus loads and response characteristics for about 200 water bodies in 22 countries over a five-year period. From these data Jones and Lee(1982) developed the following cross-sectional model to predict mean summer chlorophyll concentrationst[Chl] (μg/ℓ) from mean summer total phosphorus concentrations[P] (μg/ℓ).

$$[Chl] = (0{,}45)\,[P]^{0{,}79} \qquad (6)$$

This model is used in this (uncalibrated) form in the conventional REM model.

The Jones and Lee (1982) OECD model has been tested using monthly data for both summer and winter for the Hartbeespoort and Witbank Dams. The Hartbeespoort Dam data represent month-end concentrations for the period July 1983 to January 1990. The Witbank data represent average monthly concentrations for most of the period July 1986 to December 1989. As indicated in Figs. 2 and 3 it seems that the uncalibrated Jones and Lee(1982) model is not suitable for either of these dams. For Witbank Dam the Jones and Lee model under-estimates the higher [Chl] levels. For Hartbeespoort Dam the Jones and Lee model over-estimates the lower [Chl] levels.

In an attempt to obtain a better fit the Jones and Lee(1982) model was recalibrated for the Hartbeespoort and Witbank data. To simplify the analysis, log-transformations were used resulting in the following model for ln[Chl] in terms of the logarithm of total phosphorus concentration, ln[TP].

$$\ln\,[Chl] = \ln a + b \ln\,[TP] \qquad (7)$$

The b-coefficients shown for both reservoirs in Table 6 are barely significantly different from zero, indicating a very weak relationship between phosphorus and chlorophyll concentrations. It seems therefore, that even in its recalibrated form, the Jones and Lee(1982) model should not be used to predict chlorophyll concentrations for the Witbank and Hartbeespoort Dams.

The improved RSEM chlorophyll model

Let us consider the characteristics of the Hartbeespoort and Witbank reservoirs in an attempt to understand their potential for algal growth. Table 7 describes the two reservoirs in terms of the available water quality data (Butty et al., 1980). The nutrient concentrations for Witbank Dam were lower than those for Hartbeespoort Dam for all nutrients except nitrates. In addition there was a marked difference in the mean (total nitrogen):(total phosphorus) (TN:TP) ratios for the two reservoirs.

The mean (TN:TP) ratio was much higher for the Witbank Dam than for the Hartbeespoort Dam. Ryding and Rast(1989) note that phosphorus concentrations limit algal growth for (TN:TP) ratios in excess of 7. At Witbank Dam the mean (TN:TP) ratio exceeds 7 indicating that, on average, phosphorus controls will have an effect on [Chl]. At Hartbeespoort Dam this mean ratio falls below 7, indicating that, on average, phosphorus controls will have less effect. However, the large standard deviation associated with this ratio at Hartbeespoort Dam indicates that, for a substantial proportion of the time, phosphorus levels may limit algal growth. Consequently, phosphorus controls for Hartbeespoort Dam are expected to have an important influence on [Chl].

The Jones and Lee(1982) OECD model is designed for reservoirs where algal growth is limited by phosphorus during the growing season. An attempt has been made to improve on their chlorophyll model by considering the possibility that other nutrients may be, periodically, growth-limiting in the case of the Hartbeespoort and Witbank Dams. Log transformations were applied to both chlorophyll and nutrient concentrations before performing a stepwise linear regression. As explained by Sas(1989), if no log transformation is applied, variability increases at the upper end of the chlorophyll scale resulting in inaccurate [Chl] predictions.

Of course, nutrients are not the only variables which affect [Chl]. Temperature and water clarity also have some influence. Unfortunately, no data were available for these variables so they could not be included in the [Chl] models directly. However, to some extent these are seasonal variables, highly correlated with concentrations of nutrients from non-point sources. Consequently the effect of temperature and water clarity have been considered indirectly.

When considering a linear regression model for ln[Chl], in terms of the nutrients listed in Table 7, the interpretation of the models is difficult because of the dependence between some nutrient concentrations. Indeed, such dependence between the independent variables (multicollinearity) means that the separate effects of the different nutrients cannot be assessed using their respective coefficients. Fortunately, however, multicollinearity does not affect the accuracy of the predictions obtained from the model (Neter et al., 1988).

For Hartbeespoort Dam it was found that, by incorporating concentrations for Kjeldahl nitrogen[KN], nitrates[NO_3], nitrites[$N0_2$], orthophosphate[$P0_4$] and ammonia[NH_4] in the regression as shown in Equation 8, the R^2 rose from 2% to 49%.

$$\begin{aligned}\ln\,[Chl] =& + (1{,}21 \ln\,[TP] + 0{,}58 \ln\,[KN] + 0{,}51 \ln\,[NO_3]) \\ & - (0{,}36 \ln\,[NO_2] + 0{,}76 \ln\,[PO_4] + 0{,}67 \ln\,[NH_4]) \qquad (8)\end{aligned}$$

The effect of this increase in R^2 is illustrated graphically in Fig. 4. The calibrated REM model, with an R^2 of 2%, overestimates the lower ln[Chl] level and under-estimates the higher ln[Chl] levels. The calibrated RSEM, with an R^2 of 49%, gives more reasonable estimates of ln[Chl] at all levels.

As mentioned above, some of the nutrient concentrations in this equation are highly correlated. However, the P-values associated with each of these nutrients are very small, indicating that all these nutrient concentrations are needed in the model in order to get accurate forecasts of [Chl]. But, in view of the multi- collinearity, no attempt should be made to interpret the coefficients.

The P-value associated with the [TP] coefficient in this equation was 0,0021. This indicates a very strong linear relationship between ln[TP] and ln[Chl], when the effect of [PO4] and other growth-limiting nutrients has been removed. When the effect of [PO4] and these other growth-limiting nutrients was ignored, as in Model 7, the effect of ln[TP] on ln[Chl] was masked to such an extent that this relationship seemed to be almost non-existent.

For Witbank Dam it was found that by incorporating total dissolved salts[TDS], nitrates[NO_3] and Kjeldahl nitrogen[KN] in the model as shown in Equation 9, the R^2 rose from 7% to 50%.

$$\ln [Chl] = +(0{,}70 \ln [TP] + 5{,}10 \ln [TDS] + 0{,}45 \ln [NO_3]) - (24{,}23 + 0{,}65 \ln [KN]) \qquad (9)$$

This improvement in R^2 is illustrated in Fig. 5. The calibrated REM model, with an R^2 of 7%, over-estimates the lower ln[Chl] levels and under-estimates the higher ln[Chl] levels. The calibrated RSEM, with an R^2 of 50%, gives more reasonable estimates of ln[Chl] at all levels.

Again the P-value associated with the [TP] coefficient was very low, 0,0001, indicating a strong [TP]:[Chl] relation, when the effect of these other growth-limiting factors was taken into consideration. The authors feel that [TDS] affects [Chl] indirectly through its effect on turbidity and hence water clarity. The nature of this effect has been discussed by Akhurst and Breen(1988) and Grobler et al. (1983).

Neither Equation 8 nor 9 should be regarded as final models. The R^2 value for Hartbeespoort Dam could almost certainly have been improved had data for dissolved salts, or, preferably, some better measure of water clarity been available. The intention here was merely to illustrate the necessity for considering all factors which limit growth when trying to model [Chl].

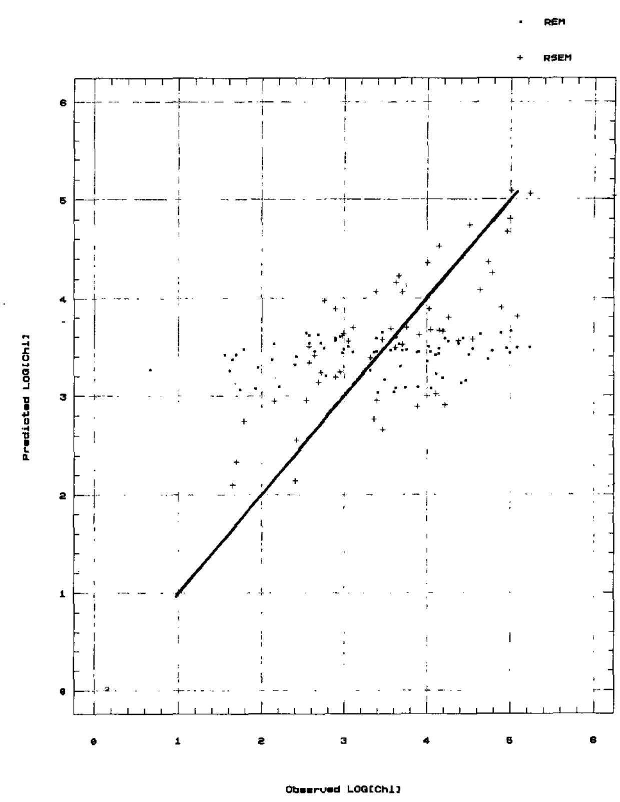

Figure 4
Calibrated REM and RSEM models for Hartbeespoort Dam

Monte Carlo simulation

The conventional and newly developed REM models have been applied to 46 months of Hartbeespoort Dam data in order to simulate monthly chlorophyll levels. The flow of point source phosphorus into the dam was obtained by deducting the non-point source phosphorus load from the measured phosphorus inflow. The total non-point source phosphorus load (TNPSP) was calculated from the phosphorus export from the Magalies River (MNPSP), the water inflow from the Magalies River (MI) and the total dam water inflow (TI), using the formula:

$$TNPSP = \frac{(MNPSP)\,(TI)}{MI}$$

Note that this estimate for the point source phosphorus relates only to that proportion of the point source phosphorus that eventually finds its way into the dam. Point source phosphorus which remains permanently trapped as river sediment is not included.

In the first simulation for both models (REM and RSEM) the 100% figures for inflowing point source phosphorus were used. In the second simulation for both models the inflowing point source phosphorus load was reduced by 20% in all months.

In all analyses runoff levels were simulated using predictions and error distributions obtained by the Pitman(1973) procedure. Non-point source phosphorus export was simulated for the Magalies River using the conventional REM Model 1 and improved RSEM Model 2 phosphorus export models. A suitable factor (TI/MI) was applied to these simulated values to obtain an estimate of the total non-point source phosphorus load entering the dam. Adding the prescribed level of point-source phosphorus(PSP) load, Models 3 and 5 were used to simulate the phosphorus budget for the dam. Finally Models 7 and 8 were used to simulate [Chl]. Observed values were used for [KN], [NO_3], [NO_2], [PO_4] and [NH_4] in Model 8 for both the 100% and 80% PSP simulations. Somewhat simplistically it has been

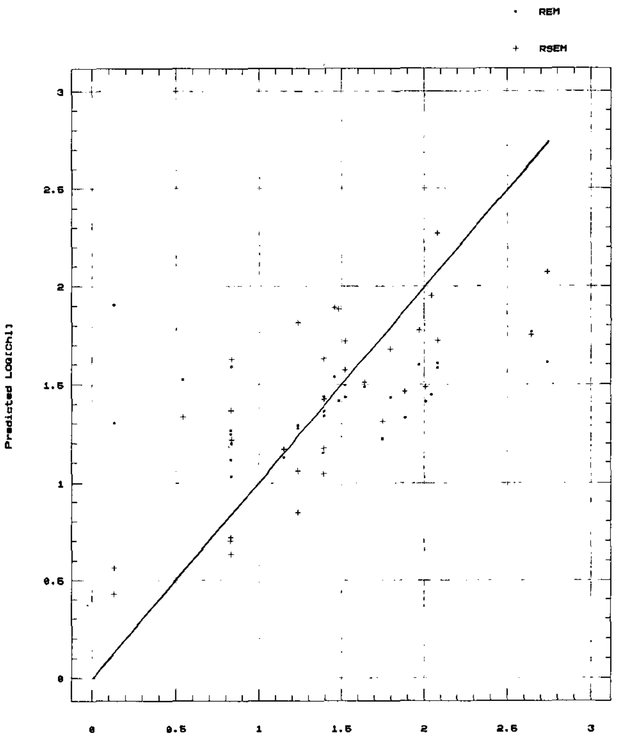

Figure 5
Calibrated REM and RSEM models for Witbank Dam

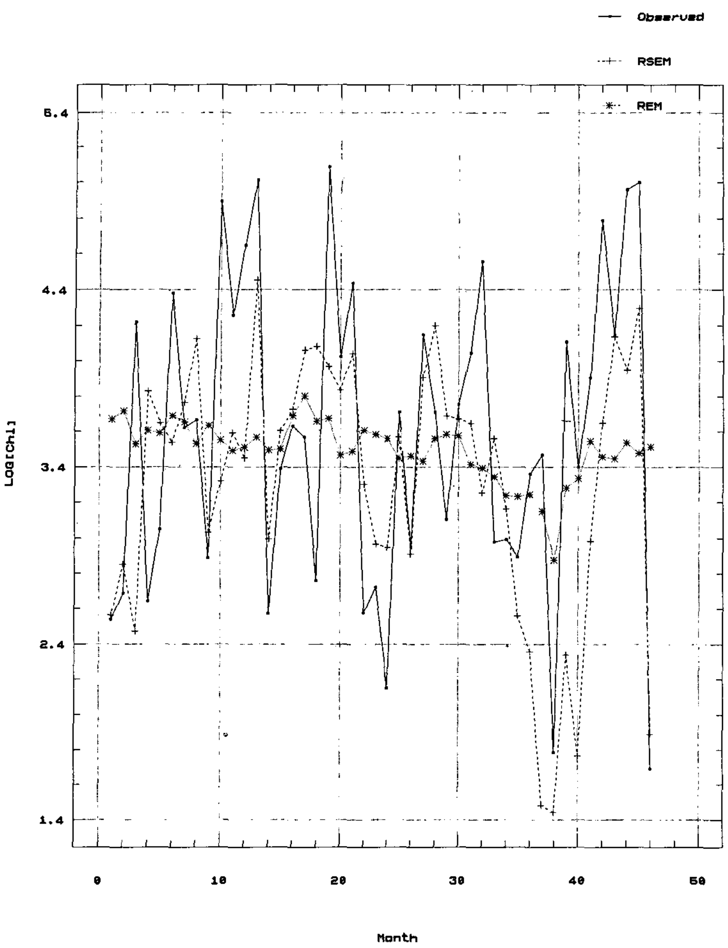

Figure 6
Comparison of observed [Chl] with mean simulated [Chl]

assumed that these concentrations will not be affected by a 20% decline in the inflow of total phosphorus from point sources. According to Osborn(1987) nitrogen levels will not be affected by a PSP control process only if the process is chemical rather than biological.

Figure 6 compares the mean simulated values for 100% PSP ln[Chl] with the observed ln[Chl] values. The simulated mean for each month is the result of 100 Monte Carlo iterations. Clearly there was considerable variation in the observed values of ln[Chl]. The RSEM model tracks this variation reasonably well, whereas the REM model cannot do this. This was expected on account of the low R^2 values associated with the REM model. If a model cannot describe historical data adequately it cannot be expected to simulate future data with any degree of accuracy. The insensitivity of the REM model to variation in [Chl] means that the REM model should not be used as a tool for simulating the changes in [Chl] that will result from PSP controls.

The conventional REM chlorophyll Model 7 indicated a very weak relationship between chlorophyll and phosphorus. The newly developed RSEM chlorophyll Model 8 indicated a much stronger relationship between chlorophyll and phosphorus, once the effect of other nutrients had been taken into account. Consequently the responsiveness or sensitivity of simulated [Chl] to simulated phosphorus levels in the case of the newly developed RSEM model was to be expected.

Figure 6 compares the simulated [Chl] for 80% point source phosphorus inflow with 100% point source phosphorus inflow using both the REM and RSEM models. Whereas the RSEM model suggests that this phosphorus control strategy will have a significant effect on [Chl] the REM model suggests the contrary. The RSEM model predicts an average reduction of 25% in [Chl] in any month whereas the REM model predicts an average reduction of only 7%. Figures given by Sas(1989) suggest that a 26,8% reduction in [Chl] can be expected as the result of a 20% reduction in average in-lake phosphorus concentration, in the case of shallow, phosphorus-limited lakes. The RSEM prediction is therefore realistic.

Conclusions

The reservoir model is, potentially, an important tool for simulating the future trophic status of South African reservoirs. However, this tool is only as good as the predictive accuracy of the three constituent models used to simulate phosphorus export, phosphorus budgets and chlorophyll concentrations. It has been shown that in its usual form the REM model does not accurately describe the historical characteristics of two South African reservoirs and, as a result, the accuracy of the chlorophyll levels it simulates is a subject for concern.

In attempting to improve the accuracy of the REM model simulations it is recommended that a reservoir-specific approach should be adopted. As illustrated in this analysis for the

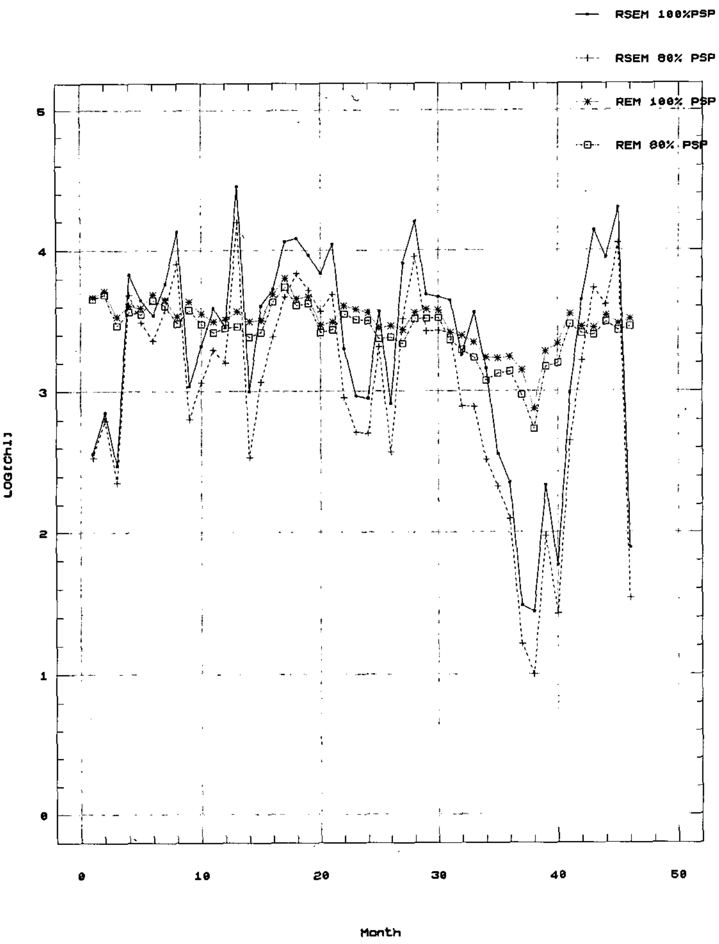

Figure 7
Simulated effect of a 20% drop in the inflow of point source phosphorus

Hartbeespoort and Witbank Dams, South African reservoirs differ markedly as regards their chemical and physical characteristics. This means that model flexibility is called for. However, it is important that modelling should not develop into a statistical exercise. Above all else meaningful models which relate directly to reservoir characteristics should be sought.

This study has shown that the conventional REM model should not be used to simulate the trophic status of the Hartbeespoort and Witbank Dams. A statistical approach has been used to produce models which reproduce past data and simulate future data more reliably than the REM models. This approach needs to be tested and developed using data for many more South African reservoirs.

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