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ASSESSMENT AND ANALYSIS OF EUTROPHICATION OF TENNESSEE RIVER SYSTEM IMPOUNDMENTS

by

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INTRODUCTION

Eutrophication is one of the most significant causes of deteriorated water quality in lakes, impoundments, estuaries, and marine waters. Excessive growths of aquatic plants can seriously impair nearly all potential beneficial uses of waterbodies. In response to concern over the increasingly eutrophic conditions of numerous lakes and impoundments in the U.S., the Congress included as Section 314-A of the Federal Water Pollution Control Act Amendments of 1972 and 1977 (PL 92-500 and PL 95-217, respectively), requirements for states to classify their lakes and impoundments in terms of their degrees of fertility and, for those found to be excessively fertile, to develop nutrient control programs "to restore the quality of such lakes." Typically algal biomass is produced in direct response to the supply or load of the limiting nutrient (i.e., that which is available in the least amount relative to algal needs), which is usually P. It should be noted, however, that the amount of growth that is obtained in response to addition of the limiting nutrient in an algal assay cannot be extrapolated to a waterbody. As discussed below, factors such as depth and hydraulic residence time of the waterbody substantially affect the way in which a load of P is used for algal production. In general, in order for discernible changes in algal biomass to be effected in a waterbody, large changes in the P load must take place.

Several years ago, the Water Quality Management sector of the multination Organization for Economic Cooperation and Development (OECD) initiated a study to determine nutrient (phosphorus) load - eutrophication response relationships for waterbodies in order to develop a basis for assessing eutrophication-related water quality and evaluating the effectiveness of P management strategies. Approximately 200 waterbodies in 22 OECD member nations were evaluated, about 34 of which were U.S. lakes, impoundments, and estuaries, or parts thereof. Based on the work of Vollenweider (1968, 1975, 1976) and the data for the US OECD waterbodies, Rast and Lee (1978) and Lee <u>et al</u>. (1977, 1978a) developed statistical correlations between areal phosphorus load (L(P)) normalized by mean depth ($\bar{z}$) and hydraulic residence time (τ_ω), and eutrophication-related water quality as measured by chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate (Figure 1). These corre-

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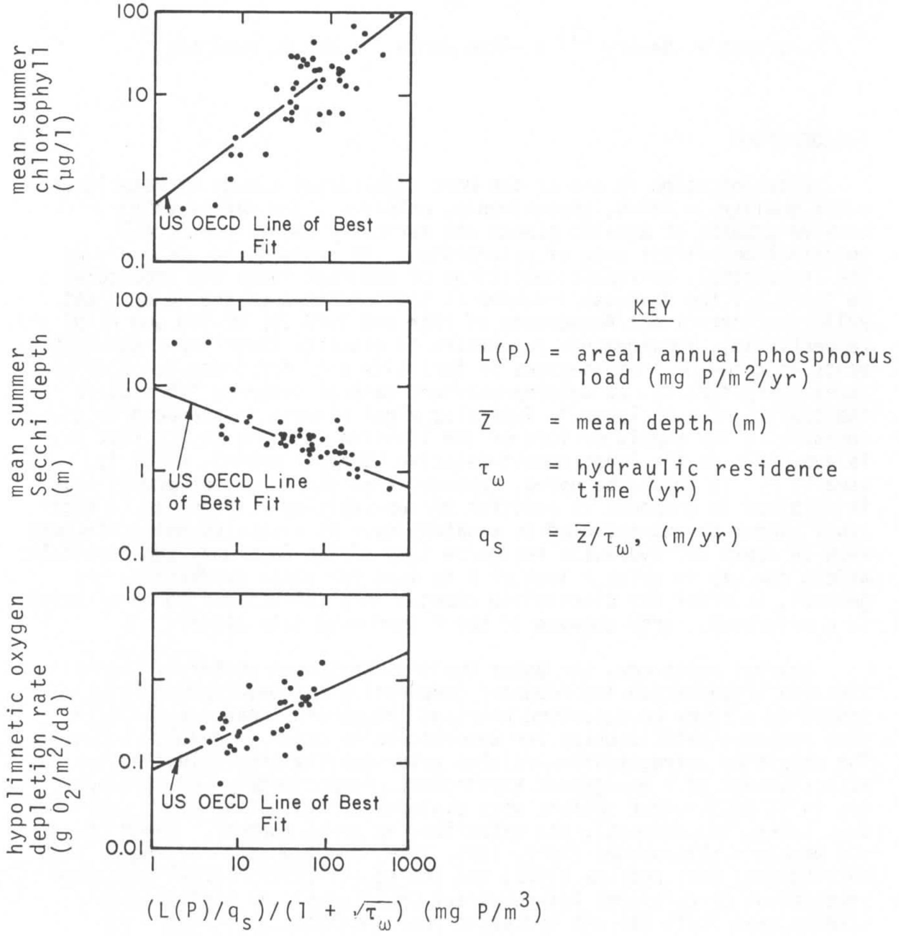


KEY

$L(P)$ = areal annual phosphorus load (mg $P/m^2/yr$)

$\overline{Z}$ = mean depth (m)

τ_ω = hydraulic residence time (yr)

q_s = $\overline{z}/\tau_\omega$, (m/yr)

Figure 1. US OECD P load - eutrophication response relationships (After Rast and Lee, 1978)

lations have been found to describe the load response relationship not only for the remaining OECD waterbodies, but also for the additional 50 or so waterbodies evaluated by the authors and their associates subsequent to the completion of the U.S. portion of the OECD study.

Rast et al. (1980) discussed the use of these models for predicting changes in eutrophication-related water quality that will result in a waterbody from an alteration in its P load, mean depth, or hydraulic residence time. Based on their evaluation of 15 waterbodies on which sufficient pre-change and post-change data were available, it was found that this approach provided sufficiently reliable forecasts of changes in chlorophyll which occurred after nutrient load alteration, for eutrophication control purposes. Lee et al. (1978b), Horstman et al. (1980), and Jones and Lee (1978) have demonstrated the utility of this approach for making such estimations. In short, the Vollenweider OECD relationships provide water quality managers with a technically valid tool with demonstrated predictive capability for estimating changes in eutrophication-related water quality based on changes in nutrient loads.

This paper presents the results of an investigation of the applicability of this approach to managing water quality in the Tennessee River System (TRS) with particular emphasis on Cherokee Reservoir. A more detailed discussion of this investigation was prepared by Newbry et al. (1979).

APPLICATION OF THE OECD NUTRIENT LOAD - EUTROPHICATION RESPONSE RELATIONSHIPS TO TRS IMPOUNDMENTS.

The focal point of this study was evaluation of nutrient load-response and the impact of P control options for Cherokee Reservoir (Figure 2). This waterbody is a 30 km long (50 former river miles), multipurpose impoundment on the Holston River; its dam is located about 48 km (30 miles) northeast of Knoxville, Tennessee. It was singled out for study because there was a large data base available on this reservoir, it is an important recreational asset to the area, and has problems of excessive fertilization, apparently manifested primarily as an undesirable extent of dissolved oxygen depletion of its hypolimnion. However, before the OECD eutrophication modeling approach could be reliably applied to Cherokee Reservoir, it was necessary to evaluate the applicability of this approach to reservoirs in the Tennessee River System. This was necessary since of the 34 US OECD study waterbodies or parts thereof, only two were located in the southern portion of the U.S. It was questioned whether or not waterbodies in a southern climate with warmer temperatures and longer growing seasons would have the same eutrophication response to phosphorus loads as those in a northern climate.

A limited amount of nutrient load and eutrophication response data on 13 apparently P limited Tennessee River System impoundments, including Cherokee Reservoir, were available through the results of the National Eutrophication Survey (NES) conducted in 1972. Pertinent NES data (Table 1) while limited, were sufficient to make a preliminary assessment of P load-response couplings for these reservoirs. Figure 3 shows the P load - response couplings for the TRS-NES reservoirs relative to the US OECD

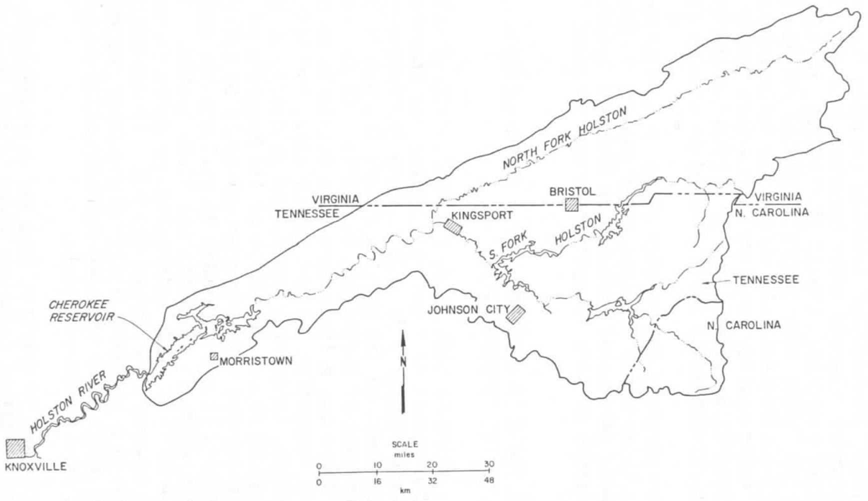


Figure 2. Cherokee Reservoir and Watershed (After Iwanski, 1978)

TABLE 1. SUMMARY OF PERTINENT NES DATA FOR TRS-NES IMPOUNDMENTS (1973 DATA)

Impoundment	No.	Area (km^2)	Mean Depth (m)	Volume (10^6 m^3)	Hydraulic res. time (yr)	P load ($g/m^2/yr$)	Altered P load[(a)] ($g/m^2/yr$)	Mean in-lake P[(b)] (mg P/l)	Chlorophyll a (μg/l)	Chlorophyll a[(c)] (μg/l)	Mean Secchi[(d)] Depth (m)
HIWASSEE	1	25.4	21.3	541	0.32	1.8	1.6	0.017	5.5	5.5	1.8
GUNTERSVILLE	2	275.0	4.6	1256	0.036	6.7	6.6	0.045	8.6	8.6	0.94
NOTTELY	3	17.4	13.1	227	0.63	0.75	0.72	0.015	6.6	6.6	2.2
CHATUGE	4	28.9	10.6	307	0.81	0.39	0.38	0.014	6.3	6.3	2.6
PICKWICK	5	174.6	6.5	1140	0.025	16.1	15.7	0.056	3.5	3.5	1.1
WILSON	6	62.8	12.5	783	0.016	38.3	38.3	0.049	7.4	7.4	1.2
TIMS FORD	7	42.9	15.2	750	0.82	1.3	0.65	0.025	6.7	3.0	2.5
BLUE RIDGE	8	13.4	18.4	247	0.48	0.91	0.65	0.010	3.1	3.1	2.6
BOONE	9	17.8	13.3	239	0.11	10.7	5.9	0.071	11.3	7.3	1.4
SO. HOLSTON	10	30.7	26.4	942	0.93	1.8	1.1	0.019	7.7	5.0	2.2
FONTANA	11	43.2	41.3	1782	0.49	2.9	2.7	0.017	3.4	3.4	2.3
DOUGLAS	12	123.1	14.1	1819	0.30	5.6	5.5	0.026	4.6	4.6	1.4
CHEROKEE	13	122.6	14.9	1901	0.49	3.8	3.6	0.058	12.2	12.2	1.3

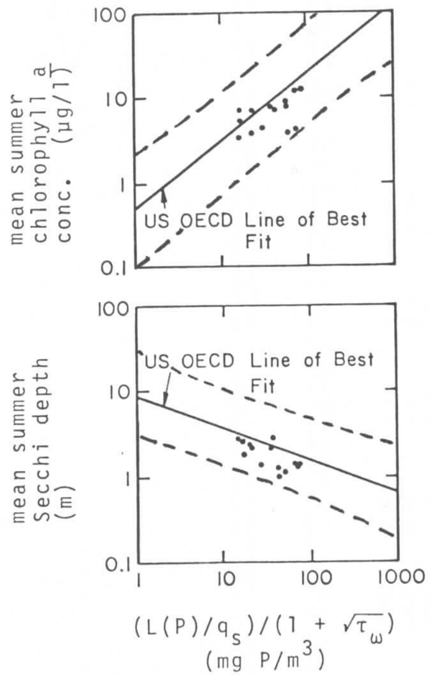
[(a)] Areal P load with 90% reduction in NES-cited wastewater treatment plant effluent P load. This 90% reduction is based only on those discharges directly to the reservoir or to local tributaries and does not include all upstream discharges.

[(b)] Average over 0 to 2 m depth.

[(c)] Altered chlorophyll a concentration resulting from 90% reduction in NES-cited wastewater treatment plant effluent P load (i.e., direct discharges to the reservoir or local tributaries), as determined using OECD modeling approach (Figure 4).

[(d)] Geometric mean of data collected.

Data from US EPA (1976).



(See Figure 1 for definition of terms)

Dashed lines are approximate 95% confidence limits based on approximately 80 US waterbodies (Jones and Lee, 1980)

Figure 3. Application of selected OECD eutrophication models to TRS impoundments (After Newbry et al., 1979)

lines of best fit relating normalized P load with mean chlorophyll concentration and with mean Secchi depth.

It is apparent from comparison of Figures 1 and 3 that the Tennessee River System impoundments plot within the scatter about the lines of best fit developed based on the US OECD data, suggesting that this eutrophication modeling approach is suitable for application to Cherokee Reservoir as well as other TRS impoundments. While the P load - chlorophyll couplings for the TRS impoundments deviate little from the US OECD line of best fit, the P load - Secchi depth couplings for the TRS-NES reservoirs typically plotted below the US OECD line of best fit. It was hypothesized that this was due to the substantial amounts of inorganic erosional materials present in the watercolumn, a phenomenon characteristic of the geology and soil types of the region. Interestingly, the lower inorganic turbidity-related water clarity apparently had little or no effect on the use of the phosphorus load in the production of planktonic algal chlorophyll as evidenced by the close fit with the US OECD relationship between normalized P load and chlorophyll.

Using the information provided in Table 1 and the US OECD P load - chlorophyll relationship shown in Figure 3, estimates were made of the improvement in eutrophication-related water quality (as measured by chlorophyll concentration) that would be expected to result if 90% of the phosphorus were removed from the effluents of the domestic wastewater treatment plants reported by US EPA (1976) to discharge to each of the TRS-NES reservoirs. This degree of phosphorus control is commonly achieved in a number of areas of the U.S. and Canada, as well as in a number of European countries and can typically be readily accomplished by precipitation of P with iron or aluminum salts at a cost of less than 0.25¢ ($0.0025) per person per day for the population (> 10,000) served. The estimated chlorophyll levels for the 13 impoundments are presented in Table 1 and show that for three of the impoundments (Tims Ford, Boone, and South Holston) a 90% reduction in domestic wastewater treatment plant effluent P load would be expected to result in a perceptible decrease in planktonic algal chlorophyll concentration. Using the same approach, it was determined that banning detergent phosphate use in the reservoirs' watersheds, which could reduce the P load from domestic wastewater treatment plants by 30 to 35%, would not improve eutrophication-related water quality in any of the waterbodies studied.

ASSESSMENT AND CONTROL OF EUTROPHICATION IN CHEROKEE RESERVOIR

Cherokee Reservoir is physically a long, narrow impoundment. Preliminary data review and a site visit indicated that for the purposes of this study, the reservoir should be evaluated in two sections, the Upper Reservoir and the Lower Reservoir. The data characterizing the physical and chemical properties of the impoundment as two sections and as a whole, which are pertinent to assessing P load - response characteristics, are presented in Table 2. As indicated in this table, estimates were made of the current P load to Cherokee Reservoir and its subsections, based on land use and domestic wastewater discharges. Estimates were also made of the P loads which would result if the P inputs from domestic wastewater discharges in the watershed were decreased by 90% ("current" and "point source management" conditions, respectively). These sources were somewhat more inclusive than those considered in the NES by the US EPA.

TABLE 2. DATA USED FOR TROPHIC STATUS ESTIMATES FOR CHEROKEE RESERVOIR

Parameter	Upper Reservoir	Lower Reservoir	Total Reservoir[a]
Holston River Reach	HRM[b] 76-HRM102	HRM52.3-HRM76	HRM52.3-HRM102
Surface Area (km^2)	15.9	55.8	71.7
Mean Depth, $\bar{z}$ (m)	7.99	15.9	14.2
Volume (m^3)	1.22×10^8	8.89×10^8	10.2×10^8
Hydraulic Residence time, τ_ω (yr)	0.031	0.22	0.25
P Load (10^4 kg P/yr)[a]			
Current Level			
Diffuse	14.4	8.17	16.0
Domestic Wastewater	15.2	7.34	15.5
Industrial Waste	11.8	5.43	11.8
Total	41.4	20.9	43.3
90% Point Source P Control:			
Diffuse	14.4	8.17	16.0
Domestic	1.52	0.734	1.55
Industrial	1.18	0.543	1.18
Total	17.1	9.45	18.7
Chlorophyll a (µg/l)			
Current	20.2	7.3	9.8
90% Point Source P Control	10	4	6
Areal Hypolimnetic Oxygen Depletion Rate ($g\ O_2\ m^{-2}\ day^{-1}$)			
Current	-[c]	1.3	-[c]
90% Point Source P Control	-	1	-

[a] Note that 46% of the load to the Upper Reservoir is fed to the Lower Reservoir. Therefore, the Total Reservoir load is not the sum of the first two columns.

[b] HRM = Holston River Mile.

[c] Dash indicates not considered.

Based on the US OECD load-response relationship, the NES chlorophyll data, and the "current" and "point source management" P load estimates presented in Table 2, estimates were made of the chlorophyll concentration that would result in the Upper and Lower Reservoirs if 90% removal of P were accomplished at the wastewater treatment plants in the Cherokee Reservoir watershed. These predictions were made following procedure outlined by Rast and Lee (1978). As illustrated in Figure 4, the NES chlorophyll value was plotted as a function of current P load; the chlorophyll level predicted to result after 90% point source P load reduction corresponds to the intersection of a vertical line drawn through the new P load and a line drawn through the "current" load-response point, parallel to the US OECD line of best fit. As shown in Figure 4 and Table 2, this nutrient control strategy is predicted to result in a decrease in the average chlorophyll concentration in the Total Reservoir from 9.8 to about 6 µg/l; in the Upper Reservoir, from 20.2 to about 10 µg/l; and in the Lower Reservoir, from 7.3 to about 4 µg/l. Such decreases in chlorophyll level would likely be noticeable to the people using Cherokee Reservoir for recreation. However, before this projected decrease can be equated to an improvement in water quality - usability of the reservoir, the impact of the lower algal production and associated increase in water clarity in the reservoir on the production of attached algae and aquatic macrophytes must be evaluated. This coupling is not quantifiable for waterbodies in general at this time.

Following a procedure similar to that used for chlorophyll, the projected decrease in hypolimnetic oxygen depletion rate in the Lower Reservoir that would result from a 90% reduction in point source P load was computed. This estimation is illustrated in Figure 4 which shows that even with 90% point source P control there will likely be a period of time near the end of the summer when the hypolimnion of the Lower Reservoir will be anoxic, resulting in releases of anoxic water to the Holston River downstream of the dam.

Figure 4 also shows that Cherokee Reservoir plots a considerable distance above the US OECD line of best fit for P load - hypolimnetic oxygen depletion rate although within the general variability found by Rast and Lee (1978). This apparently somewhat greater oxygen depletion rate for the normalized P load can likely be at least partially explained by the substantial load of ammonia to the reservoir, and its subsequent nitrification in the hypolimnion. Additional studies would be necessary, however, to verify this hypothesis.

The other factor that should be considered in estimating changes in water quality that may result from P load alterations is the time that it would take for the change in water quality to occur, i.e., the "recovery time." Sonzogni et al. (1976) have determined that the time required for a waterbody to reach a new equilibrium with the new P load is about three times the residence time of P in the reservoir water-column. The P residence times for the Upper, Lower, and Total reservoir sections were computed (total P content of the water ÷ annual P load) and were found to be about 8 days, 2 months, and 1 month, respectively. Essentially complete adjustment to new P loading conditions could be expected to occur within one year of P management program initiation.

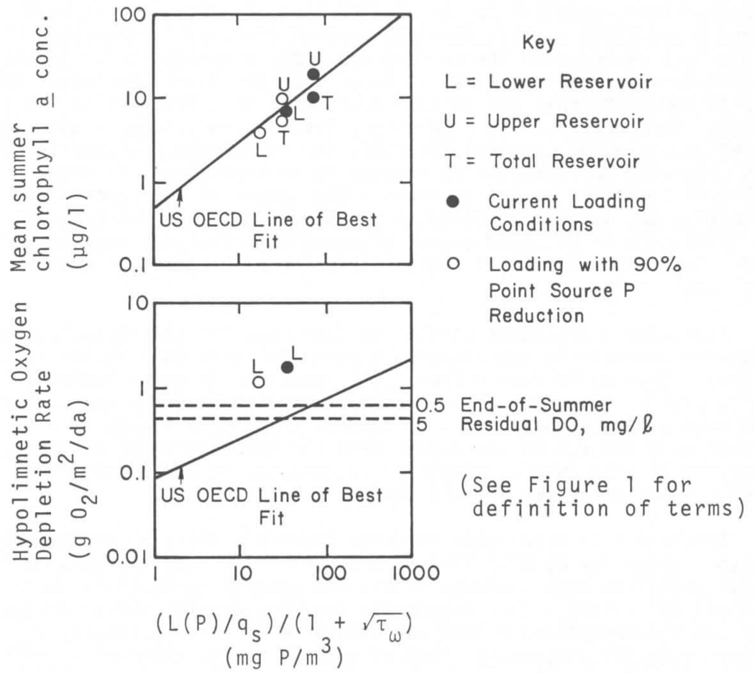


Figure 4. Application of Selected OECD Eutrophication Models to Cherokee Reservoir (After Newbry et al., 1979)

SUMMARY

This investigation has demonstrated the applicability of the OECD nutrient load - eutrophication response relationships to TRS impoundments. The responses of TRS impoundments to P loads were found to be similar to those of the US OECD lakes and impoundments. The utility of the OECD approach for characterizing the eutrophication-related water quality of these waterbodies, and the potential for providing projections upon which to base management decisions, has been shown. It is recommended that this type of evaluation be incorporated into the overall water quality management strategy for lakes and impoundments.

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