PREDICTING DOMESTIC WATER SUPPLY RAW WATER QUALITY IN PROPOSED IMPOUNDMENTS*

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The degree of eutrophication (fertilization) is an important parameter for assessing the quality of an impoundment use as a raw water supply. Water utilities which draw from more eutrophic (excessively fertile) waterbodies tend to have greater taste and odor problems, shorter filter runs, greater chlorine demand, higher trihalomethane precursor concentrations, and more prolific slime growths within the water supply transmission lines. As discussed by Lee[1], there are a variety of measures that can be taken to improve the eutrophication-related water quality of water supply impoundments. Because these measures generally involve retrofitting an impoundment after it has been constructed, frequently funding problems are encountered which make adding eutrophication control measures difficult, if not impossible.

In the early 1970's, under the auspices of the Organization for Economic Cooperation and Development (OECD), a five-year, 22-country, 200-waterbody study was initiated to examine and quantify the relationships between phosphorus loads to lakes and reservoirs and their eutrophication-related water quality characteristics. The OECD eutrophication study results provide a basis by which estimates can be made of the eutrophication-related water quality expected in a water supply impoundment before it is developed. This information can be used to develop eutrophication control measures as part of impoundment design and dam construction. Usually it is far easier and less expensive to take steps for eutrophication management as part of reservoir development than it is to retrofit them after the reservoir has been constructed.

This paper reviews an approach that may be used to estimate, before construction, the eutrophication-related water quality that will occur in a proposed water supply impoundment. It provides guidance on the appropriate use of the OECD eutrophication study results in making such estimates and in predicting the potential impact of various eutrophication management options on the eutrophication-related water quality characteristics of an impoundment. This paper is similar to a paper developed by the authors concerned with predicting water quality in proposed hydropower impoundments[2]. The emphasis in this paper, however, is on eutrophication control of importance to domestic water supply utilities who take water from the impoundment. Limited attention is given in this paper to the impact that impoundments may cause for water supply

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utilities whose water supply source is the discharge from an upstream reservoir. For further information on that topic, the reader should consult Lee and Jones[2].

SUMMARY OF US OECD EUTROPHICATION STUDY RESULTS

In the mid-1970's the senior author had a contract with the US EPA, the lead agency for the US portion of the OECD eutrophication study, to conduct a comprehensive review of the US OECD eutrophication study data base, in light of the load-response relationships proposed by Vollenweider[3]. This review was completed in 1976 and was published by the US EPA in 1978[4]. A summary of the results was also published in 1978[5]. Since the completion of the US part of the OECD study, the authors and their associates have continued to investigate nutrient load eutrophication response relationships for lakes and especially impoundments in other areas of the US as well as in other countries. A summary of the expanded studies was published by Jones and Lee[6a, 6b]. The results of the international OECD study were published in 1982[7]. While the OECD data base included the 34 US OECD waterbodies, it did not include the data for the approximately 50 additional US waterbodies and the equal number of other waterbodies abroad subsequently evaluated by the authors. The phosphorus load - eutrophication response relationships developed on these two data sets were, however, essentially identical. Thus, the statistical relationship between normalized P load and mean summer epilimnetic chlorophyll shown in Figure 1 has as its basis, data on approximately 750 waterbodies around the world. The relationships between normalized P load and planktonic algal-related Secchi depth, and between normalized P load and hypolimnetic oxygen depletion rate were defined from the data on 200 to 250 waterbodies.

Examination of Figure 1 shows that there is remarkably good agreement between the normalized phosphorus loads to these waterbodies and the various eutrophication response parameters, especially considering all of the factors that affect how phosphorus is used to develop algae in lakes and reservoirs. The key to the widespread applicability of these relationships is the normalizing terms formulated by Vollenweider. It is only by properly taking into account hydrology (hydraulic residence time) and morphology (waterbody area and volume) that such "universal" relationships between nutrient load and eutrophication response can be developed from a data base of highly heterogeneous waterbodies located in various areas of the world.

Jones and Lee[6a, 6b] examined the load – response relationships of reservoirs versus those of lakes. Indeed, in Figure 1, the load - response couplings of lakes are distinguished from those of reservoirs. This figure shows, and Jones and Lee[6a, 6b] concluded, that when the data are normalized following the OECD eutrophication modeling approach, lakes and reservoirs have the same P load – eutrophication response relationships; algal production in response to a given normalized phosphorus loading to a lake is the same as it would be to a reservoir.

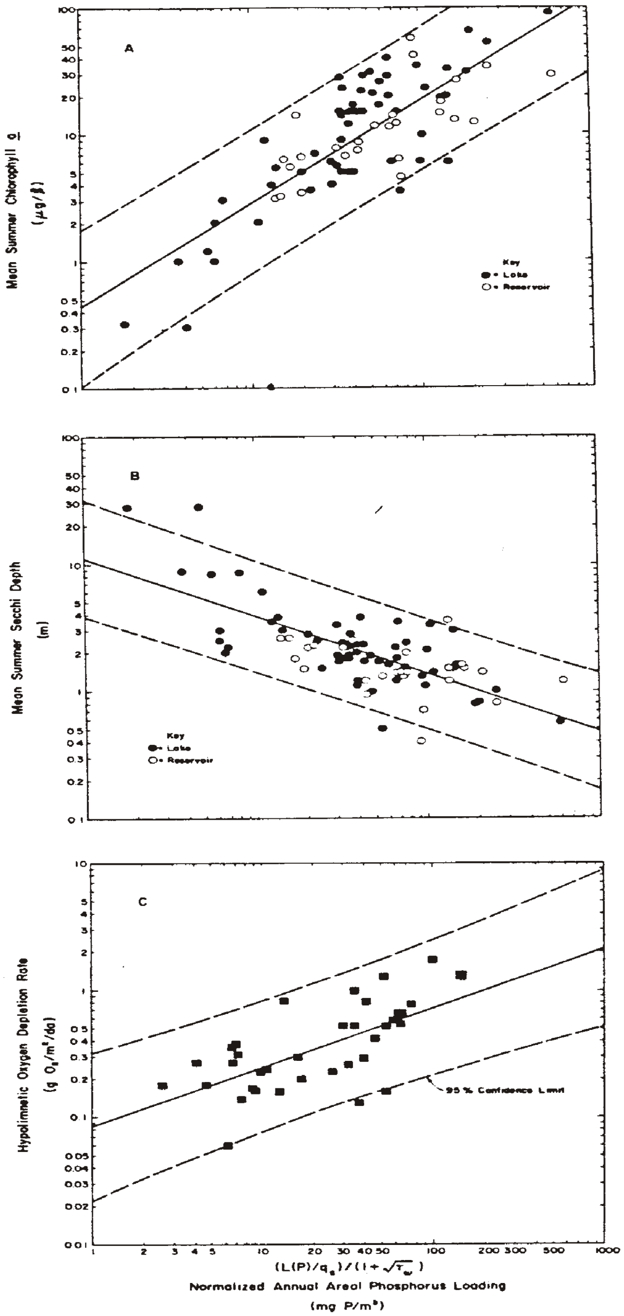

Figure 1. US Waterbody P Load -- Eutrophication Response Relationships (After Jones and Lee[6])

KEY

$L(P)$ = 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)

While there may be some reservoirs in which hypolimnetic withdrawal of water is an important factor in overall phosphorus utilization, thus far, of the several hundred reservoirs that have been investigated, there is no evidence that this is an important overall factor that would cause reservoirs' load - response relationships to be significantly different from those of lakes or from reservoirs which do not have hypolimnetic water withdrawal.

With the relationships shown in Figure 1 it is possible to estimate a waterbody's planktonic algae-related chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate based on the waterbody's P load and its hydrology and morphology. The mean depth of a waterbody is computed by dividing the waterbody's volume by its surface area. The hydraulic residence time is the estimated filling time of the waterbody and is computed as the volume divided by annual water inflow. The dependence of the eutrophication-related water quality characteristics on P load, hydraulic residence time, mean depth, and surface area makes it possible to estimate the eutrophication-related water quality for a proposed waterbody. This dependence also provides an opportunity to create reservoirs with higher eutrophication-related water quality by manipulating the shape and operation specifications in the design stage of a proposed reservoir and to evaluate the eutrophication-related water quality characteristics that would be expected under each scenario. The water quality characteristics and associated costs for domestic water treatment could be balanced with the cost of construction and operation associated with the various management options, before the reservoir is built.

The key to properly estimating the eutrophication-related water quality characteristics of a proposed reservoir lies in the ability to estimate the phosphorus load to the waterbody. The US OECD eutrophication study provided a basis for making such estimates. In the 1950's and early 1960's, work done on the watershed of Lake Mendota, Madison, Wisconsin, by several individuals showed that it was possible to develop nutrient export coefficients to describe the amounts of nitrogen and phosphorus derived from various types of land use. Rast and Lee[8] developed nutrient export coefficients for the watersheds of the various lakes and reservoirs that were investigated by the US OECD eutrophication study investigators. They selected for study watersheds which had relatively uniform land uses. From the watershed area and the total mass of each nutrient passing a gaging station over an annual cycle, it was possible to develop a series of nutrient export coefficients describing the mass of nitrogen and phosphorus derived from a unit area of each particular type of land use, per year. Rast and Lee[4] found that there was little justification for defining land use in any more detail than three dominant types: forest, agriculture, and urban. Attempts to subdivide land use into more refined categories within each of the dominant areas proved to be of little value since there were insufficient data available to develop reliable nutrient export coefficients for these sub-areas.

Based on the US OECD eutrophication study results and the literature, Rast and Lee[4] and Jones and Lee[6a, 6b] formulated generalized nitrogen and phosphorus export coefficients for land use in the US (Table 1). Rast and Lee[4] evaluated the reliability of these general nutrient export coefficients by comparing nutrient loadings measured in the US OECD eutrophication study with the values predicted based on the land use and nutrient export coefficients. It was found that, with few exceptions, the predicted and measured values agreed within a factor of two. In general, this type of agreement is more than adequate to estimate the nutrient loads to a proposed reservoir for eutrophication-related water quality management.

Table 1. Phosphorus Export Coefficients

Land Use -- Source	Total P Export Coefficients
Urban	0.1 g $P/m^2/yr$
Rural/Agricultural	0.05 g $P/m^2/yr$
Forest	0.005 g $P/m^2/yr$
Rainfall/Dry Fallout	0.02 g $P/m^{2*}/yr$
Domestic Wastewater	1 kg P/person/yr

* Waterbody area

After Jones and Lee[6]

Rast and Lee[8] provided a more detailed discussion of the development of these nutrient export coefficients and guidance on their appropriate use. Thus, by knowing the watershed area, and land use and expected changes in land use that will occur in the future, it is possible to estimate the P load that will be received by the proposed reservoir and what changes in P load will be effected by future changes in land use. Current watershed area and use information can be obtained from US Geological Survey topographic maps and aerial photographs. Satellite imagery can also be used for this purpose. The phosphorus loading estimates normalized through the OECD eutrophication modeling approach by the design morphology and hydrology can then be translated via the US OECD load - response relationships (Figure 1) into eutrophication-related water quality characteristics which have meaning to the public.

APPROPRIATENESS OF USING PHOSPHORUS LOADING MODELS FOR PREDICTING WATER QUALITY

The OECD eutrophication modeling approach is based on the premise that phosphorus is the key element controlling eutrophication-related water quality characteristics of waterbodies. While this has been found to be the case for most waterbodies of the world, some waterbodies have grossly surplus amounts of available P in their waters compared to the amounts needed by algae for growth. Rast et al.[9], however, demonstrated that even waterbodies with seemingly "excessive" amounts of available P respond in eutrophication-related water quality characteristics to changes in P loading. They evaluated the P load and response characteristics of about a dozen waterbodies on which data were available, for before and after they had undergone sizable P load reductions, comparing the results with predictions made through the OECD modeling approach. They found that the US OECD models (Figure 1) could be used to provide reliable estimates of the change in chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate that would result from changes in phosphorus loading. Waterbodies included in their evaluation were not restricted to those known to be P-limited. To date, this is the only demonstration of the predictive capability of a eutrophication model.

As noted by Lee and Jones[10], when average summer epilimnetic soluble ortho P concentrations exceed 500 µg P/L or so, unit increases in normalized P load produce chlorophyll level increases of decreasing magnitude. This signal level roughly corresponds to a normalized P loading of about 1100 mg P/m^3 which is at the upper limit of the data base used to formulate the US OECD load - response models[10]. Thus, caution should be exercised when applying the models to waterbodies above the range shown in Figure 1 as the response characteristics predicted may be worse in terms of eutrophication-related water quality than what would actually be found in the waterbody. The consequences of this error would be expected to be of limited significance to domestic water supply reservoirs, however, since any reservoir which has a predicted average soluble ortho P of 500 µg P/L or more would almost certainly have sufficiently deteriorated water quality so as to cause serious consideration to be given to the remedial measures that should be taken to try to mitigate these problems. This point will be discussed further in a subsequent section.

APPROACH FOR ASSESSING EXPECTED WATER QUALITY IN PROPOSED IMPOUNDMENT

An important consideration in the estimation of eutrophication- related water quality in a proposed impoundment is the sensitivity of the management decisions to the water quality characteristics. There may be some who would argue that the 95% confidence intervals on the relationships shown in Figure 1 are sufficiently wide so as to justify not using this approach. However, most of the more than 750 waterbodies that make up the relationships have P load - eutrophication response relationships near the line of best fit. Only a few of them deviate substantially from it. Further, when one compares the sensitivity of a eutrophication management decision to the precision and accuracy necessary in these data, one finds that small differences in the response characteristics do not usually cause different management decisions to be made. For example, if the predicted chlorophyll in a proposed reservoir was 30 µg/L and a particular management option could potentially reduce this to 10 µg/L, then it is likely that those responsible for making the decision would recommend this option.

They would likely also make the same recommendation, however, if instead of 30 µg/L, the initial predicted value was 25 or 35 µg/L. About the only time that a management decision might be more sensitive to the accuracy of the chlorophyll estimate, especially if the proposed management program was highly expensive, would be when the predicted chlorophyll level is on the edge of needing control -- i.e., on the order of 15 to 20 µg/L. Under these conditions, or for that matter at higher chlorophyll concentrations as well, if the proposed management technique would likely change the chlorophyll by only a few µg/L, then it would be reasonable to question the appropriateness of proceeding with that particular management option.

It is important to emphasize that the OECD eutrophication modeling approach does not address the wide variety of non-eutrophication-related water quality problems that may occur in reservoirs. Problems such as excessive sediment filling rate due to erosion in the watershed; sanitary quality related to domestic wastewater discharges; runoff from lands with large numbers of domestic animals - livestock; and heavy metal, pesticide and other contaminant problems are not addressed by the OECD eutrophication modeling approach. While significant to beneficial uses of a reservoir where they occur, these problems and programs for their management are highly reservoir-specific.

ESTIMATING EXPECTED PHOSPHORUS LOADS

The first step in estimating the eutrophication-related water quality of a proposed reservoir is to determine the phosphorus loading. The principal potential sources of phosphorus that should be considered are land runoff, tributaries, the atmosphere, and expected domestic wastewater discharges. For estimating P contributions from tributaries and land sources, the watershed should be identified, sized, and examined. The P load from land which would drain directly into the proposed reservoir can be determined based on area and land use (Table 1). Phosphorus entering via tributaries can also be estimated in this manner. However, if any of the tributaries that would drain into the proposed impoundment have existing or proposed impoundments on them, then the watersheds of those impoundments must be identified separately. The reason for this is that reservoirs that have hydraulic residence times greater than about two weeks typically tend to remove on the order of 50 to 75% of the phosphorus added to them on an annual basis. Therefore, to estimate the phosphorus load that will be received by a proposed reservoir having an existing or proposed reservoir within its watershed, it is necessary to account for this removal of phosphorus.

The export coefficients in Table 1 would be applied to the sub-watershed and domestic wastewaters received by the watershed reservoir. Once the P load to the watershed reservoir is computed, 25% of that load should be assumed to be passed downstream. If there is a series of impoundments on a tributary within the watershed, this procedure should also be followed sequentially for each reservoir in the series.

The hydrologic information developed in the planning of the impoundment will generally include an assessment of the watershed characteristics as well as the reservoir hydrologic characteristics. If it does not, then aerial photographs of the watershed should be obtained. In the US, county planning agencies and councils of government normally have this type of information. It should be noted that relatively crude estimates of the amounts of land devoted to agriculture, urban area, and forest are adequate for these calculations.

The amount of phosphorus contributed directly to a waterbody from the atmosphere can be estimated by applying the precipitation/dry fallout coefficient presented in Table 1 to the surface area of the waterbody. Nutrients received over the waterbody's watershed from this source are accounted for in the land-use export coefficients. Anticipated domestic wastewater treatment plant discharges to the proposed reservoir or tributaries thereof can be significant sources of phosphorus. The amount of P contributed is readily estimated from the population discharging to the sewerage system and the 1 kg P/person/yr coefficient. It is important to define the ultimate disposition of the wastewaters, however, since, while most wastewaters are discharged to watercourses, the increasing use of land disposal of wastewaters must be recognized and accounted for in nutrient estimates from domestic wastewater sources. Domestic wastewaters applied to land either directly or indirectly via septic tank systems generally contribute little, if any, phosphorus to surface waters unless there is a system failure[11]. This should be verified for the particular system under investigation, however. Furthermore, the algal availability of the phosphorus in domestic wastewaters discharged to a tributary of a reservoir will be different from (usually less than) the availability if they are discharged directly to a reservoir.

Estimating the phosphorus loads from industrial wastewaters is somewhat more difficult. The dominant types of industries in the watershed should be determined and information collected on the loads of phosphorus and patterns of discharge from each. Particular attention should be given to estimating nutrient sources from cattle and other feedlot operations. Intensive animal husbandry can add significant amounts of nutrients to a waterbody. For most industries, NPDES permits should provide fairly reliable estimates of annual phosphorus loads.

Where such information is not available, it may be necessary to conduct studies to determine the P load from these sources. It is important to determine the seasonality of the nutrient sources. For some areas and sources, such as in areas where the ground freezes or for feedlot operations, contributions of nutrients can be highly seasonal. This could impact the effect of the nutrient loads on water quality characteristics. As discussed in a subsequent section, seasonality of major sources should be considered in light of potential seasonality of water quality concern.

In estimating the nutrient loads for a proposed impoundment, it is also important to anticipate changes in land use that will occur as a result of impoundment construction. The construction of an impoundment in a region can have a pronounced impact on land use patterns and intensity. Because an increase in urban area will increase the nutrient flow significantly as shown in Table 1, it is important to pay particular attention to the potential for new urban development within the proposed reservoir's watershed especially with regard to the disposition of domestic wastewaters. Because of the relatively large nutrient contribution from people as compared with most other sources, the addition of domestic wastewaters even from a small or seasonal population can significantly impact eutrophication-related water quality characteristics.

Special Considerations

Hydrology/Morphology. As discussed previously, the US OECD P load -eutrophication response models require that the hydraulic residence time of the waterbody be at least two weeks. If the hydraulic residence time of the whole reservoir is less than about two weeks, water, but most importantly phosphorus, may pass through the waterbody before the algae have had sufficient time to grow to their maximum based on the phosphorus load. Waterbodies with hydraulic residence times of less than two weeks tend to have chlorophyll levels lower than those predicted based on US OECD load - response relationship. In order to estimate the appropriate effective P load for waterbodies having short hydraulic residence times, the total P load must be adjusted by the amount of phosphorus lost during flushing[6a, 6b, 12]. For example, if the reservoir flushes out completely late each spring, then the nutrients contributed during the previous fall and winter, and part of the spring, are not present to stimulate algal growth the following summer.

Another factor that must be considered in assessing the nutrient load to a waterbody is the potential for short-circuiting of added nutrients. If the major nutrient additions are to an arm of the waterbody that adjoins the reservoir near the dam, then a substantial part of the nutrient load may short-circuit through the waterbody without stimulating algal growth. While for existing waterbodies it is relatively easy to determine the degree of short-circuiting, for a proposed waterbody, estimates must: be made based on the expected intermixing of waters to determine the effective load of phosphorus added to the waterbody that will actually be available to stimulate algal growth.

The shape of the proposed impoundment may also affect the effective P load. It is well-known that the upper ends of elongate impoundments, and arms and bays having restricted exchange with the main body, can remove a significant part of the phosphorus added to it from the watershed or point sources[6a, 6b]. In computing the load that will be received by the area of the reservoir of water quality concern, usually the main body near the dam, it is therefore important to make appropriate allowances for expected nutrient removal in upper reaches, arms or bays. If, using a plug flow model, it is estimated that the hydraulic residence times of such areas are two weeks or more, then on the order of 50% or so of the phosphorus entering the area may be removed before it reaches the main body.

The depth of water in some reservoirs can be highly variable over an annual cycle. Depending on the filling and draw-down patterns, it may be more appropriate to use the mean depth found in early summer rather than at full pool in normalizing the P load. Estimates of eutrophication-related water quality characteristics can be in considerable error if these morphological characteristics are not taken into account.

ESTIMATING EUTROPHICATION RESPONSE

Planktonic algal chlorophyll, planktonic algal-related Secchi depth, and hypolimnetic oxygen depletion rate can, for most waterbodies, be estimated by substituting the estimated, or where necessary, adjusted values for areal annual total P Load [L(P)], mean depth (z), and hydraulic residence time (τ_ω) into the P loading term $\{[L(P)/(\tau_\omega)]/(1+\tau_\omega^{1/2})\}$ and finding the corresponding response based on the US OECD lines of best fit shown in Figure 1.

Special Considerations

As with the P loading estimates, the characteristics of each individual system should be evaluated before estimates of response are made.

Hydrology/Morphology. The impact that morphology (i.e., arms, bays, or elongate shape) can have on the eutrophication response of the main body has already been discussed. It should be understood therefore, when making predictions of "waterbody" response, what portion of the waterbody is the focus. If it is the main body near the dam, a proper response will be estimated only if it is the P loading received by that area that is used in the computation. Also mentioned previously is the importance of understanding the hydrologic characteristics of the waterbody in order to make appropriate estimates of P loading and response.

Water Clarity. The clarity of a water controls the amount of light penetration into the water and hence has an influence on aquatic plant growth. The penetration of light to the bottom may allow the growth of rooted aquatic plants. Large amounts of turbidity may effect a lower production of planktonic algae and may encourage the growth of floating macrophytes. Since some reservoirs tend to have substantial inorganic turbidity loads as a result of erosion in the watershed, and wind and animal-induced stirring of the nearshore sediment, it is likely that there will be some reservoirs, as well as some lakes, in which phytoplankton production is lower because of the turbidity. While some claim that the OECD eutrophication modeling approach cannot be used for reservoirs because of their higher inorganic turbidity levels, it is the experience of the authors that appreciable amounts of inorganic turbidity can be present in a waterbody without significantly affecting chlorophyll production. While at this point the authors have not found a particular level of inorganic turbidity that causes chlorophyll production for a given phosphorus load to be less than that predicted based on the normalized P load, they have found that the P load - chlorophyll coupling used in conjunction with the P load - Secchi depth coupling can provide considerable insight into the situation[13].

It appears that the inorganic turbidity-related Secchi depth must be on the order of a few tenths of a meter before chlorophyll production is less than predicted. For a proposed reservoir, this assessment will be somewhat subjective and dependent on the experience of the observer in assessing the behavior of the types of solids being contributed to the water column and the shape of the reservoir. Of course, if the waterbody is elongate and of appreciable depth in the upper reaches, much or most of the inorganic turbidity (as well as phosphorus) would be expected to settle in the upper part of the reservoir. This would cause the load - response relationships in the water near the dam to be more in keeping with those shown in Figure 1. Lee et al.[13] discuss in greater detail how load - response relationships can be evaluated in highly turbid systems.

Type of Aquatic Plant Growth Produced

The OECD eutrophication modeling approach can be used to predict planktonic algal-related characteristics. It cannot be used at this time to predict the biomass of attached algae or submerged, emergent, or floating macrophytes. It is important before predicting the expected response of a proposed waterbody, to be certain that the conditions within the waterbody would favor phytoplankton rather than macrophytes. While a wide variety of factors control the type of crop produced, the most important factors seem to be water depth and inorganic turbidity. Waterbodies with large areas of shallow water (i.e., with depths of less than about 2 m) will likely develop attached algae and attached macrophytes in these areas. The exception to this would be high energy areas where the waves and the nature of the bottom would inhibit or preclude the growth of attached algae or macrophytes. Inorganic turbidity also plays an important role in determining the primary plant crop in a waterbody. If the tributaries to a proposed impoundment will carry a large amount of finely divided suspended material and if this material is not expected to settle out before it reaches the dam, then there may be sufficient suspended materials in a nutrient-rich water to cause floating macrophytes such as water hyacinth to develop. While water hyacinth can cause severe problems in blocking irrigation canals, it rarely causes problems for domestic water supply projects. The characteristics of most domestic water supply projects are such that the primary aquatic plant crop produced is usually phytoplankton. Therefore, the US OECD eutrophication study results should generally be applicable to predicting water quality characteristics of importance to water utilities.

Phosphorus limitation of Algal Growth

In a strict sense, the US OECD eutrophication study results should be applicable only to waterbodies in which phosphorus is controlling phytoplankton growth. However, as discussed elsewhere in this paper, it appears that these models are applicable to waterbodies containing even gross surpluses of phosphorus. Thus, it appears that within the constraints discussed above, it is not necessary to make detailed speculations about whether nitrogen or phosphorus will limit planktonic algal growth in a proposed impoundment before its expected eutrophication-related water quality characteristics can be estimated[6a, 6b, 10, 14].

IMPLICATIONS FOR MANAGEMENT

If the special conditions described above are not adjusted for in the load or response estimate, the predicted chlorophyll will generally be somewhat higher than the level that would actually occur in the waterbody; i.e., the model output would generally lend to be a conservative (from the point of view of insuring adequate water quality) estimate of the amount of algal growth. If the average summer chlorophyll predicted for a particular waterbody is above about 10 to 15 µg/L, the waterbody will have degraded water supply water quality and the management decision would likely be that there is need to implement nutrient control programs as part of the design of the impoundment. The load - response relationships would be useful in evaluating the impact of various management options[6, 9]. If, on the other hand, the chlorophyll in the proposed impoundment is predicted to be a few µg/L, then it is highly likely that the waterbody will have little or no impairment of the desired beneficial uses due to excessive growths of algae.

It is the group of waterbodies with estimated chlorophyll levels between 5 and 10 µg/L, especially when the estimates may be low at the upper end of the range, or high at the lower end, for which consideration should be given to conducting additional studies or more in-depth review of the expected characteristics of the impoundment before eutrophication management decisions are made. It is within this region that critical examination of the characteristics of the proposed system can provide useful information. For example, if it is believed that there will be high levels of inorganic turbidity (Secchi depths of less than about 20 cm due to inorganic turbidity) near the dam, then it may be best to put less emphasis on the predicted chlorophyll values and on design nutrient control programs. However, if there is the possibility of low results due to the shape of the waterbody, such as arms or bays which could remove appreciable amounts of the nutrients, then it would likely be appropriate to design water quality control measures taking advantage of the likelihood of nutrient removal in these areas.

It is important in making the evaluation of a waterbody's expected water supply water quality, to consider year-to-year variability in the factors influencing this quality. One of the most important of these factors is the flow. For many waterbodies, there are appreciable year-to-year differences in tributary flows. These differences affect not only the hydraulic residence time of the waterbody, but also the amount of nutrients contributed from the watershed. The nutrient export coefficient values presented in Table 1 are averaged values which reflect, to some extent, the effects of wet and dry periods on nutrient transport. Climatic extremes can have a dramatic impact on the nutrient transport in any given year which can cause the nutrient loads to vary appreciably from those predicted using Table 1 values. If a proposed impoundment is on the borderline of having significantly degraded water quality based on the use of Table 1 values, then it is almost certain that in some years, the year-to-year variations in nutrient fluxes will cause the waterbody to have significantly degraded water quality during some periods. Under these conditions then, it is best to design phosphorus control programs as part of the impoundment design. If the phosphorus control system has a high operating cost, then to the extent that it is possible to predict the occurrence of water quality problems, it would only need to be operated just prior to and during the worst-case conditions.

RESERVOIR WATER QUALITY CRITERIA

Since most water supply reservoirs have many more uses than just a water supply, it is necessary to consider the wide variety of potential uses and develop criteria by which to evaluate whether the phosphorus load to the waterbody will impair any of these uses. Vollenweider[15] and Lee[1] have reviewed the effects of eutrophication on water quality; while these reviews were prepared more than 20 years ago, they are still appropriate as far as they go. This section discusses various potential effects of eutrophication on beneficial uses of lakes and reservoirs, and areas that may require eutrophication management to prevent unacceptable impairment of beneficial uses of water supply reservoirs.

TRIHALOMETHANE PRECURSORS

The area which has come to light since the Vollenweider and Lee reviews is the increasing evidence that the eutrophication of a waterbody can increase the amounts of trihalomethane (THM) precursors in the water. Thus there is additional justification for phosphorus control, based on its potential for stimulating the growth of algae that lead to THM precursor formation. At this time it is impossible to predict with any degree of reliability the relative role of aquatic algae versus terrestrial vegetation in serving as a source for trihalomethane precursors. This is an area of research by the authors as well as others at this time. It should be possible, within a few years, to predict the impact of a waterbody's trophic state on its trihalomethane precursor content.

DISSOLVED OXYGEN

From a downstream water quality point of view, probably the most significant impact of eutrophication is the increase of the hypolimnetic oxygen depletion rate. The discharge of anoxic waters is a well-known consequence of designing water supply impoundments without properly addressing nutrient control in the waterbody's watershed. Until the completion of the US OECD eutrophication study, however, it was not possible to reliably predict the extent of deoxygenation of the hypolimnion that could occur in a waterbody. Now, through the use of the relationship shown in Figure 1, it is possible to estimate whether potentially significant deoxygenation problems are likely to occur in a proposed impoundment.

In making predictions from Figure 1, it is necessary to prescribe an acceptable level of deoxygenation for the particular waterbody which will still allow a sufficient concentration of dissolved oxygen (DO) to maintain desired beneficial uses of the waterbody. As a guideline, if at least 5 mg/L of dissolved oxygen can be maintained in the hypolimnion then the likelihood of significant impairment of any beneficial uses of the water due to low DO is small. This level of dissolved oxygen will prevent downstream problems due to low DO levels and associated problems with hydrogen sulfide, iron, and manganese[16, 17]. It will also allow the development of a highly desirable cold water fishery in the waterbody.

A minimum DO of 5 mg/L, however, will not allow the development of the optimum cold water fishery. This requires at least 6 mg/L DO. If a cold water fishery is not attainable because of temperature (i.e., if temperatures will be above about 15°C either within the waterbody or downstream), and there is no interest in developing a warm water fishery downstream of the reservoir, then the dissolved oxygen discharge levels can be allowed to drop to about 2 to 3 mg/L. These values are suggested because of problems that can arise at DO levels below this, due to the release of manganese from the sediments. Delfino and Lee[18] found that manganese is released from the sediments while the overlying waters are still oxic; iron and sulfide were not released under those conditions. This difference is due to the effect of pH on the kinetics of oxidation of manganous, ferrous and sulfide forms. Both ferrous iron and sulfide are rapidly oxidized by dissolved oxygen in the neutral to slightly alkaline pH region, while manganous requires more alkaline conditions to be oxidized at a higher rate.

If there is a desire to maintain a warm water fishery below the reservoir, then 5 to 6 mg/L DO must be maintained in the discharge. The notion that warm water fish are less sensitive to low DO concentrations than cold water fish has been found to be incorrect. Warm water fish such as bass and pike have essentially the same oxygen requirements for optimum growth as cold water fish. There are some warm water fish such as carp which have high tolerances for low dissolved oxygen levels but this does not appear to be the general case for warm water game fish.

PLANKTONIC ALGAE

There are no fixed values for an "appropriate" amount of algae in a waterbody. Some generalized guidelines can, however, be formulated. It is indeed rare that planktonic algal chlorophyll levels below 5 µg/L are considered objectionable by the public or a water supply authority. Generally, water quality deterioration for various types of uses starts to become readily evident at about 10 µg/L chlorophyll. When chlorophyll levels reach 40 to 50 µg/L, there is severe deterioration which will significantly impair most uses of the water.

Normally, eutrophication control programs start to be considered when the planktonic algal chlorophyll is routinely above 10 to 15 µg/L during the summer months. However, as discussed by Jones and Lee[6a, 6b], the point at which the level of chlorophyll present is judged to be "excessive" depends on the desired beneficial uses as well as on a variety of cultural factors and the morphology of the waterbody. For example, a waterbody with a relatively small hypolimnion will show a greater oxygen depletion for a given chlorophyll production than a waterbody with a large hypolimnetic volume. It is for this reason that Rast and Lee[4] formulated the oxygen depletion response in Figure 1 as the rate of oxygen depletion.

Section 314A (Clean Lakes) of PL 92-500, the 1972 Amendments to the Federal Water Pollution Control Act, required that each state classify the trophic state of its lakes and reservoirs. As discussed by Jones and Lee[6a, 6b, 14], however, there is considerable confusion in the literature about developing trophic state classification systems for waterbodies.

This confusion stems from the fact that many of the trophic state classification systems that have been proposed and/or used are based on limnological rather than water quality - beneficial use considerations. Even though one of the most important impacts of eutrophication on the beneficial uses of water is on the quality of the water for domestic water supply purposes, those within the

US EPA responsible for administration of the "Clean lakes" section in the late 1970's and early 1980's focused the trophic state classification on limnological characteristics to the exclusion of domestic water supplies. As a result, the typical state trophic state classification of waterbodies has limited applicability to the needs of the state's water utilities.

Similar problems exist with the US EPA National Eutrophication Survey trophic state classification of the National Eutrophication Survey waterbodies. Lee et a1.[14] discussed various trophic state classification systems for lakes and reservoirs and recommended an approach that specifically focuses on the water quality aspects of trophic state. The Lee et a1.[14] approach utilizes eutrophication response parameters such as planktonic algal chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate while the other trophic state classification systems utilize nutrient concentration and a variety of peripheral parameters, some of which can change by orders of magnitude without affecting the water quality-related trophic state of a waterbody. Lee et al.[14] recommended that trophic state be established based on a site-specific evaluation of the desired water quality characteristics of a waterbody. Trophic state classification systems for domestic water supply lakes and impoundments should consider frequency and severity of tastes and odors, amount of activated carbon used, length of filter runs as influenced by algae, amount of THM precursors above those derived from terrestrial sources, etc. Factors such as the greenness of the water, water clarity, and types of fisheries within and downstream of the waterbody should also be considered by those residing in the vicinity of the waterbody as well as anyone else who could be affected by its quality. The process should be similar to the approach used for stream use classification in the United States in which the regulatory agency proposes maintenance of certain water quality characteristics based on specific uses and the public has the opportunity to determine the appropriateness of the proposal.

Once the public has decided the appropriate water quality for a proposed water supply impoundment, then through the US OECD eutrophication study results it is possible to determine whether the selected water quality can be met in the proposed impoundment as designed. If this water quality cannot be obtained, then the various management options discussed below should be considered.

FISHERIES

An important aspect of many water supply impoundments is the quantity and quality of the fishery developed in the reservoir. The quality of the fishery of a reservoir is dependent on a variety of factors, one of the more important being the trophic state of the water. Figure 2 presents a relationship developed by the authors[6a, 6b, 19] between the phosphorus load to a waterbody and the fish yield of that waterbody. Similar results have been recently published by Hanson and Leggett[20].

It is evident from this relationship that as the phosphorus load to a waterbody is decreased, the fish yield will also decrease. However, the quality of fish also changes as a function of phosphorus load, generally with the poorer quality fish dominating at high nutrient loads. For any waterbody, there should be an optimum between fish yield, fish quality, and overall aesthetic water quality that can be assessed through the US OECD eutrophication modeling approach.

WATER QUALITY MANAGEMENT OPTIONS FOR PROPOSED RESERVOIRS

There are usually several options available to the design engineer for maximizing eutrophication-related water quality of a proposed reservoir. These include the physical and operating specifications for the reservoir, operation of other existing facilities that could impact the characteristics of the proposed reservoir, use of natural or constructed modifications of the reservoir or tributaries, as well as phosphorus load control strategies. Each should be evaluated for its potential effectiveness in controlling planktonic algae using the OECD eutrophication modeling approach, and compared for overall cost-effectiveness before reservoir construction. The cost of the dam associated with the construction of an impoundment is usually so great compared to the cost of various water quality management options that could be incorporated into the design of the impoundment at the time of construction that eutrophication or phosphorus control options should be critically evaluated and incorporated where practicable, as part of initial project design. Some of the management options that should be considered are discussed below.

RESERVOIR SPECIFICATIONS

Every attempt should be made to select design specifications for the reservoir, such as depth, volume, area, and shape, to maximize eutrophication-related water quality. These factors all

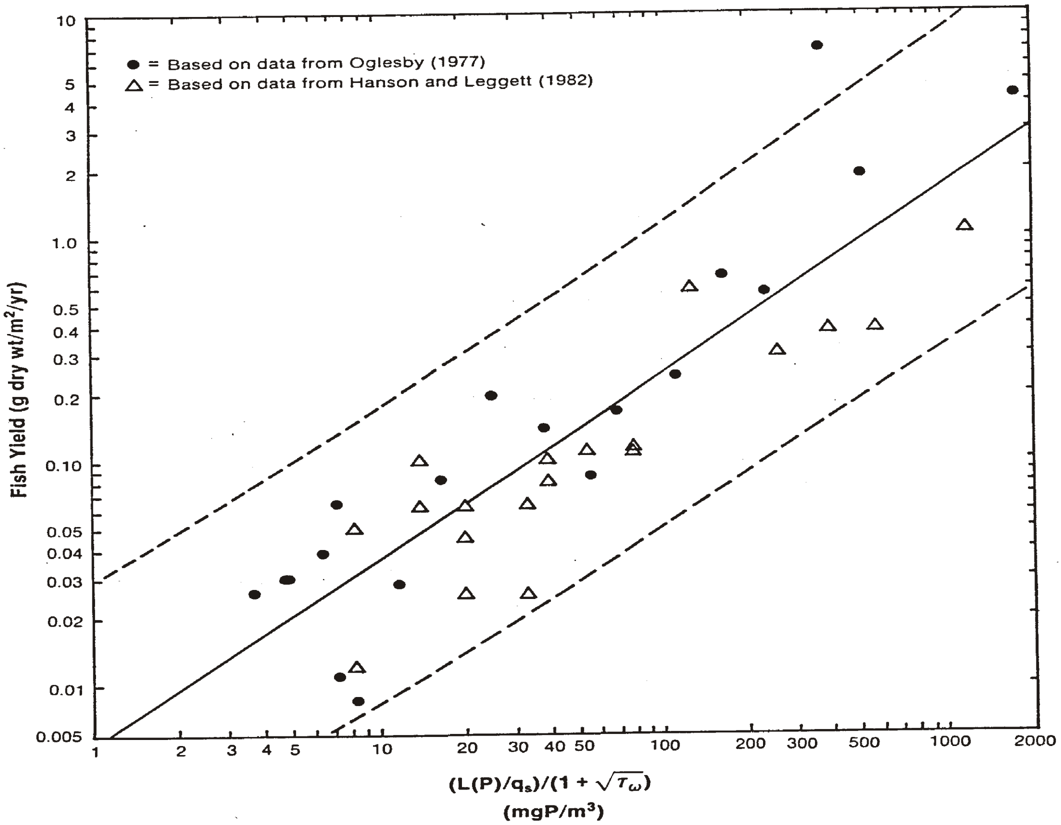

Figure 2. Relationship between normalized P load and fish yield (After Lee and Jones[20], 1983)

impact how a waterbody utilizes its P load in the production of phytoplankton. Table 2 shows how altering mean depth and/or hydraulic residence time could have altered the eutrophication-related water quality characteristics of Rawhide Cooling Impoundment in northern Colorado[21]. In that case, manipulating those two parameters could have changed the water characteristics from "pea soup" (at almost 50 µg/L chlorophyll) (Condition C), to just over 10 µg/L chlorophyll (Condition E), which is substantially less fertile. These computations and evaluations can all be made in the design phase and in the case of the Rawhide Cooling Impoundment, could have meant that significantly less money would have had to be spent retrofitting P load controls if these computations had been made prior to construction.

As mentioned previously, as part of the design of any impoundment, consideration should be given to how changes in the pool elevation can change the eutrophication-related water quality in the waterbody. Also, if there are upstream impoundments which could be used to alter the hydraulic residence time of a proposed impoundment, then consideration should be given to the impact of the range of operating conditions that could be used on the waterbody's eutrophication-related water quality.

Table 2. Projected Impact of Altering Mean Depth, Hydraulic Residence Time and Influent P Concentration on Eutrophication-Related Water Quality Characteristics of Rawhide Cooling Impoundment

Condition	Mean Depth (m)	Hydraulic Residence Time (yr)	Influent P (mg P/L)	Chlorophyll (ug/L)
"Current Characteristics"	9.1	3.4	7	225
A	15	3.4	7	125
B	15	1	7	60
C	9.1	3.4	1	47
D	15	3.4	1	30
E	15	1	1	12
F	9.1	3.4	0.2	13

DOMESTIC WASTEWATER PHOSPHORUS CONTROL

The first and possibly most significant and readily controllable source of phosphorus that should be considered in any nutrient control program is the phosphorus present in domestic wastewater as well as some industrial wastewater. There are over 50 million people in North America served by wastewater treatment facilities that currently practice phosphorus removal by precipitation during conventional treatment. This removal is being accomplished at a cost of less than one-quarter of one cent per day per person for the population served.

It is a relatively inexpensive way to remove approximately 90% of the phosphorus in the domestic wastewaters. If a particular proposed impoundment shows the potential for excessive fertility, then as part of construction, provisions should be made to fund phosphorus removal from the wastewater treatment plants that are contributing potentially significant amounts of phosphorus.

PRE-IMPOUNDMENTS

The next management option that should be considered is the construction of a pre-impoundment in the upper part of the reservoir. As discussed above, impoundments in general remove about 50 to 75% of the phosphorus entering them on an annual basis. In designing and siting a proposed impoundment consideration should be given to the natural features that could lead to the development of pre-impoundments at a relatively small cost. If, as a result of a preliminary assessment of phosphorus sources based on land use within each tributary's watershed, it is found that a particular tributary represents a highly significant source of phosphorus for the waterbody, then consideration should be given to developing a pre-impoundment on that tributary which would allow for at least two weeks hydraulic residence time during the critical water quality period of the year.

In making the assessment of the necessity and the appropriateness of constructing a pre-impoundment, consideration must be given to the role of nutrients added during any given month in causing water quality deterioration during the critical periods of the year. The critical periods are defined in terms of when the greatest adverse impacts on the beneficial uses of the water within the waterbody or downstream thereof are likely to occur. With few exceptions, it is during the summer months that there is the greatest potential for impairment of uses for domestic water supplies due to taste and odor production, and recreation (boating, fishing, and water skiing). If, for a particular proposed waterbody, it is anticipated that a time of the year other than the summer might be the most significant water quality period, then appropriate adjustments in the analysis of the critical period and the need and utility of pre-impoundments or other management options should be made.

SELECTIVE WITHDRAWAL

Water supply impoundments are typically designed to remove water from the reservoir at several depths. Frequently the bottom waters are more desirable for use by a water utility because of the presence of fewer algae in those waters. In eutrophic waterbodies, the waters near the bottom (i.e., in the hypolimnion of the waterbody) typically have low DO or are anoxic in the summer months and often have elevated concentrations of hydrogen sulfide, iron, and manganese. The OECD eutrophication modeling approach provides a basis by which to estimate the rate of dissolved oxygen depletion that will take place in a proposed reservoir. Modeling approaches such as those discussed by Stefan[22] can be used to predict temperature profiles needed to compute saturation DO at the onset of stratification from which DO concentrations can be computed. This information can also provide estimates of the position of the thermocline and insights into the locating of water supply intakes to optimize temperature and oxygen conditions in the intake water. For further information on the impact of water supply intake location on water quality, consult Lee & Harlin[23].

If the proposed impoundment is predicted to have an anoxic hypolimnion which cannot be effectively handled by altering the depth of water intake, then consideration should be given to making provisions for hypolimnion aeration of the waterbody near the dam. Hypolimnion aeration can usually be added at a small additional cost compared to that of the dam at the time of dam and water supply intake construction. Providing hypolimnetic aeration could significantly improve the raw water quality to allow the withdrawal of colder water with less algae, and therefore fewer potential problems of taste and odors, length of filter runs, and possibly THM precursor content.

It is clear from the above discussion that there are a variety of factors related to reservoir design and operation that should be evaluated as part of the design of a proposed impoundment in order to maximize eutrophication-related water quality in water supply impoundments. It is likely that proper attention to factors that affect the eutrophication-related water quality of a water supply impoundment during the design phase could, for minimal additional cost, immensely improve the quality of the raw water and hence reduce the cost and improve the quality of the finished water.

CONCLUSIONS

The design and operation of water supply impoundments of the future will almost certainly require that much greater attention be given to water quality management than has been done in the past. The US OECD eutrophication study results provide a technical basis for predicting eutrophication-related water quality in a proposed impoundment. Through a combination of land use in the proposed impoundment's watershed, nutrient export coefficients, and the OECD eutrophication modeling approach it is possible to predict, for most proposed impoundments, planktonic algal chlorophyll, Secchi depth, and hypolimnetic oxygen depletion rate. It is also possible to estimate the fish yield of the proposed waterbody from such relationships. The US OECD eutrophication study results provide a guide to the formulation and assessment of management techniques for those proposed impoundments that are predicted to be excessively fertile.

The design of all new water supply impoundments should include an evaluation of the potential water quality that would exist within the waterbody under various design and operation scenarios. For those waterbodies that are judged to be excessively fertile, specific phosphorus control programs or reservoir modifications should be incorporated into the design of the impoundment in order to reduce the water quality deterioration due to planktonic algae.

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