Application of OECD eutrophication modelling approach to South African dams (reservoirs)

R. ANNE JONES AND G. FRED LEE
Department of Civil Engineering, Texas Tech University, Lubbock, Texas 79409, USA.

Abstract

The paper makes use of information collected during an earlier study of the eutrophication of 21 dams in South Africa, in order to evaluate the applicability of the OECD eutrophication modelling approach to South African dams. Through the OECD (Organization for Economic Cooperation and Development) Eutrophication Program, statistical regressions were developed based on data on about 350 waterbodies around the world to describe the relationship between the nutrient loading to a waterbody and its eutrophication-related water quality as measured by chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate. These regressions which have demonstrated predictive capability, have been found to be applicable to the South African dams evaluated. This modelling approach can be used by water quality managers in South Africa to evaluate the impact that a variety of nutrient control options will have on the eutrophication-related water quality of the dams.

Introduction

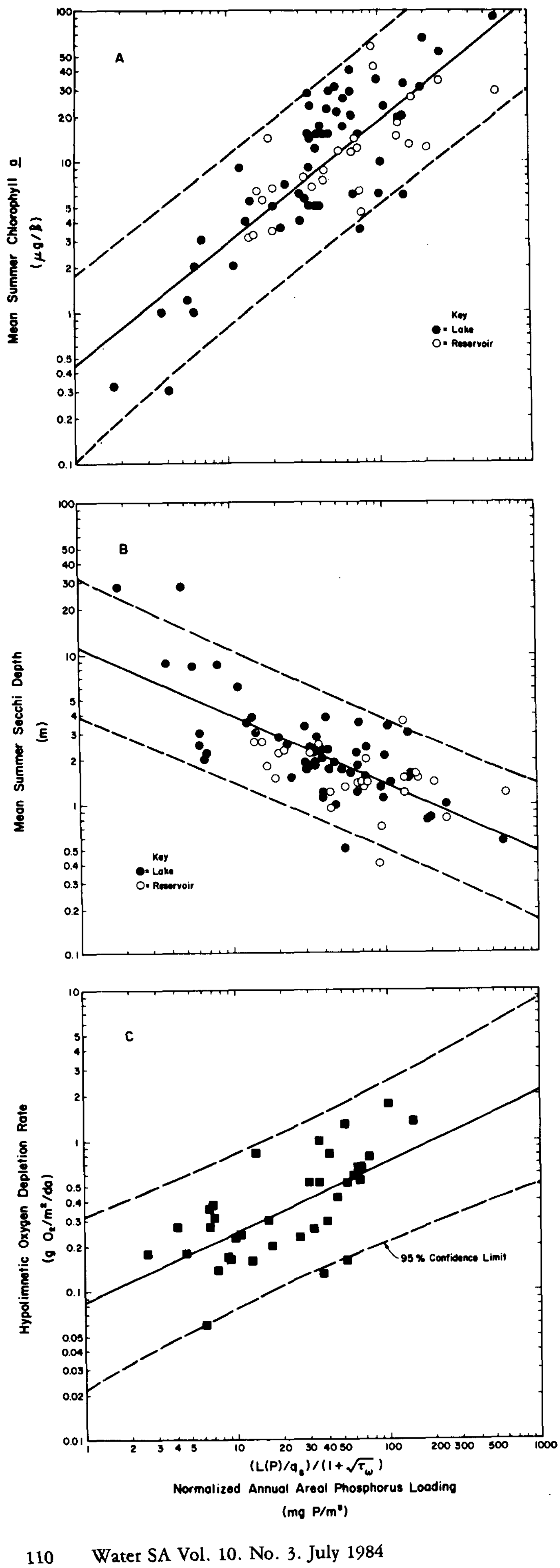
The Republic of South Africa has more than a hundred dams (reservoirs) constructed largely as irrigation water storage facilities and some for domestic water supplies. With the increasing population of the country, many of the reservoirs are receiving increased use as drinking water supplies and recreational sites. Because of the demographic, climatological, and hydrological characteristics rather unique to South Africa, many of the headwaters as well as other dams in the country also receive extensive use as receiving waters for domestic wastewater treatment plant discharges. These discharges typically contain large quantities of aquatic plant nutrients (nitrogen and phosphorus) which in many instances contribute significantly to the excessive fertilization-eutrophication of impounded waters. Increasing population pressures, the relative scarcity of water in the country and the associated need to use and re-use its waters, and the costs associated with treating or managing poorer-quality water for beneficial use, heighten the significance of eutrophication of South African dams.

In the early 1970's, governmental agencies in South Africa began to express their concern over eutrophication-related water quality problems which were being manifested as problems with water treatment and recreationally aesthetically poor-quality water. The National Institute for Water Research (NIWR) of the Council for Scientific and Industrial Research (CSIR), was contracted by the Water Research Commission (WRC) to investigate the causes, consequences, and control of eutropication of South African impoundments. As part of this work, a one-year study was conducted on each of 21 dams to gather information to develop an empirical nutrient load – eutrophication response relationship for South African impoundments (WRC and NIWR-CSIR, 1980). A report, produced from this overall eutrophication study, by Walmsley and Butty (1980) considered a number of empirical load-response relationships that had been reported in the literature. It also prescribed a relationship between phosphorus load and chlorophyll concentration that appeared to best fit the available data on South African dams. That report, however, did not consider or evaluate the applicability of the results of the most extensive global nutrient load-eutrophication response study ever undertaken, i.e. the OECD (Organization for Economic Cooperation and Development) Eutrophication Study (Vollenweider, 1976; Rast and Lee, 1978; Lee *et al.*, 1978a).

The OECD eutrophication modelling approach has been found applicable to the over 350 waterbodies to which it has been applied throughout the world and has a demonstrated predictive capability (Jones and Lee, 1982; Rast *et al.*, 1983). Further, some of the parameters that have been repeatedly found to be crucial to describing the relationships between nutrient load and eutrophication-related water quality characteristics, specifically waterbody mean depth, hydraulic residence time, and surface area, were not included in the Walmsley and Butty (1980) load-response formulations for South African dams. The authors therefore felt it appropriate to evaluate whether or not the OECD modelling approach would indeed be applicable to South African impoundments.

OECD Eutrophication modelling approach

In the early 1970's a 5-year, 22-country, 200-waterbody study was begun under the auspices of the OECD to quantify a relationship between nutrient loads to waterbodies and their respective eutrophication-related water quality responses. It was designed in part to collect necessary information to evaluate the relationship developed by Vollenweider (1976) between P load, normalized by mean depth, hydraulic residence time and surface area, and chlorophyll concentration for its general applicability to waterbodies located in various parts of the world. The junior author had the contract to describe and evaluate the load-response relationship for the approximately 34 US waterbodies or parts of waterbodies included in the international OECD study and also served as an adviser to the overall OECD Eutrophication Study. The results of Lee's evaluations, which unlike those for the rest of the OECD waterbodies were not based on new studies but rather on the substantial amounts of existing data on the US waterbodies, were completed in the mid-1970's and were published by the US Environmental Protection Agency (EPA) (Rast and Lee, 1978). A summary paper was also published on this work (Lee *et al.*, 1978a). Subsequent studies by Lee and his associates as summarized by Jones and Lee (1982), added about 40 more waterbodies to the data base constituting the empirical relationships between P load (normalized by waterbody mean depth, hydraulic residence time, and surface area) and mean summer chlorophyll (greenness), mean summer Secchi depth (water clarity), and hypolimnetic oxygen depletion rate, for US waterbodies. These



<u>**KEY**</u>

$L(P)$ = Areal Annual Phosphorus Load (mg P/m^2/yr)

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

τ_ω = Hydraulic Residence Time (yr)

Figure 1
Phosphorus load-eutrophication response relationships for US waterbodies following OECD modelling approach
After Jones and Lee (1982)

relationships and the data points upon which they were formed are shown in Figure 1. These lines of best fit are essentially the same as those subsequently developed by Vollenweider (OECD, 1982) from the entire 200-waterbody OECD data base.

Based on measured values, Rast *et al.* (1983) and Jones and Lee (1982) determined the change in position of a waterbody's load-response coupling that occurred after its phosphorus load had been altered. They found that a waterbody will track parallel to the lines of best fit in Figure 1 when the P loading (abscissa) term is changed. Thus, by knowing an initial P load-response coupling for a waterbody, the change in chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate that will be brought about by a change in P load can be estimated.

There seems to be considerable confusion among some not familiar with the development and use of these relationships, regarding the "95 % confidence" levels shown in Figure 1. These were developed to describe the area within which 95 % of the points plotted. Their only relevance is for the situation in which no waterbody response information is available for a waterbody, and the response must be estimated based on load. For example, if the normalized P loading to a dam was 100 mg P/m^3, it would be expected that the average summer epilimnetic chlorophyll concentration would be about 20 $\mu g/\ell$; it could, however, be anywhere between 6 and 70 $\mu g/\ell$ based on the data base used to formulate the relationships. However, the 95 % confidence intervals have nothing whatever to do with predicting the chlorophyll level (or Secchi depth or hypolimnetic oxygen depletion rate) that will result from a change in P loading if an initial P load-chlorophyll coupling (point) for the waterbody can be determined. As shown by Rast *et al.* (1983), the load – response relationships for a waterbody will track parallel to the lines of best fit when the P load is changed. Whatever causes a waterbody's point to plot above or below the "norm," i.e., the lines of best fit, appears to be a log constant when the loading term is changed. The confidence intervals have no bearing on the reliability of those predictions under the conditions described above.

Application to South African impoundments

South African data base

The report summarizing the results of the study on 21 South African impoundments (WRC and NIWR-CSIR, 1980) (see Figure 2) provided information pertinent to developing load-response couplings for 21 reservoirs included in that study. Since that report provided only averaged data, it was not possible for the authors to screen the data as recommended by Jones and Lee (1982) and modify them as appropriate for this modelling. Possible problems with use of these data are discussed below. Jones and Lee (1982) and Rast *et al.* (1983) provide more detailed discussion of screening data and necessary modifications for using the OECD eutrophication modelling approach.

It appears that the phosphorus loadings were calculated by multiplying monthly average flows by monthly average P concentrations. In systems with variable flows and concentrations, as the South African dam systems appear to be, this method of calculation could cause the loading estimates to be substantially different from the load actually received by the dam (Rast and Lee, 1983).

The total phosphorus load to a waterbody having arms (dendritic) or large bay areas, or to one which is highly elongate,

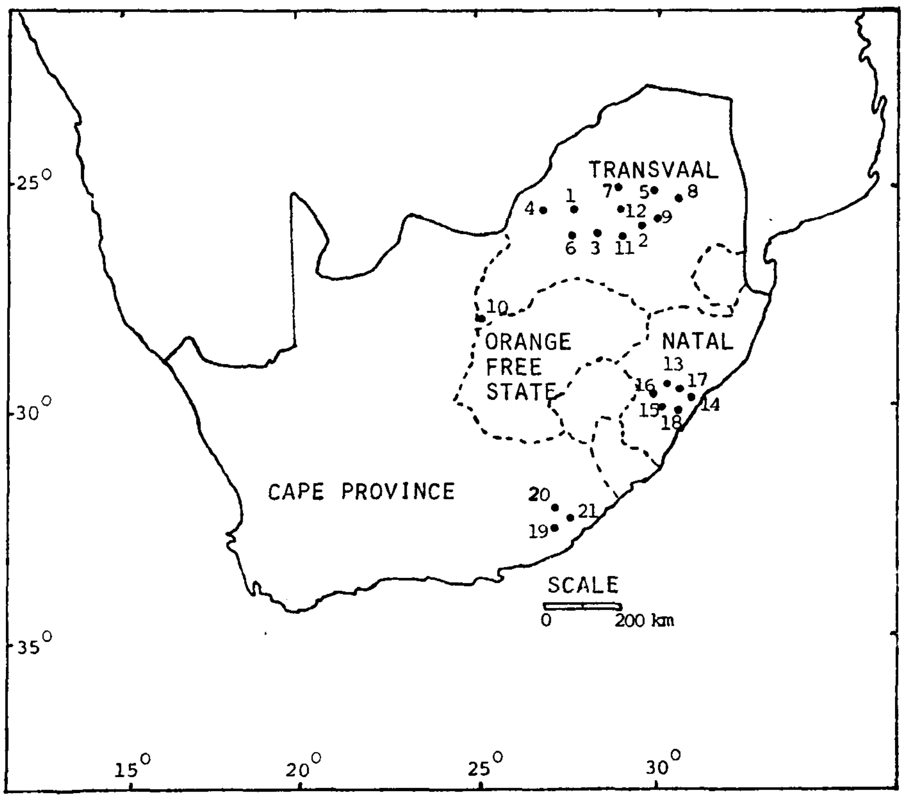


Figure 2
Map of South Africa showing the position of the 21 study impoundments (see Table 1 for waterbody identification)

often needs to be modified to more appropriately represent the load received by the main body of the reservoir or the specific area which the chlorophyll or other response data represent. This effect could not be properly evaluated by review of the WRC and NIWR-CSIR (1980) report; it would, however, tend to cause the chlorophyll responses of this waterbody to be somewhat lower than the US OECD Eutrophication Study line of best fit, since there were few waterbodies in that data base which had morphological characteristics that enabled an appreciable part of the P load to be removed before it reached the main body of the waterbody.

As noted in Figure 1, the US OECD P load-chlorophyll response model was developed based on mean, summer, epilimnetic chlorophyll concentration. The chlorophyll data provided in WRC and NIWR-CSIR (1980) report were annual average concentrations of chlorophyll in what appeared to be depth-integrated samples. Thus the chlorophyll levels presented would be expected to be lower than those indicated by the US waterbody line of best fit. It was also not possible to determine if the sampling occurred during unusual conditions of weather, load alterations, changes in dam height, etc. which could cause the load-response relationships to be atypical.

Load – response relationships

Even with these caveats, the authors felt it a useful exercise to evaluate, albeit in a preliminary way, whether or not the South African waterbodies for which some data were available tended to fall in the same general population of points representing about 350 other waterbodies around the world.

Table 1 presents the data, derived from the WRC and NIWR-CSIR (1980) report, used to describe the normalized P load-eutrophication response couplings of the 21 South African impoundments in the OECD eutrophication modelling approach framework.

Figure 3 shows the positions of the 21 South African dams on the OECD P load-chlorophyll response model, relative to the US waterbody line of best fit (Figure 1A). It can be seen that, for the most part, the relationships between normalized P load and chlorophyll for these South African dams are within the same family as the US waterbodies, as well as the international OECD waterbodies. As a group, the South African waterbodies tend to plot below the "average" of the waterbodies evaluated indicating at first glance that the South African waterbodies tend to produce fewer algae for a given phosphorus load relative to US waterbodies. However, this positioning would be expected for several reasons related to the way in which the data were collected and manipulated as noted previously. The authors believe that the principal reason that these waterbodies plot low relates to the fact that most of these dams are elongate and dendritic in morphology. The phosphorus loads reported were those received by the upper ends of the waterbody arms whereas the chlorophyll concentrations represent the conditions in the main body, near the dam walls (dams) often tens of kilometres downstream. For example, New Doringpoort Dam (No. 9) is on the order of 45 km long; its loading was determined at a point near where the Olifants River swells to become the dam (reservoir), and chlorophyll was measured at the dam wall. The hydraulic residence time of this waterbody overall (0,88 years) is likely sufficient to allow substantial algal growth all along the course of the dam. When this occurs, substantial amounts of phosphorus are re-

TABLE 1.
CHARACTERISTICS OF SELECTED SOUTH AFRICAN DAMS*

Dam**	Mean depth (m)	Hydraulic residence time (yr)	Areal total P load (g P/m²/yr)	Annual average chlorophyll (µg/ℓ)
1. Bospoort	5,2	0,16	7,71	12
2. Bronkhorstspruit	6,7	0,37	1,14	5
3. Buffelspoort	7,7	0,36	7,71	6 4
4. Lindleyspoort	8,0	0,12	1,58***	3,4
5. Loskop	9,6	0,36	1,93	11
6. Olifantsnek	5,4	0,23	0,86	3
7. Rust der Winter	5,8	0,29	1,1	4
8. Tonteldoos	3,8	0,033	1,34***	1,1
9. New Doringpoort	8,1	0,88	0,91	3
10. Bloemhof	4,5	0,55	7,85***	22
11. Rietvlei	5,9	0,33	32,5	9,9
12. Roodeplaat	10,6	0,38	15	17
13. Albert Falls	12,4	1,5	0,25	5,4
14. Hazelmere	10,8	0,35	4,58	5,7
15. Henley	8,2	0,11	7,64	4
16. Midmar	11,1	1,0	0,46	2,5
17. Nagle	15,2	0,17	2,11	2,6
18. Vernon Hooper	8,8	0,05	26,3	16
19. Bridle Drift	11,8	0,56	18,7	0,15
19A.				(36)****
20. Laing	10,2	0,42	33,9	0,17
20A.				(42)****
21. Nahoon	5,9	1,7	6,18	0,75

*After WRC and NIWR-CSIR (1980).
**The numbers that appear with the dam name correspond to the points shown in Figures 2 and 3.
***Total P loads were not available; these values are for soluble ortho-P loads.
****February 1983 mean, provided by Hart (1983)

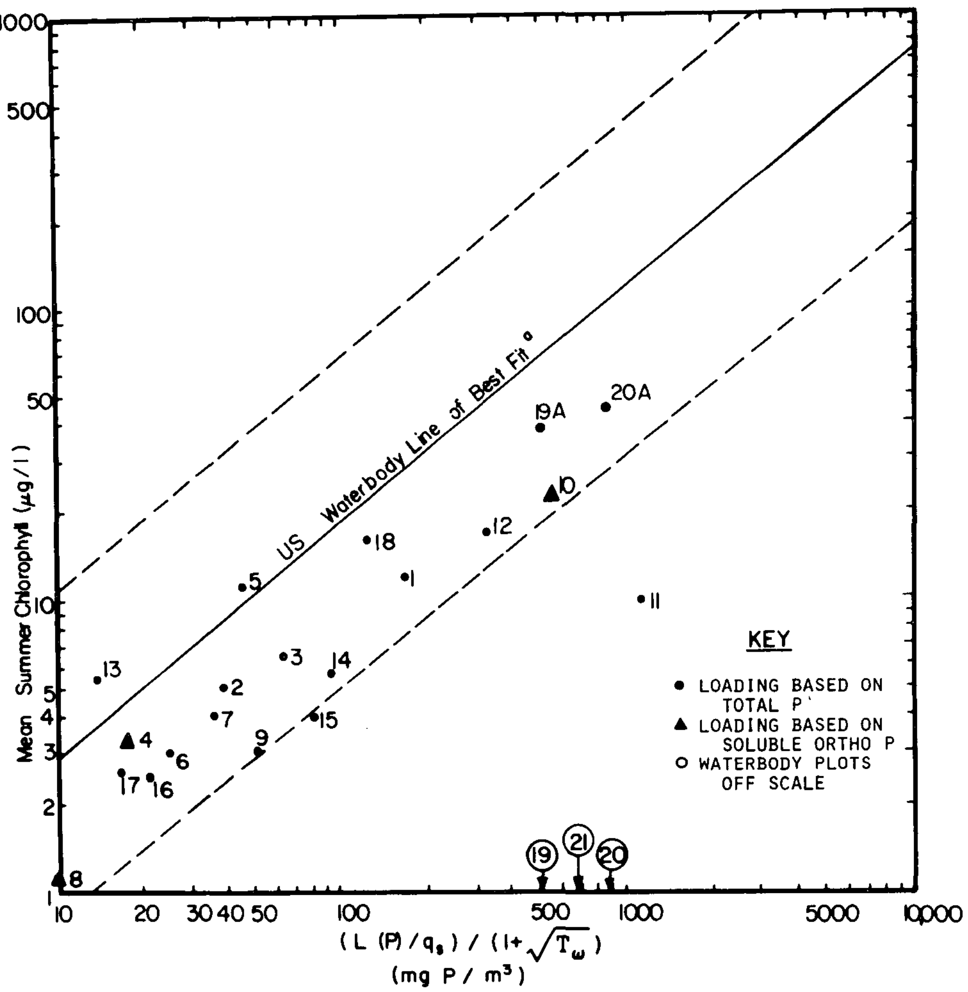


Figure 3
Phosphorus load-annual average chlorophyll relationship for South African dams (reservoirs) OECD eutrophication modelling approach. See Table 1 for waterbody identification). [a]After Jones and Lee (1982a)

moved from the watercolumn into the sediments. This was documented for one example, by Lee *et al.* (1978b) and Archibald and Lee (1981) who found that an arm of Lake Ray Hubbard near Dallas, Texas, USA removed to the sediment about 90 % of the phosphorus it received, because of algal growth, and thus only contributed 10 % of its P load to the main body of the reservoir. Typically, this removal is 75 to 95 % or so when the residence time of the area is 2 weeks or more. It is also well-known that there are mechanisms acting in riverine systems which decrease the availability of phosphorus (Lee *et al.*, 1980). This factor is also likely acting in the New Doringpoort Dam. If the total P load to New Doringpoort Dam was reduced by 75 % as might be expected in such a system, the new loading term would be about 13 mg P/m³, which would put point No. 9 nearly on the US waterbody line of best fit. There are undoubtedly other factors to consider in the load-response coupling for New Doornpoort Dam. However, this exercise does demonstrate the importance of using a P loading which is representative of the loading to the area of concern.

Another factor which would make the waterbodies tend to plot below the "average" line in Figure 3, as mentioned previously, is the fact that the chlorophyll data available were annual averages of depth-integrated samples, whereas the ordinate in Figure 3 is mean summer, epilimnetic (about 0,5 to 1 m-depth) chlorophyll. Diluting the sample with water from below the area commonly having the highest density of algae, as would occur in taking a depth-integrated sample, and averaging in lower values commonly found during the winter months, would both act to lower the average concentration of chlorophyll found during the summer.

It has been reported that the "unusually" high turbidity characteristics of many South African dams preclude their fitting a model such as the Vollenweider type load-response models. The results shown in Figure 3 effectively refute such claims since they plot no differently from the OECD or US post-OECD waterbodies evaluated. Furthermore, the US waterbody lines of best fit shown in Figures 1 and 3 include in their formulation a number of moderately turbid waterbodies, such as several of the US Tennessee Valley Authority (TVA) system. It appears that substantial amounts of inorganic turbidity can be present in a dam without significantly affecting the amount of planktonic algal chlorophyll that is produced for a given normalized phosphorus load.

For several waterbodies in the 21-dam study, Lindleyspoort, Tonteldoos, and Bloemhof, only soluble ortho-P information for loading was available. The US OECD Eutrophication Study results were based on total P loads. Ordinarily, there is a substantial difference to the total P and soluble ortho-P loads in the waterbody. However, for many of the South African dams for which there were data on both types of P load, it was found that there was very little difference between the two types of loads.

This likely reflects the fact that an appreciable part of the phosphorus loads to many South African dams is domestic wastewater discharges, the majority of which normally have their phosphorus in the soluble ortho-P form.

The points for several dams, Bridle Drift, Laing, and Nahoon, were not of the same population of points that the rest of the dams were. While it is not generally proper to match one year's loading to another year's response, summer (February) 1983 chlorophyll data from a study of Bridle Drift and Laing Dams by Hart (1983), are also included in Table 1. The positions of these waterbodies using the 1983 chlorophyll data are also included in Figure 3 (points 19A, and 20A). Understanding the limitations of the validity of the position of the points 19A and 20A in Figure 3, it nonetheless appears that given a more typical data base, these two waterbodies would likely plot with the population of South African, and indeed, OECD waterbodies.

The only other waterbody which plots substantially out of the area expected is Rietvlei Dam. No specific information was provided to the authors which would suggest why this waterbody produces less chlorophyll than would be expected for its phosphorus loading.

One other waterbody that was not included in the 21-dam study, that was reviewed by the authors, was Hartbeespoort Dam. Based on preliminary data made available to the authors, the load-response relationship for this dam also follows the pattern shown in Figure 3. The Hartbeespoort Dam situation has been evaluated separately by the authors (Lee and Jones, 1984).

Implications of findings

Finding, albeit in a preliminary way, that South African dams fit the US OECD phosphorus load-eutrophication response models represents a significant advance in eutrophication management in South Africa. It means that the demonstrated predictive capabilities of these models can be used to evaluate the impact that various phosphorus mangement strategies may have on eutrophication-related water quality characteristics. Using this approach, the authors have made preliminary assessments of the changes in water quality characteristics and their implications for beneficial uses of Roodeplaat Dam in South Africa, that would result from implementing a 1 mg P/ℓ domestic wastewater treatment plant effluent standard, enactment of a detergent phosphate ban, as well as doing nothing in the way of eutrophication management (Jones and Lee, 1984). Thus by making a few simple calculations, water quality managers in South Africa can evaluate what will be achieved in terms of water quality characteristics that can be perceived by the public (i.e., greenness, clarity, and whether certain fish can be maintained year-round) by spending funds for a given eutrophication management approach.

It should be emphasized that before these results can be used for eutrophication-related water quality management decision-making in South Africa, the existing data on phosphorus loading and response characteristics should be reviewed and screened according to the procedures outlined by Jones and Lee (1982) and Rast *et al.* (1983). These waterbodies should then be re-plotted on the load-response models. The back-up literature describing the use of this approach should be thoroughly reviewed and adhered to. Numerous errors in interpretation are possible if the approach is misapplied.

Acknowledgement

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