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The seasonality of phosphorus deposition in Lake Washington

Empirical descriptions of data on lakes have long permitted useful limnological predictions and generalizations about the relations among concentrations of nutrients, abundance of organisms, and other conditions. Many of the studies involve correlations of mean concentrations of these properties for a year or a large part of a year in the epilimnion or the whole lake.

This approach is useful for both applied and theoretical limnologists, but we can profit further by studying in detail the processes that determine the magnitude of the mean concentrations and how they are related functionally. If conclusions based on studies of groups of lakes differ from those based on single lakes that have been modified by changes in nutrient input, we need to know the reason for the difference. If there are important differences between individual lakes when modified the same way, we need to know why.

In an introductory paper on the eutrophication and recovery of Lake Washington we gave an account of changes in nutrient loading and of some of the chemical changes in the lake (Edmondson and Lehman 1981). To permit direct comparison with other studies of relations between nutrient income (loading) and conditions in lakes we gave most attention to total phosphorus, although we gave data on dissolved P also. As a matter of descriptive fact we showed that the net loss of P to the sediments was somewhat more closely correlated with P loading than with the P content of the whole lake. To evaluate the biological significance of the observed difference is not simple, but the observation has generated some concern as expressed in the comment by Chapra and Reckhow (1983). Loading, P content, and deposition are all closely related functionally and statistically. If one wants to use P content in a model as a measure of

deposition, it is possible to do so. Our paper can in no way disturb the pursuit of correlative models.

Some general comments are needed before we mention specific points. Most knowledge of the relations under discussion are based on analyses of correlations among measurements of different properties in a large number of lakes. Many features that affect the relationships vary: size, shape, proportion of littoral zone, relative volume of epilimnion, duration and degree of thermal stratification, concentrations and proportions of major ions, to name a few. More information exists on the P content of lakes than on loading because the information is easier to get. In most cases nutrient loading has not been measured; it has been approximated by calculations based on the character of the watershed, the density of human population, and sewage disposal practices. Relatively few studies have been made of individual lakes subjected to large changes in loading, as was Lake Washington.

Chapra and Reckhow point out that Lake Washington had 3 years of high flow, and if they are omitted, deposition is more closely related to P content. But 1964, 1972, and 1975 did happen, and an improvement of our understanding probably will be better made by modifying the theory to accommodate exceptional times than in trying to decide which data to ignore. For example, the most obvious thing about a year of high flow might be that a larger proportion of phosphorus would be carried in silt and clay which would go directly to the bottom without passing through the biological cycle of production. Thus the year 1970 could also be omitted on the basis that the particulate fraction of the input was relatively high (Fig. 1). The year 1968 had a flow almost as high as the three listed and could be omitted on the same basis. The year 1950

was second only to 1972 in flow, but unfortunately total P content was not measured. With many more selections of this sort against the data from years of higher flow we would have a perfect regression fitted to two points. It seems to us that people who need to preserve models with mean annual concentration as a measure of deposition should do so for the obvious reason that that is what is usually available to them. Research can continue on the limnological processes involved.

Next we discuss some specific points made by Chapra and Reckhow. They minimize the seasonality of P deposition. Even if P were added steadily to a lake like Lake Washington, which does not freeze, it would accumulate and increase in concentration during winter because uptake is minimal then. Concentrations decrease rapidly during late winter or spring with the development of phytoplankton. Although it is true that the flow of sewage nutrients did not vary strongly with season, the effect was seasonal. Three of the sewage treatment plants had their outfalls deep enough to deliver into the meta- or hypolimnion during much of the season of stratification (p. 180: Edmondson 1972; table 4: Edmondson and Lehman 1981). Phosphate from these treatment plants, responsible for more than half the sewage phosphorus, accumulated out of reach of phytoplankton until fall mixing which is usually too late to permit much growth of phytoplankton.

Rather than omit data based on hundreds of analyses, let us see how and why the models work and why Lake Washington behaves as it does. We examine 2 years in detail as examples. We consider 12-month periods starting 1 October, the so-called water year. The water year is especially appropriate for this discussion because in the Lake Washington drainage peak hydrologic discharge generally occurs from November to February of a water year, whereas that single period of flow would otherwise be divided between two calendar years.

We select WY66 and WY75. Neither water year was influenced by floods (floods in calendar year 1975 occurred in

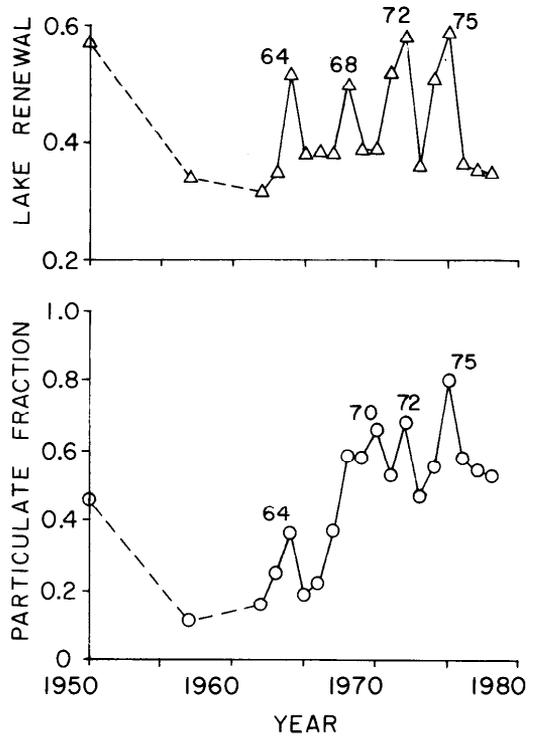


Fig. 1. Above—fraction of the volume of Lake Washington renewed by hydrologic loading, by years. Below—fraction of the total P loading to Lake Washington that is particulate (from Edmondson and Lehman 1981).

WY76). WY66 includes the effects of sewage enrichment. We purposely omit flood years because Chapra and Reckhow agree that floods bring P into Lake Washington which sediments quickly. They argue that P deposited to the sediments would depend less on inputs if flood years were not considered. For each water year we plot observed lake total P together with the lake P expected from initial lake P on 1 October plus net input each month (Fig. 2). The “observed” and “potential” values agree very well during winter months because algae use little P during winter. The rapid drops in lake P that occur in April of each year correspond to material that settles during diatom blooms. In short, the seasonality of the flux of P to the sediments of Lake Washington has less to do with seasonality (or lack of seasonality) of P inputs than with biological seasonality in that temperate lake.

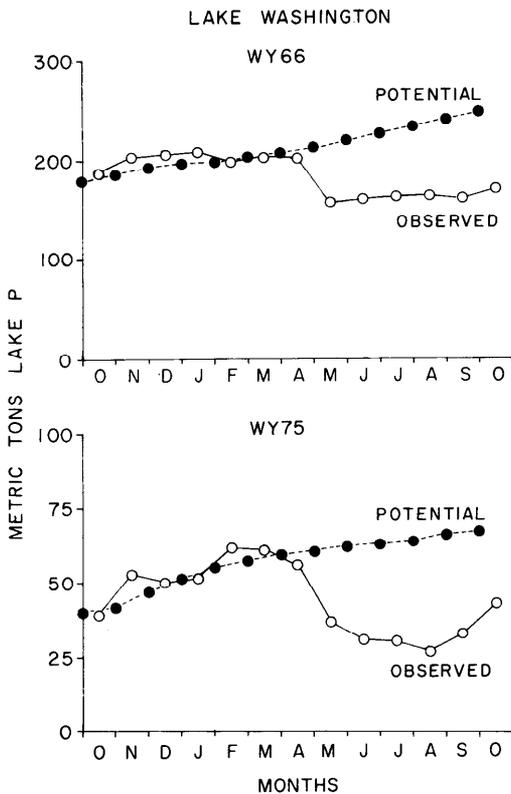


Fig. 2. Monthly mean mass of P measured in Lake Washington (○) for two years, and theoretical amounts computed from initial lake totals on 1 October plus monthly net inputs (●).

Lake P at any one moment is thus a *product* of sedimentation as much as a cause of it. Annual mean lake P is a product of sedimentation and loading. It is easy to see that these quantities are related by studying two correlations calculable from Edmondson and Lehman's (1981) tables 6 and 11: mean lake total P *versus* P input ($R = 0.833$), and mean lake total P *versus* P input minus fluvial particulate P ($R = 0.949$). The latter correlation accounts for the fact that much of the particulate load supplied by rivers sinks immediately to the bottom. The evident similarities among these quantities implies that they must have comparable predictive value in further correlations. That alone may be sufficient for some purposes. Progress in basic limnology,

however, requires something more: substantive reasoning based on causation and mechanism. Understanding the causative factors behind these correlations is a key to understanding the processes at work.

We consider a simple "concentration-based" model of the sort that Chapra and Reckhow advocate:

$$dP_L/dt = I - (Q/V)\alpha P_L - \sigma P_L \quad (1)$$

where

α = portion of lake P (P_L , kg) lost with the outflow (Q , $m^3 \cdot \text{time}^{-1}$) owing to stratification and the difference between outflow concentrations and mean lake concentrations. In practice for Lake Washington, $\alpha = (\text{total P [0-10 m] : total P [lake]} / (\text{volume [0-10 m] : volume [lake]})$;
 I = total P loading rate ($\text{kg} \cdot \text{time}^{-1}$);
 V = lake volume (m^3);
 σ = net fraction of P_L that is sedimented (time^{-1}).

Its discrete analog is

$$P_{L_{i+1}} = P_{L_i}(1 - Q_i\alpha_i/V - \sigma_i) + I_i. \quad (2)$$

We approve of this model also, at time scales of less than a year. Let us consider first that $\Delta t = 1$ month. Thus α_i , σ_i , Q_i , and I_i are monthly values; for any given year α_i , Q_i , P_{L_i} , and I_i are known. Thus,

$$\sigma_i = 1 - Q_i\alpha_i/V - (P_{L_{i+1}} - I_i)/P_{L_i}. \quad (3)$$

We propose a simple numerical exercise with data from Lake Washington to show why mean lake P varies with input. For this example we pick WY64 and WY75 because WY64 was a year of maximal loading and WY75 was a nonflood postsewage year. We will use our simple model to investigate the sensitivity of mean annual lake P to hypothetical changes in P loading. We proceed as follows.

1. Find α_i and σ_i by months empirically for each year.

2. Use these empirical values for α_i and σ_i for all simulations of a given year. First, vary input (I_i) by scaling it with an arbitrary factor:

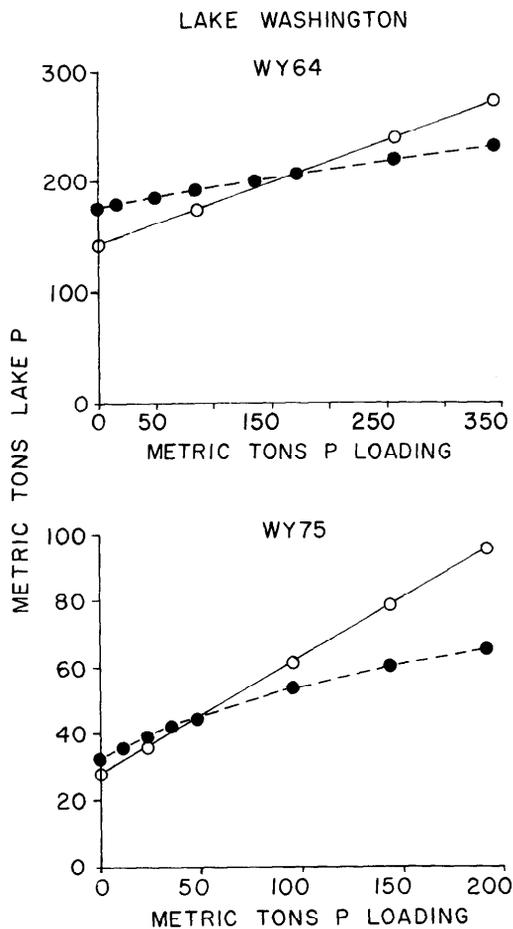


Fig. 3. Mean annual lake P computed after 1-year simulations of alternative P-loading scenarios. Either P loading alone was varied (○), or both P and hydrologic loading varied (●). See text.

$$I'_i = \beta \cdot I_i.$$

This is like saying that concentrations change systematically in the inputs.

3. Alternatively, vary both I_i and Q_i by the same factor β :

$$I'_i = \beta \cdot I_i,$$

and

$$Q'_i = \beta \cdot Q_i.$$

This is like saying that fluvial volumes change but concentrations are the same. One assumption (3) changes the flushing regime. The other does not.

4. For each case, simulate a year by Eq. 2 and calculate mean lake P. Repeat the procedure with different values of β . Finally, plot the many pairs of [mean lake P] and [ΣI_i = annual loading].

In each case the relation between mean lake P and loading is a straight line, or a nearly straight line (Fig. 3).

We can demonstrate that this is true necessarily by solving the discrete model (Eq. 2) for mean annual P.

$$\bar{P}_L = C_o + \beta \Sigma C_i I_i \quad (\text{vary } I \text{ only})$$

where C_o and C_i are constants. When both I and Q are varied, the analytical solution is a polynomial in β , which accounts for the slight curvature evident from simulations.

The point is, for the range of hydrology and P loading relevant for Lake Washington one can expect that mean annual lake P will be correlated with input P just as we see. That is why either correlate can be used to predict sedimentation from a point of practicality. But annual mean lake P does not *cause* the sedimentation rate. It is just a statistical composite of events and processes that have occurred. Consequently, quite aside from statistical arguments we can see persuasive mechanistic reasons for predicting sedimentation in Lake Washington from loading data, although we are pleased that statistical procedures reinforce our view.

We reiterate points we made in our 1981 paper:

—Biotic events are strongly seasonal in temperate lakes.

—P flux to the sediments varies seasonally.

—Lake P increases during winter in Lake Washington because of inputs. The added P fuels a spring diatom bloom which leads to a flux of P to the sediments.

We value the last sentence of the comment of Chapra and Reckhow with its implicit recognition that our paper is but the tip of the iceberg. We have a large amount of information about chemical and biological conditions in Lake Washington. As we proceed to interrogate the record, we will try to be both interesting and useful.

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Announcements**G. Evelyn Hutchinson Medal**

The American Society of Limnology and Oceanography presented the G. Evelyn Hutchinson Medal of 1983 at the June Meeting in St. John's, Newfoundland, to John E. Hobbie "who has caused a revolution in our understanding of the importance of bacteria in natural waters, including the water column and the benthos, from ponds and lakes to estuaries and oceans."

Ocean Sciences Meeting

The 1984 Ocean Sciences Meeting of the American Geophysical Union (AGU) will be held 23-27 January 1984, in New Orleans, Louisiana. Housing and registration information will be published in *Eos* and mailed to anyone requesting information on the meeting. Cosponsoring societies are the American Society of Limnology and Oceanography (ASLO); the Acoustical Society of America (ASA); the American Meteorological Society (AMS); the Marine Technology Society (MTS); and the Institute of Electrical and Electronics Engineers Oceanic Engineering Society (OES).

Abstracts must be received at AGU by 19 October 1983. Details and submittal requirements are available from: Ocean Sciences Meeting, American Geophysical Union, 2000 Florida Ave. N.W., Washington, D.C. 20009.