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January 1980

Principles of Lake Quality Management

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PRINCIPLES OF LAKE QUALITY MANAGEMENT

by

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Seminar Presented at the Building Dedication
Utah Water Research Laboratory
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Logan, Utah 84321
December 4, 1980

Management Approaches for Lakes and Reservoirs

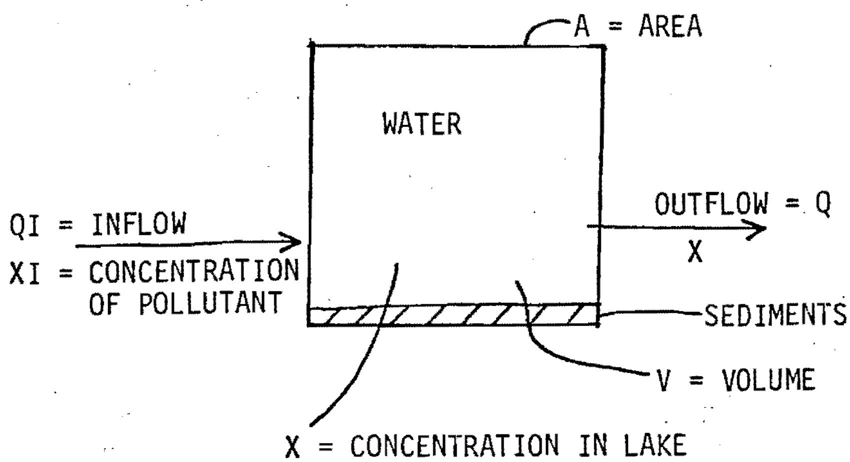
Management to protect, enhance, or restore lake and reservoir water quality for existing and future beneficial uses depends on defining and conceptualizing the problems that are specific to a particular lake and geographic region, quantifying the processes and materials that affect that lake and water quality, and preparing management tools that will in fact relate to that water quality and lead to feasible and effective solutions.

Three levels of lake management can be defined to help focus on lake quality questions. The management approaches defined here apply to small and large lakes and reservoirs, cold and warmwater systems, high and low elevation watersheds and all ranges of salinity. The first level is a broad scale management level applied to the situation where many lakes need to be evaluated and rather broad policy developed for maintenance of water quality. The second is a similar level of detail, but directed towards a single lake, recognizing the uniqueness of every lake in its size, watershed, water chemistry, and physical and biological relationships. The third level is an extremely detailed management approach which attempts to look at alternatives and may be used to develop predictions about an existing lake or a proposed reservoir. These approaches all require that the user understand lakes and reservoirs well enough to obtain a solution that will actually work and provide beneficial uses.

I will briefly review several tools that are used in these three management levels with phosphorus and eutrophication as examples, and then use them to identify the research that is needed to protect lake water quality in the Intermountain region and specifically in the Colorado River Basin.

The first level is the Vollenweider (1968, 1976) or OECD (Organization for Economic Cooperation and Development) mass balance approach which is based on using total phosphorus loading values to evaluate eutrophication in lakes as a function of the limiting nutrient, phosphorus (Table 1). This loading approach provides an estimate of the amount of phosphorus in the lake. Lake phosphorus is controlled by the influent and by processes that remove or recycle phosphorus. Because this is a management approach it uses an averaging technique that assumes complete mixing and steady-state for the

Table 1. Formulations for Evaluating Management Options for Pollutants in Lakes and Reservoirs



For Example - Phosphorus = P

LOADING

$$PL = QI \cdot PI / A, \ \mathrm{mg/m^2 \ year}$$

MASS BALANCE

Assumptions: completely mixed, steady state, $Q \cong QI$, annual average rates are constant

Definitions: $ZB = V/A$, $D = Q/V$, $QS = Q/A$, $Pext = QI \cdot PI$, K = net rate of removal and release (proportional to P)

$$P = \frac{D \cdot PI}{D + K}$$ (Mass Balance Form)

$$P = \frac{Pext}{Q}\left(\frac{D}{D + K}\right)$$ (Mass Inflow Form)

$$P = \frac{PL}{ZB(D + K)}$$ (Loading Form)

entire lake. The removal and recycle processes are frequently lumped into a single term that is determined by measuring influent and effluent flows and phosphorus concentrations on an annual basis and obtaining a ratio of the phosphorus mass flow. It is most commonly used in the loading form. An equation derived by Jones and Bachmann (1976) using a data base of 143 lakes showed the following "least squares" relationship:

$$P = \frac{0.84PL}{QS+K}$$

The value of K was estimated to be 0.65. Various others have developed similar equations (Larsen and Mercier, 1976; Dillon and Rigler, 1975; Lee *et al.*, 1978).

The amount of phosphorus in the lake is then related to the chlorophyl *a* concentration in the lake as a measure of the potential for phosphorus to cause eutrophication. The amount of chlorophyll *a* in a lake is the resultant of growth and of removal processes: respiration, sedimentation, grazing, and less significant removal processes. The ratio of chlorophyll *a* to phosphorus in a lake is not a physiological ratio as would be observed in the laboratory because of these removal processes and the fact that growth may be limited by a factor other than phosphorus (Table 2). It is an ecological ratio and measurements indicate a broad range of values (Table 3). A typical ratio against which various environmental conditions can be evaluated is shown in Table 2.

There are prescribed levels that allow you to estimate what the eutrophication level is in a lake (Figure 1). Reducing the inputs of phosphorus by waste treatment or best management practice in the watershed will reduce loading. An important aspect of this management tool is the linkage between treatment and loading. This method is now considered to be the most practical technique for evaluating nationwide water quality policy for phosphorus and eutrophication control. Although the additional step is not necessary for these management approaches, fish yield (Oglesby, 1977) and fish biomass (Grieb *et al.*, 1980) have been shown to be related to chlorophyll *a* and, ultimately, phosphorus.

The second level is an application of a detailed loading model to a particular lake, analyzing all the influents and effluents, performing a mass balance, essentially using the same loading relationships as for the OECD approach, and then determining the best method for controlling the lake water quality (Table 4). Generally, lake restoration approaches depend on control of influent phosphorus (PL), manipulation of in-lake phosphorus (affects recycle, K) or controlling the lake biological productivity. Again, the ratio of chlorophyll *a* to phosphorus (Table 2) can be used to evaluate the potential success of restoration approaches.

The third level is an application of an ecosystem model which integrates hydrologic data, climatic data, water quality data, and biological relationships to produce a simulation of significant, variables in the lake (Chen and Orlob, 1973; Tetra Tech, 1980; Scavia, 1979; Thomann *et al.*, 1977). Inputs of materials or other system alterations can be changed to evaluate relationships and provide a means of evaluating alternative management schemes in the lake or reservoir. This third level

Table 2. Relating Eutrophication Effects to Phosphorus

CA = Chlorophyll *a*

P = Total Phosphorus

a,b,c = Coefficients

$$CA = a\,P^{b} + c$$
$$\log CA = b \log P + \log a, \text{ for } c = 0$$

a = ratio of chlorophyll *a* produced in a lake ecosystem per unit of phosphorus present when phosphorus is the growth limiting factor for phytoplankton based production; unitless.

Major factors that affect the ratio are: P limiting (N/P ratios), light, toxic substances.

b = coefficient to reflect species shifts and changes in limiting factors; unitless.

c = lumping coefficient, mg/m^3; should be zero since CA = 0 when P = 0.

Management coefficient:

$$CA = 0.5\,P^{1.0} = 0.5\,P$$

Table 3. Range of Reported Values for Coefficients for the Chlorophyll a / Phosphorus Relationship

Form of Equation	Source of Information	Number of Data Sets	a	b	c
linear	1	10	0.2 to 0.6	1.0	-4.2 to 4.2
	2	8	0.1 to 0.9	1.0	-16 to 30
logarithmic	1	7	0.04 to 0.2	0.9 to 1.6	assumed zero
(log 10)	2	8	0.004 to 3.8	0.6 to 2.2	" "

Notes:

(1) - Nicholls and Dillon, 1978; one averaged data point per lake; many lakes.

(2) - Smith and Shapiro, 1980; one lake each; more than three growing seasons of averaged data points.

Each data set represents a variable set of lakes and/or measurements.

Table 4. Classification of Lake Restoration Techniques

I. Source Controls
   A. Treatment of inflows
   B. Diversion of inflows
   C. Watershed management (land uses, practices, nonpoint source control, regulations and/or treatments).
   D. Lake riparian regulation or modification
   E. Product modification or regulation

II. In-Lake Controls
   A. Dredging
   B. Volume changes other than by dredging or compaction of sediments
   C. Nutrient inactivation
   D. Dilution/Flushing
   E. Flow adjustment
   F. Sediment exposure and dessication
   G. Lake bottom sealing
   H. In-lake sediment leaching
   I. Shoreline modification
   J. Riparian treatment of lake water
   K. Selective discharge

III. Problem Treatment (directed at biological consequences of lake condition)
   A. Physical techniques (harvesting, water level fluctuations, habitat manipulations)
   B. Chemical (algicides, herbicides, piscicides)
   C. Biological (predator-prey manipulations, pathological reactions).
   D. Mixing (aeration, mechanical pumps, lake bottom modification)
   E. Aeration (add DO; e.g. hypolimnetic aeration)

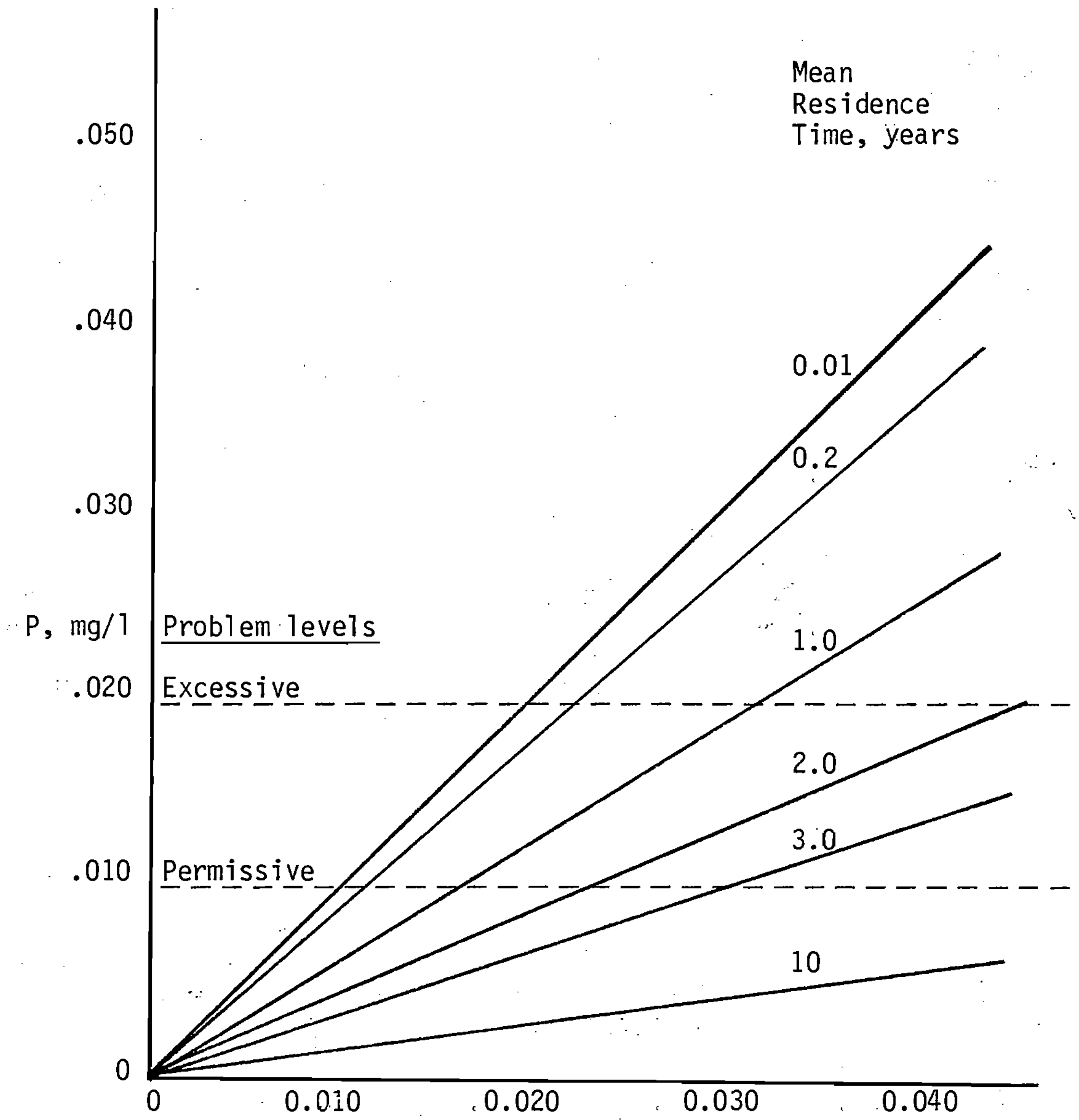


Figure 1. Relationship between phosphorus influent concentration (PI) and lake concentration (P) at different resident times (1/D, years). Net phosphorus removal (K) assumed to average 0.65. Calculated from mass balance form of steady state equation (Table 1). Problem levels based on Sawyer (1947).

is probably the most costly, but is extremely useful for evaluating potential sites and for predicting the effects of future alternatives.

Measured lake quality variables as part of a Level I or II analysis or output from Level III models can be evaluated by using indices. For example, the Lake Evaluation Index (LEI) was devised for evaluating U.S. EPA lake restoration projects and would be used to evaluate alternative controls (Porcella et al, 1980). The LEI is a rating scheme that includes macrophytes, chlorophyll a, total phosphorus, Secchi depth, and dissolved oxygen.

A particularly interesting example of the use of an ecological model is to evaluate the effects of toxicants, hydraulic mixing, or discharges on the biogeochemical transport of an element. As shown in Figure 2, phosphorus is an extremely dynamic element that cycles rapidly between various compartments. Rates of transport (mg/l day) are greatest at lower trophic levels. Management alternatives of operation and uses of lakes and reservoirs can be evaluated in terms of their effects on phosphorus transport as well as on biomass.

Research Needs

These management approaches are now among the body of tools that are used for managing water quality in lakes and reservoirs. These tools are also useful for conceptualizing research approaches for studying water quality problems so that practical and effective solutions can result from the research. To illustrate this concept, the major water quality problems of the Colorado River basin are described: salinity, eutrophication, toxic substances.

Salinity

In the Colorado River basin, salinity is a major factor relating to water quality (UWRL, 1975). Salinity in rivers is a relatively simple process to model because it is a conservative substance; however, the complexity of the hydrology and the weathering reactions in the Colorado River basin make this an extremely difficult and expensive problem to solve. Loading relationships have been applied to salinity as well as to phosphorus but in a broad sense, further development of loading models might lead to some simplified Level 1 management procedures for application to a reservoir system. Salinity might be very well handled by such an approach. Stratification often introduces some complexity but this can be evaluated by applying the level two management approach to each layer. Understanding and control of the components of salinity in reservoirs of the Colorado River could be enhanced by application of level 3 models.

Eutrophication

With the burgeoning energy industry and populations of the Intermountain region and further demands for water supply and increased water use, the biggest problem facing regional reservoirs is likely to be

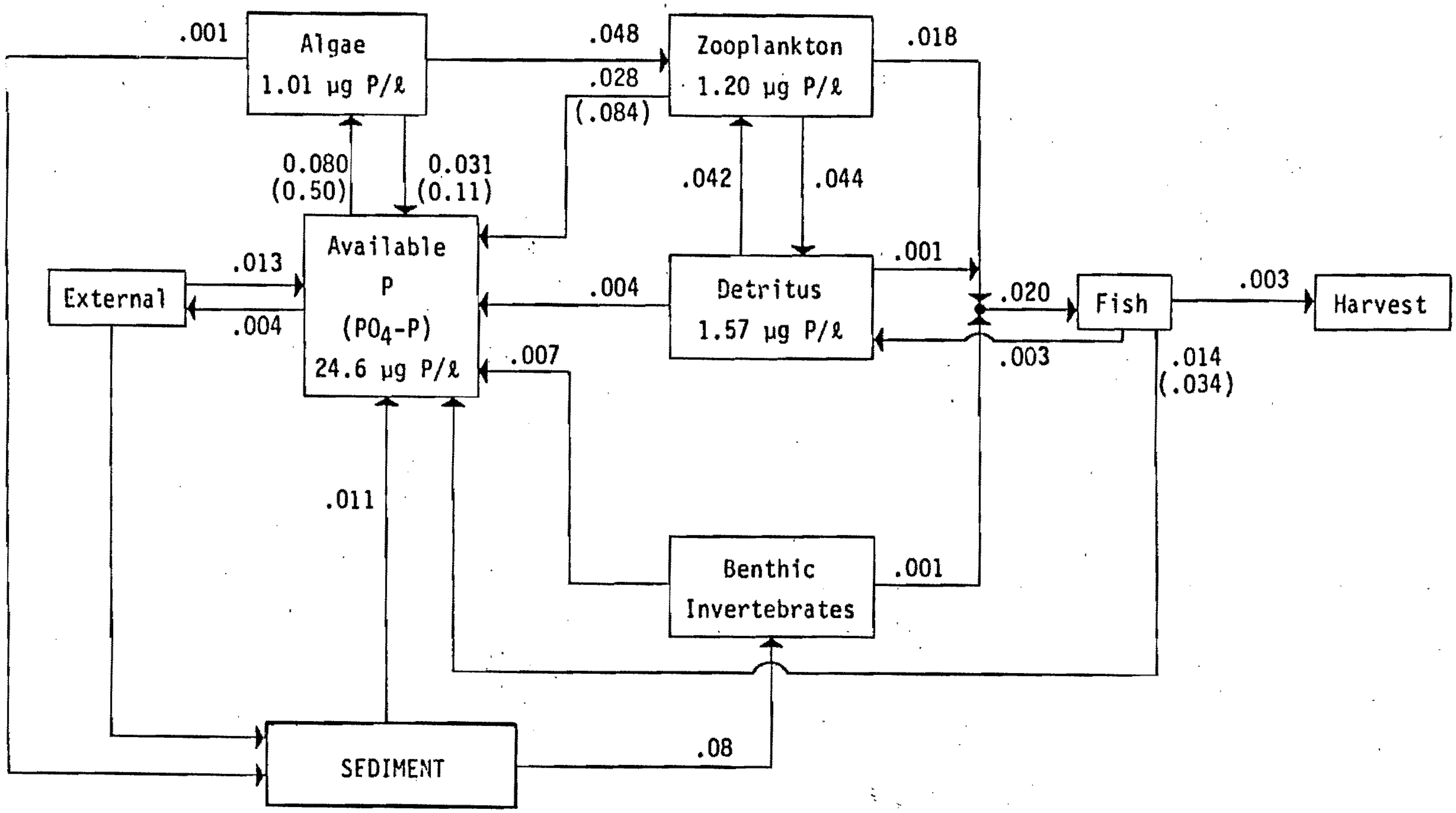


Figure 2. Total lake-annual phosphorus flux predicted in Cayuga Lake for conditions approximating 1974 (Scenario 2). Units on arrows are µg/ℓ day. Values in parantheses are for photic zone (<10m). Available P increases from 20 to 28.6 µg/Pℓ, accounting for imbalance around available P box. (From Tetra Tech, 1980).

eutrophication, that is, the increase of nutrients with consequent changes in biological productivity, dissolved oxygen, and water quality in general. This kind of problem can be approached at all three management levels; however, data need to be compiled for defining relationships for each of the management levels. Perhaps at this point in time, research on modeling should focus more on the problems of simulating the long, deep, narrow reservoirs of the Colorado River system with their complicated mixing patterns than upon chemical and biological relationships simulated in Level 3 models.

Toxic Chemical Substances

The water quality problem that has the most potential for damaging beneficial water uses in the Colorado River basin is toxic chemical substances. There are two aspects to the threat of toxic substances. On the one side is the fact that toxics may not be a problem, but yet prevent development of scarce and needed energy reserves. On the other side is the problem that grave damage to the environment and to beneficial uses of water might occur by inputs of toxic chemical substances derived from energy development.

At the first level, there have been some attempts to develop loading relationships for toxic chemical substances. Simplified hand calculator screening methods for evaluating consent decree compounds have been developed for the USEPA (Hudson and Porcella, 1980). This approach provides an estimate of how serious the problem is without actually investing a great deal of time, expertise, or money. Further development of loading models incorporating some of the concepts of the screening methodology might be very useful for analyzing and prioritizing potential toxic chemical problems.

The screening methodology is particularly useful for the second management level. Wasteload allocation is an important part of managing toxics, but there needs to be research on the fate and distribution of specific toxic substances in the Colorado River system, especially those associated with fossil fuels. Previously, wasteload allocation models have been applied to conservative and non-conservative substances that reach a relatively low steady-state concentration and do not build up in the environment. However, toxic substances do not behave that way. Inorganic toxicants do accumulate and, under the appropriate circumstances, recycle and present possible hazards to ecosystems and to society. In some cases, new reservoirs have been constructed in areas where toxic metals could accumulate and interfere with development of a water supply.

Organic chemicals are quite often very slowly degraded and serious consequences have been observed in human as well as ecological situations. Research on the factors that affect the distribution, build-up and subsequent release of toxic substances, particularly, in the sediments of lakes is needed. The kinds of toxic substances that should be focused on are those that will result from the synfuel development that is projected for the Intermountain region. Other toxicants, such as heavy metals, pesticides, and industrial products will of course become very important as these industries begin to increase in number and production.

Summary

In conclusion, I would like to congratulate the Utah Water Research Laboratory for their commitment to the development of water quality research. In the long run this research must be based on an integrated process that consists of accurately defining and conceptualizing the problem, quantifying the problem, and devising solutions that will be practical and achievable. Without the proper design of the study which incorporate the solution and accurate qualification the optimal solution cannot be obtained.

The present and future major water quality problems in the Intermountain region are salinity, eutrophication, and toxic chemical substances. The three levels of management models presented herein are helpful aids to researchers in conceptualizing these problems and devising solutions. For the waters of the Intermountain region, information is lacking for defining the specific relationships between the problems and the management variables, total phosphorus and other elements, chlorophyll *a*, fish and other beneficial uses. Selected suggestions on resarch projects for the Utah Water Research Laborator on these relationships include the following:

- Determine theoretical and measured applicability of management modes (Levels I, II, III) to control of salinity, eutrophication and toxic substances.

- At management Levels I and II, evaluate the time dependent character of K; evaluate the dynamics of removal processes and release (recycle) processes separately; determine sensitivity of rate processes for salinity compounds, nutrients and toxic chemical components.

- Determine coefficients that are specific to a given lake or reservoir for Levels II and III.

- Evaluate effects on fisheries for a Level I type of model; relate to Level III ecological model.

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