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GEOLOGICAL SURVEY

ESTIMATION OF BACKGROUND LOADINGS AND CONCENTRATIONS OF PHOSPHORUS FOR LAKES IN THE PUGET SOUND REGION, WASHINGTON

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Multiply	By	To obtain
Meters (m)	3.281	feet (ft)
Square kilometers (km^2)	247.1	acres
	.3861	square miles (mi^2)
Kilograms (kg)	2.205	pounds (lbs)

ABSTRACT

For lakes in watersheds that include substantial developed land, the evaluation of eutrophication is facilitated by a knowledge of changes in the lake's P (phosphorus) concentrations that have occurred since development. However, background (predevelopment) concentration data do not exist for many lakes. A method for estimating background P concentrations in lakes of the Puget Sound lowland has been developed. Using a mass-balance "Vollenweider-type" model, P loadings were calculated from present-day P concentrations measured in lake water and easily measured physical characteristics for 24 lakes in undeveloped, or insignificantly developed, watersheds. From other studies, annual P loading by bulk precipitation directly on a lake's surface was estimated to be 20 kilograms per square kilometer. Loading of P from forest (undeveloped) land was derived for each lake as the difference between the calculated P loading to the lake and loading by bulk precipitation. Forest-land loading to each lake was converted to the yield (mass per unit area) of the forested portion of the watershed. The yield of P from forest land was logarithmically related to annual runoff, and the regression equation expressing this relationship explained 73 percent of the sample variance. By applying that regression equation to the appropriate annual-runoff data, the yield of P from forest land can be estimated for any lake in the study area. Loading of P from forested watershed land, calculated from forest-land yield, then can be added to direct loading by bulk precipitation to estimate background P loading for each lake. By applying the mass-balance model to these calculated background loadings, background total-P concentrations can also be calculated for all lakes in the study area that have stable thermal stratification during the summer. The standard error of estimate

for calculated background loadings and concentrations averages about 25 percent for most lakes in the area. The method presented provides reliable estimates of background (predevelopment) P loads and concentrations for Puget Sound region lakes, using data that are presently available for most lakes in the region. These estimates are valuable for detecting and assessing the impacts of land-use changes that adversely affect the quality of lake waters by evaluating the difference between estimated background concentrations and present-day concentrations.

INTRODUCTION

Eutrophication caused by nutrient pollution from nonpoint sources is a recurrent problem for both rural and urban lakes. The Puget Sound region contains more than 500 lakes, which have a wide range of trophic conditions and land-use settings. The large number of lakes in this region, the increasing use of these lakes and development in their drainage basins, makes control of eutrophication a pressing and difficult task for local and state agencies. Control of eutrophication requires land-use management based upon quantitative evaluation of nutrient sources and their impacts on lake-water quality. To be effective, the methods for evaluating eutrophication must be applicable within the staff or financial capabilities of local and state agencies. Effective, but simple, evaluation is possible based on concentrations of the nutrient, P (phosphorus) in the lakes. Phosphorus is generally considered to be the limiting and most-controllable nutrient affecting algal productivity in the majority of lakes in temperate regions of the world (Vollenweider, 1968; Shindler and Fee, 1974; Schindler, 1977; Rast and Lee, 1978; Schindler, 1978), and P also appears to control productivity in most Washington lakes (Bortleson, 1978).

The purpose of this study was to develop an empirical model that can be used to estimate background (predevelopment) loadings and concentrations of P for Puget Sound region lakes from available data. Background P concentrations that are estimated from the model then can be compared to measured concentrations in the lakes that have development in their drainage basins in order to evaluate eutrophication caused by the development.

USING PHOSPHORUS TO EVALUATE LAKE EUTROPHICATION

Phosphorus and Lake Quality

Phosphorus concentration is the most common criteria used to classify a lake as either oligotrophic, mesotrophic, or eutrophic (Rast and Lee, 1978), and in lakes there is a strong correlation between total-P concentration and chlorophyll-*a* concentration, representing algal standing crop (Sakomoto, 1966; Dillon and Rigler, 1975; Jones and Bachmann, 1976; Vollenweider, 1976). Moreover, total-P and chlorophyll-*a* concentrations can be quantitatively related to water clarity as measured by Secchi-disc depth (see Rast and Lee, 1978 for several examples), and descriptively related to dissolved-oxygen depletion in a lake's hypolimnion and the general suitability of a lake for different uses (Dillon and Rigler, 1975). Therefore, if changes in land use can be related to changes in P loading to a lake, and then to concentration measured in the lake water, much is known about the impact of the land-use changes on the quality of the lake.

Mass-Balance Model of Phosphorus

There are several simple, deterministic models that relate the total-P concentration in a lake at steady state to P loading (Dillon, 1974; Rast and Lee, 1978). A mass-balance, "Vollenweider-type" model, orginally developed by Piontelli and Tonolli (1964) and refined by Dillon and Rigler (1975), Vollenweider (1969), and Vollenweider (1976), has consistently produced accurate results in different areas of North America (Larsen and Mercier, 1976; Rast and Lee, 1978). The same model has also been validated in the Puget Sound region (Gilliom, 1978), and may be written as,

$$(\overline{P})_{\infty} = \frac{L \cdot (1-R)}{\overline{z} \cdot A \cdot \rho} \qquad (1)$$

where

$(\overline{P})_{\infty}$ mean concentration of total P at steady state in the lake, in $\mu g\ L^{-1}$;

L the total-P loading to the lake, in $kg\ yr^{-1}$;

R the lake-retention coefficient (decimal percent of L retained in the lake, but not causing an increase in total-P concentration), dimensionless;

$\overline{z}$ mean depth, in m;

A lake-surface area, in km^2; and

ρ lake-flushing rate, in yr^{-1}.

Larsen and Mercier (1976) and Vollenweider (1976) independently found that R can be approximated by

$$R = \frac{1}{1 + \sqrt{\rho}} \, . \qquad (2)$$

Flushing rate can be calculated from

$$\rho = \frac{WSA \cdot RO}{A \cdot \overline{z}} \, , \qquad (3)$$

where

WSA watershed area, including lake surface, in km^2; and

RO annual average runoff (depth of water), in m.

Runoff depth, in this case, refers to statistical estimates of runoff based on observed streamflow from many watersheds in this region (see table 1). Therefore, these estimates include water reaching lakes directly, or indirectly from inflow streams, by surface runoff, subsurface stormflow (ephemeral ground water), and baseflow of ground water.

Several assumptions are necessary in order to use the previous equations:

1. The lake can be represented as a completely mixed body of water.
2. Lake volume is constant.
3. Inflow equals outflow volume on an annual basis.
4. Lake sediments are a net P sink.
5. Steady-state retention of P in the lake is proportional to P-loading rate, L.
6. Ground-water inflow to the lake that is not accounted for by runoff estimates is negligible.
7. Annual lake evaporation is equal to evapotranspiration from the land.

All the above assumptions were found to be generally valid for lakes in the Puget Sound lowland. (See Gilliom, 1978, for detailed discussion.)

STUDY AREA

This investigation utilized data for 39 lakes in the lowlands of the Puget Sound region, Washington (fig. 1). The study area has a mild, maritime climate characterized by cool, wet winters and warm, fairly dry summers. Average precipitation ranges from 0.5 to 1.5 m yr^{-1}, depending mainly on elevation but also location relative to rain-shadow effects of the Olympic mountains. About 80 percent of the precipitation occurs from October through April. All lakes in the area receive most of their inflow during

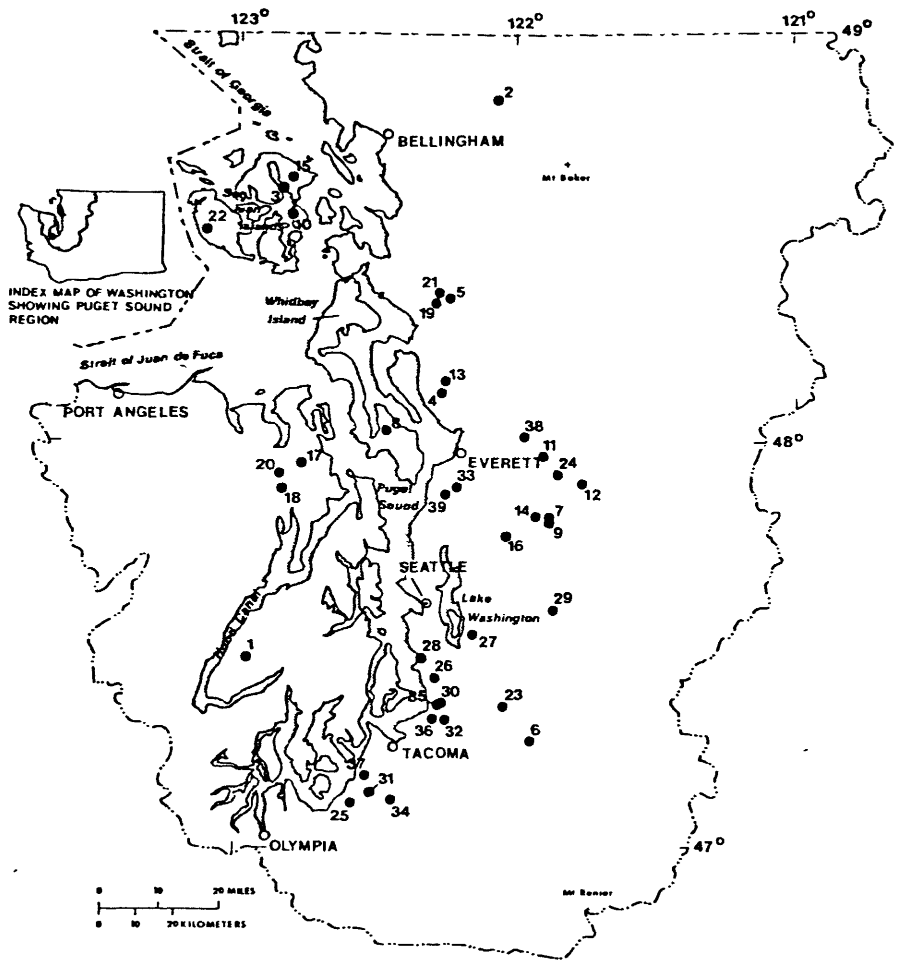

Figure 1. - Location of the Puget Sound region and lakes studied. Numbered lakes are listed in Tables 1 and 2.

the winter season, even though they are distributed among localities having wide variations in annual runoff.

Most lakes in the Puget Sound lowland occupy depressions in sediment deposited by the most recent continental glaciation. Elevated areas are generally covered by compact glacial till and low-lying areas are commonly covered by more permeable glacial outwash. Soils surrounding the lakes are mainly shallow, gravelly sandy loam with local deposits of peat, muck, and finer-textured soils. Native vegetation is dominated by a dense growth of conifers, but most merchantable timber has been harvested once, resulting in a mixed forest containing second-growth conifers as well as deciduous trees.

The mixing and flushing cycles of lakes in the study area are dictated by the area's climate. Surface-water inflows are generally intermittent, and lake flushing is distinctly confined to the winter season for most lakes. During this period lakes are completely mixing. Thermal stratification commonly begins in May and remains through September or early October, though lakes with a mean depth of less than 3 m generally do not stratify.

Generalizations about the seasonal dynamics of P are useful for lakes in the area that stratify during the summer. Most P loading occurs during periods of high runoff when lakes are completely mixed and are also flushing relatively rapidly. The total-P concentration in the surface waters of a lake typically reaches its annual-high value during this winter period, shortly after fall turnover, and then gradually decreases to a late-summer low, after stratification is established in early summer. Although some of the most intense algal blooms of the year occur in early fall and spring because of the combination of mild climate in the area and relatively high nutrient concentrations, the most critical season for nuisance growth of algae is the summer when recreational use is high.

The location of each of the 39 lakes evaluated in this study is shown in figure 1. This sample of 39 was limited to lakes with a mean depth greater than 3 m (generally assuring thermal stratification during the summer), and those lakes in the Puget Sound region that receive 1.5 m or less of annual runoff. Physical data, values for terms that are described subsequently, and measured total-P concentrations for 24 of the lakes that represent background (predevelopment) water quality, are given in table 1. A similar compilation of data and values of terms for 15 lakes with substantial development in their basins is listed in table 2. The types of data shown for these lakes are available for most lakes in the Puget Sound region from the reports indicated in the tables.

ESTIMATING BACKGROUND PHOSPHORUS LOADINGS

Background P loading is mainly from P in bulk precipitation (in dry fallout as well as dissolved in precipitation) falling directly upon a lake's surface, and from P in water entering the lake from the land portion of the drainage basin that is in an undeveloped state. Additional loading may occur by inflow of P-bearing ground water that is not accounted for in forest-land drainage, but this is assumed to be negligible in the study area. For undeveloped lakes, background loading can be directly measured or estimated from existing conditions. However, for lakes that have development in their basins, background P loading must be indirectly estimated either from data for other drainage basins in the vicinity, or by a model that relates loading to known characteristics of the basin in question. The methods described below combine these two general approaches for evaluating the predevelopment P loading of a developed lake using data from lakes with no development in their basins. The following is an overview of these methods.

TABLE 1.--Selected physical parameters and measured phosphorus concentrations for lakes in the Puget Sound lowland representing background water-quality conditions.

Lake	Watershed area, WSA [a] (km^2)	Lake area, A [a] (km^2)	Mean depth, $\bar{z}$ [a] (m)	Annual runoff, RO [b] (m)	Flushing rate, ρ [c] (yr^{-1})	Sediment phosphorus retention, R [d] (dimensionless)	Measured total phosphorus concentration $(\bar{P})_{ss}$ [e] ($\mu g\ L^{-1}$)
1. Bennettsen	0.47	0.11	3.4	0.89	1.4	0.46	7±4
2. Canyon	10	0.10	8.3	1.5	18	0.19	7±4
3. Cascade	8.9	0.69	8.2	0.15	0.26	0.66	6±3
4. Crabapple [f]	3.1	0.14	5.5	0.31	1.3	0.47	12±3
5. Devils	2.3	0.16	4.3	0.76	2.8	0.37	13±7
6. Fish	37	0.07	4.0	0.51	65	0.11	17±9
7. Fontal	1.8	0.18	4.9	0.89	2.0	0.42	10±5
8. Goss [f]	3.7	0.19	9.8	0.23	0.47	0.59	11±3
9. Hannan	1.1	0.20	4.0	1.0	1.7	0.43	7±4
10. Horseshoe	1.7	0.57	10	0.15	0.04	0.83	8±4
11. Hughes	2.3	0.09	5.8	1.3	6.2	0.29	8±4
12. Kellogg	7.3	0.07	4.0	1.5	44	0.13	10±5
13. Ki [f]	1.9	0.40	10	0.31	0.17	0.71	9±3
14. King	0.41	0.07	6.4	0.76	0.83	0.52	13±5
15. Mountain	5.9	0.73	15	0.28	0.17	0.71	8±4
16. Paradise	11	0.07	5.2	0.51	14	0.21	20±10
17. Peterson	1.4	0.10	8.8	0.23	0.37	0.62	8±4
18. Sandy Shore	1.4	0.24	6.1	0.23	0.25	0.67	9±5
19. Sixteen [f]	3.8	0.19	5.5	0.64	2.5	0.39	15±6
20. Taboo	0.65	0.10	8.5	0.23	0.21	0.69	10±5
21. Ten	0.44	0.05	9.8	0.76	0.73	0.54	9±5
22. Trout	3.6	0.26	7.0	0.13	0.27	0.66	6±3
23. Webster	0.29	0.04	4.0	0.64	1.4	0.46	15±8
24. Woods	4.2	0.09	5.2	1.5	15	0.21	11±6

TABLE 1.--Continued

[a]Bortleson and others (1976)

[b]Gladwell and Mueller (1967), except for lakes 3, 8, 10, 15, and 22, which were estimated from Dietrich (1975).

[c]Calculated by equation 3.

[d]Calculated by equation 2

[e]All reported concentrations are total P measured in lake surface waters (1-meter depth) during summer stratification, $(\overline{P})_{ss}$. For all lakes except the following, $(\overline{P})_{ss}$ is based on one observation as reported by Bortleson and others (1976). Three to four observations each are available for lakes 4, 8, 13, and 14, from McConnell and others (1976) and Dion and others (1976). Two observations are available for lake 19; one from Bortleson and others (1976) and one from unpublished data collected for this study. Standard errors of the estimates of the true means from these data were approximated by a method described by Gilliom (1978) for Puget Sound region lakes.

[f]Drainage basins included a relatively small amount of residential development, which was considered to have an insignificant impact on the lake water.

TABLE 2.--Selected physical parameters and measured phosphorus concentrations for lakes in the Puget Sound lowland with 20 percent or more of their watershed in residential land use.

Lake	Watershed area, WSA [a] (km^2)	Lake area, A[a] (km^2)	Mean depth, $\bar{z}$ [a] (m)	Annual runoff, RO [b] (m)	Flushing rate, ρ [c] (yr^{-1})	Sediment phosphorus retention, R[d] (dimensionless)	Measured total phosphorus concentration $(\bar{P})_{ss}$ [e] (μg L^{-1})
5. American	66	4.6	16	0.38	0.34	0.63	16±3
6. Angle	2.1	0.41	7.6	0.46	0.30	0.64	16±4
7. Boren	2.8	0.07	5.5	0.51	3.5	0.35	16±5
8. Burien	1.0	0.18	4.0	0.46	0.67	0.55	19±7
9. Echo	1.2	0.05	4.3	0.46	2.0	0.39	20±7
0. Fenwick	2.3	0.10	7.3	0.51	3.2	0.36	13±7
1. Gravelly	1.7	0.65	12	0.38	0.09	0.77	16±6
2. Mirror	0.67	0.08	3.7	0.63	1.4	0.46	13±7
3. Silver	2.8	0.45	7.3	0.51	0.47	0.60	21±11
4. Spanaway	44	1.1	4.9	0.38	3.0	0.36	22±8
5. Star	1.5	0.14	7.6	0.51	0.72	0.54	13±5
6. Steel	0.98	0.19	7.3	0.63	0.84	0.60	15±6
7. Steilacoom	230	1.3	3.4	0.38	20	0.18	22±6
8. Stevens	18	4.1	19	0.51	0.11	0.75	15±5
9. Stickney	9.2	0.08	4.5	0.51	14	0.22	20±4

[a] Bortleson and others (1976).

[b] Gladwell and Mueller (1967).

[c] Calculated by equation 3.

[d] Calculated by equation 2.

[e] All reported concentrations are total P measured in lake-surface waters (1 meter depth) during summer stratification, $(\bar{P})_{ss}$. All values are from Gilliom (1978), summarized from data collected by other researchers.

1. Total background P loading to each of 24 lakes in the study area with forested-drainage basins was estimated by using the mass-balance model described earlier to calculate loading from measured total-P concentrations.
2. The portion of background loading attributable to P in bulk precipitation was calculated from an areal loading rate that was estimated from available data and assumed constant for the study area.
3. Forest-land P yield (mass per unit of forest land) to each of the 24 lakes was then calculated from the difference between total background loading estimated in step 1 above and loading by bulk precipitation estimated in step 2.
4. Regression relationships between forest-land P yield and annual runoff and drainage area were evaluated for the sample of 24 lakes. The best regression equation was chosen to calculate forest-land P yield for other lakes in the area.
5. Background P loading to any lake could then be calculated by summing loading by forest-land drainage, estimated from the regression equation developed in step 4, and loading by bulk precipitation estimated in step 2.

Application of the Mass-Balance Phosphorus Model to Calculate Loading

The mass-balance model represented by equation 1 can be arranged and redefined for the purpose of this study to allow calculation of lake P loading from the P concentration measured in a lake. Equation 1 was modified to be

$$L^* = \frac{(\overline{P})_{ss} \cdot \overline{z} \cdot \rho \cdot A}{(1-R)} , \qquad (4)$$

or

$$(\overline{P})_{ss} = \frac{L^* \cdot (1-R)}{\overline{z} \cdot A \cdot \rho} , \qquad (5)$$

where $(\overline{P})_{ss}$ the mean, steady-state concentration of total phosphorus in the surface waters of a stratified lake during the summer, in μg L^{-1};

A, $\overline{z}$, R and ρ as defined for equation 1; and

L^* is an empirically derived P loading rate in kg yr^{-1}.

Phosphorus loading rates, L^*, calculated by equation 4 require careful definition. Values of L^* are not generally equivalent to total-P loading (L in eq. 1) and, therefore, are not freely interchangeable with values of L. Equation 1, the mass-balance model in its original form, was derived from, and is usually used for, an evaluation of the average-annual total-P budget of a lake on a whole-lake basis. Thus, in equation 1, L is the total-P loading and $(\overline{P})_\infty$ is the total-P concentration averaged over the entire year and the total volume of a lake. Equation 4, in contrast, relates P loading to the summer surface-water concentration of P, $(\overline{P})_{ss}$, which is generally lower than the average whole-lake concentration for the entire year. Therefore, L^* is generally a lower value than the actual total-P loading to a lake. L^* and L could theoretically be equal only if $(\overline{P})_{ss}$ and $(\overline{P})_\infty$ were equal. Although the precise relationship of the empirical P loading to actual chemical species of P is unknown, the value of L^* is generally between loading of dissolved ortho-P and loading of total P.

Summer surface-water concentrations of P were used rather than annually averaged, whole-lake concentrations to calculate loading because (1) many more data were available for summer measurements, and (2) the impact of P loading on a lake is the most critical during the summer season. The mean concentration of total P in the epilimnion of a stratified lake, measured during the summer period of low inflow and low P loading, is an approximate estimate of the amount of P involved in phytoplankton productivity during the most critical season for recreational use of a lake. Therefore, empirical P loading, calculated from the epilimnion P concentration, is an estimate of the portion of annual loading that actually impacts the lake during the critical growth period.

Phosphorus loading to lakes with completely forested (undeveloped) drainage basins is expressed as

$$L^* = PREL \cdot A + (WSA-A) \cdot FORY, \quad (6)$$

where PREL P loading by bulk precipitation, in kg $km^{-2}yr^{-1}$; and

FORY P yield from forest land, in kg $km^{-2}yr^{-1}$.

L^* can be calculated by equation 4 from the measured concentration of P in an "undeveloped" lake, leaving PREL and FORY as the two unknown values in equation 6. Equation 6 can be utilized to evaluate FORY if PREL can be estimated independent of the equation.

Estimation of Phosphorus Loading by Bulk Precipitation

Available data were used to estimate PREL, independent of equation 6, but these data for the Puget Sound region are limited in areal coverage and number of observations. Data from other regions were not considered acceptable because of the variability between regions evident in P loading by bulk precipitation (Uttormark and others, 1974). The limited data base necessitated the assumption that PREL is a constant for the study area. However, lakes in low-precipitation localities are generally the most sensitive to variations in P loading from bulk-precipitation (and thus to errors in PREL), because they receive a greater portion of their annual water and P input directly from the atmosphere (compared to runoff) than do lakes in high-precipitation localities. Therefore, relatively small changes in PREL for these lakes (as compared to lakes in high-precipitation localities) could have a significant impact on the total loading assessment for the lake. Because of the greater sensitivity of these lakes, data most representative of lakes in low-precipitation localities were used to derive a value of PREL for all lakes in the study area.

Ellsworth and Moodie (1964) measured dissolved-P loading at two sties (Washington State Agricultural Experiment Stations) in the study area that each receive about 0.9 m of annual precipitation, resulting in about 0.4 m yr^{-1} of runoff. These are the lowest-precipitation localities for which data were available. The mean-annual loading if dissolved P calculated from their data is 13 kg km^{-2} yr^{-1}. Data from several regions of North America and a variety of land-use settings (Nicholls and Cox, 1978; Uttormark and others, 1974), and data from a forested area in the Puget Sound region (unpublished data from Dale Cole, University of Washington, College of Forest Resources, 1979), indicate that total P in bulk precipitation is typically 60 percent dissolved. The other 40 percent is particulate and is less available for biological use. According to this relationship, 13 kg km^{-2} yr^{-1} dissolved P represents a total-P load of about 20 kg km^{-2} yr^{-1}. This estimate of total-P loading was felt to provide a better approximation of PREL than dissolved loading; therefore, PREL is equal to 20 kg $km^{-2}yr^{-1}$. The uncertainty in this value is not possible to evaluate from the available data, but errors in PREL generally have a small affect on the assessment of total loading to a lake compared to errors in loading from a lake's watershed.

Estimation of Phosphorus Yield from Forest Land

Forest-land P yield (FORY) can be calculated by equation 7, with PREL determined from available data as described above, and L^* calculated from equation 4, as follows:

$$FORY = \frac{L^* - PREL \cdot A}{WSA - A} \qquad (7)$$

By use of equation 7, FORY was calculated for each lake listed in table 1. The resulting sample of values for FORY, representing 24 different lakes, allows the examination of empirical relationships between FORY and characteristics of individual lake basins that may influence P yield.

Phosphorus yield from forest land is often assumed to be a constant in regional investigations of nutrient budgets, but it may vary significantly depending on natural environmental factors. Hydrologic variables and drainage-basin morphology may cause variations in forest-land P yield even within a limited geographic area. Kirchner (1975) found a high positive correlation between P yield from forest areas in Ontario and the drainage density of watersheds (average stream length per unit area). He suggested that yield is greater from watersheds with a high drainage density because less runoff is filtered through the soil and more runoff reaches streams directly by overland flow. An alternative explanation is that drainage density is correlated with annual runoff and that P yield varies according to runoff volume. Feller and Kimmins (1979) found that the yield of several elements, including P, from 3 watersheds in western British Columbia, increased logarithmically with annual stream-flow volume. Gilliom (1978) found an inverse relationship between the size of forested drainage basins and P loading to lakes in parts of the Puget Sound region that had a narrow range of annual runoff. In the present study, the effects of annual runoff and drainage-area size on forest-land P yield are investigated by regression analysis with the goal of developing an empirical relationship for estimating FORY for other lakes in the study area.

The yield of P from forest land, calculated by equation 7 for each lake in table 1, was found to be highly correlated with annual runoff (in m) in the area of each lake. The best-fit regression equation for this data explained 73 percent of the sample variance ($r^2 = .73$) and can be expressed as,

$$FORY = 7.1 \cdot \ln RO + 16.6. \qquad (8)$$

The addition of drainage area as an independent variable in equation 8 was found to be statistically significant at a 95-percent probability level, but was not included because the variance explained was increased by only 8 percent, and estimates from the multiple-regression equation were biased.

Data used to derive equation 8, the solution to the equation over its valid range, and confidence limits on estimates of FORY from the equation, are shown in figure 2. The mean value of FORY for data shown in figure 2 is 12 kg km^{-2} yr^{-1}, and values range from 1 to 25 kg km^{-2} yr^{-1}. The confidence limits shown are standard errors that represent a 68-percent probability range, and may be doubled for a 95-percent probability range. The average

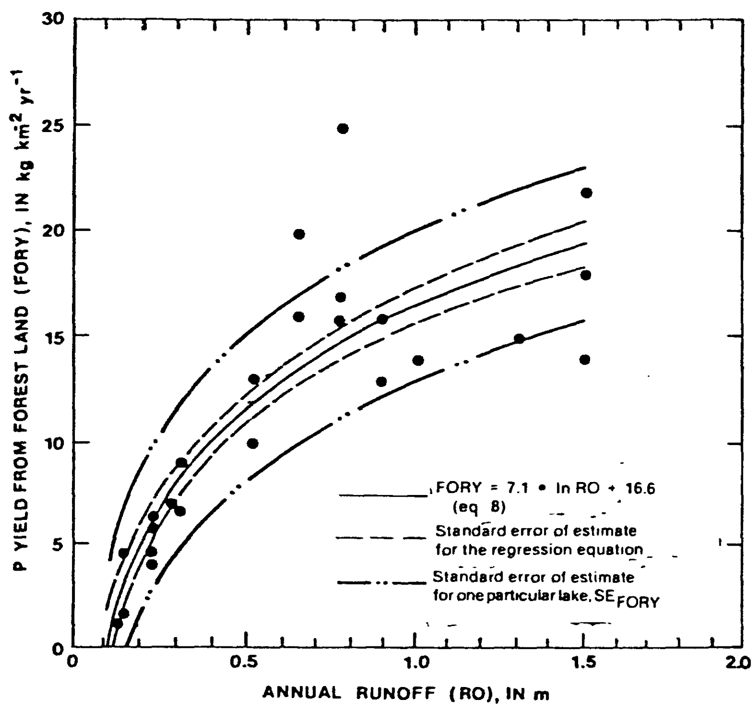

Figure 2. - Relationship between phosphorus yield from forest land and annual runoff.

standard error of estimate of FORY for individual lakes within the range of runoff conditions evaluated is about 3.6 kg km^{-2} yr^{-1}, and this varies little with runoff. As shown, however, the percent error varies considerably with runoff, being largest at the lowest values of runoff.

ESTIMATING BACKGROUND CONCENTRATIONS OF PHOSPHORUS IN LAKE WATER

Using the total background loading rate determined from equation 6, the background concentration of P in a lake can be estimated from the mass-balance model (eq. 5). Necessary equations are summarized below:

$$PREL = 20,$$

$$FORY = 7.1 \cdot \ell n\ RO + 16.6, \qquad (8)$$

$$L^* = PREL \cdot A + (WSA-A) \cdot FORY, \qquad (6)$$

$$\rho = \frac{WSA \cdot RO}{\bar{z} \cdot A}, \qquad (3)$$

$$R = \frac{1}{1 + \sqrt{\rho}} \qquad (2)$$

$$(\bar{P})_{ss} = \frac{L^* \cdot (1-R)}{\bar{z} \cdot A \cdot \rho}, \qquad (5)$$

where all symbols are as previously defined.

Uncertainty in Estimates of Background Concentrations

The standard error of estimate for any calculated value of $(\overline{P})_{ss}$ can be approximated be determining SE_{FORY} (standard error of estimate of FORY) from figure 2 and converting it to $SE_{(\overline{P})_{ss}}$, (standard error of estimate of lake water concentration), as follows:

$$SE_{(\overline{P})_{ss}} = \frac{SE_{FORY} \cdot (WSA-A) \cdot (1-R)}{\overline{z} \cdot A \cdot \rho} \quad . \qquad (9)$$

To use equation 9, one must assume that all uncertainty in a calculated value of $(\overline{P})_{ss}$ is due to FORY. This is not strictly true, but the uncertainty in values of FORY from equation 8 (used to develop the regression equation) is the result of the combined variability in all model terms, including PREL. The uncertainty in all model terms is, therefore, incorporated in estimates of standard errors in FORY from the regression equation, and the above method (eq. 9) is valid for approximating standard errors of estimates of lake-water concentrations.

Validity of Estimates of Background Concentrations

The validity of the described method for estimating background-P concentrations is mainly dependent on the regression relationship used for determining P loading from forest land (eq. 8). The primary argument for the validity of this relationship is that the regression model, as discussed earlier, explains most of the variance in the sample analyzed. Moreover, when estimates of FORY from equation 8 were used with the lake model to calculate background concentrations for the undeveloped lakes studied, the average difference between calculated and measured concentration was only

2 $\mu g\ L^{-1}$ (fig. 3). When, instead, FORY was treated as a constant (the mean of all undeveloped lakes, 12 $kg\ km^{-2}yr^{-1}$, the average difference between calculated background $(\overline{P})_{ss}$ and measured concentration increased to 6 $\mu g\ L^{-1}$ (fig. 4). The comparison shown in figures 3 and 4 demonstrates that annual runoff is a valid and important factor that is empirically related to annual P yield from forest land. With the use of individual values of FORY, the average standard error of estimate of background P concentration for most lakes in the study area is about 25 percent, but this varies with runoff approximately as was shown in figure 2 for FORY.

An additional test of model validity was performed by calculating background P concentrations for an independent sample of 15 lakes with substantial development in their drainage basins (table 2). Calculated values of background concentrations that were lower than recently measured concentrations were considered to be qualitative evidence of model validity, because the development was expected to have caused higher-than-background concentrations for these lakes. Figure 5 shows that calculated background concentrations are lower than recently measured concentrations for all but one lake (Lake Fenwick), and for that lake they are equal.

USE AND LIMITATIONS

Background concentrations of total P, calculated by the methods described, can be subtracted from total-P concentrations measured in lakes to assess the impact that existing drainage-basin development has had on lake-water P concentrations. The calculated background concentrations also may aid in setting standards for total P in lake surface waters. Standards could be varied between lakes, or groups of lakes, to account for different levels of natural fertility. Data presented in this study indicate background

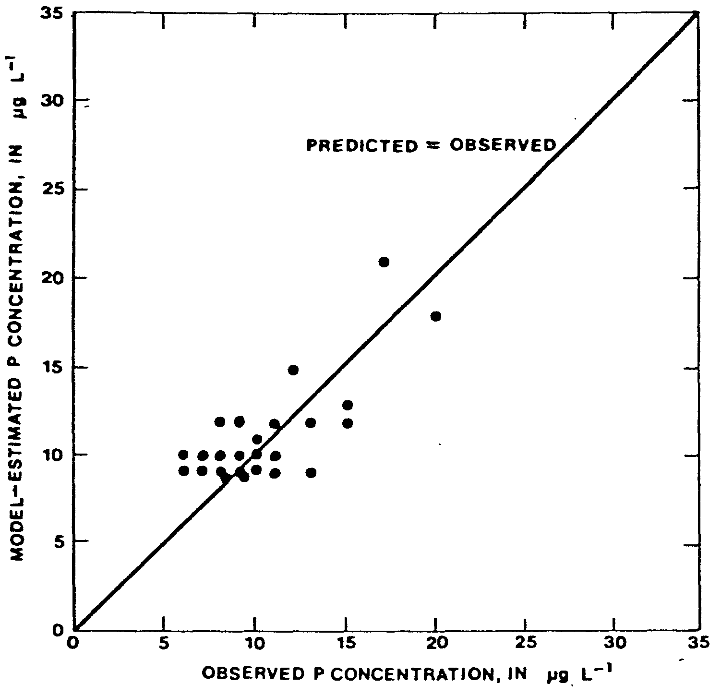

Figure 3. - Comparison between model-estimated and observed background concentrations of total phosphorus; model-estimated concentrations are based on values of phosphorus yield from forest land calculated as a function of annual runoff.

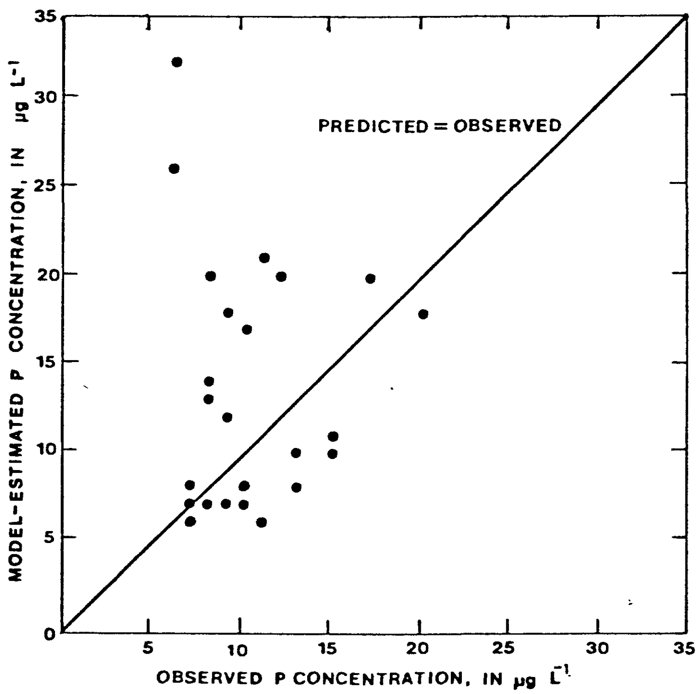

Figure 4. - Comparison between model-estimated and observed background concentrations of total phosphorus. model-estimated concentrations are based on a constant value of phosphorus yield from forest land (12 kg km⁻² yr⁻¹).

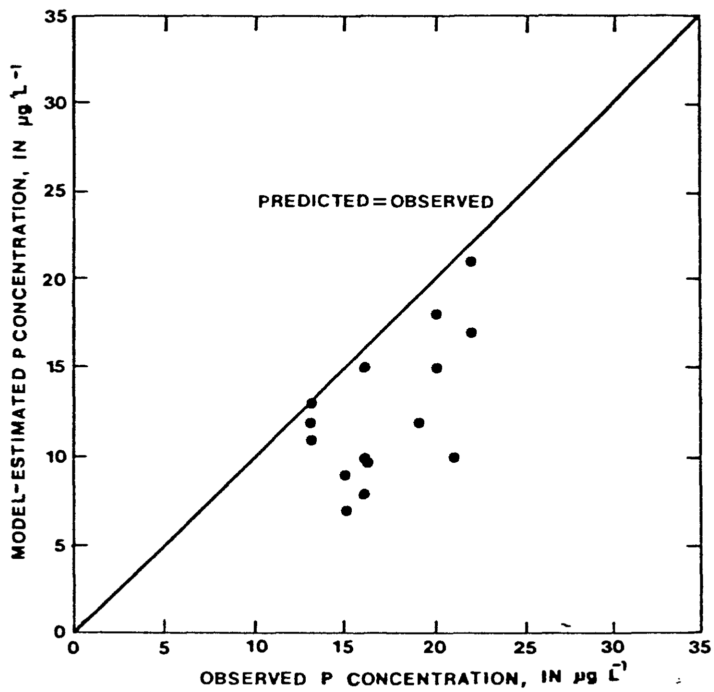

Figure 5. - Comparison between model-estimated background concentrations of total phosphorus and recently observed concentrations for 15 lakes with 20 percent or more of their basins residentially developed.

concentrations of P that range from 6 to 25 μg L^{-1}. With such a range, the application of uniform standards, or an assumption of uniform background levels of P in lakes, could result in unobtainable water-quality goals or incorrect assessments of cultural impacts on lake-water quality.

The method presented in this report allows probabalistic estimates of the background total-P concentrations in lakes which can be compared to current mean concentrations that are based on observed data. This comparison allows the planner or water-quality manager to assess the probability of different degrees of change that may have occurred from background conditions. In most cases, means of background and current values are best compared to each other, though the uncertainty in estimates of the means should always be considered. In some situations, however, such as when the environmental or economic consequences of either an under or over estimate of the background concentration are severe, it may be desirable to use the upper or lower "bound" of the mean instead of the mean.

The relationships presented in this paper for estimating P loading to lakes by bulk precipitation and drainage from forest land are not transferable to lakes that are not in the study area or in a similar environment. In addition, within the study area the model has only been evaluated for its validity for lakes that show stable thermal stratification during the summer, and which are in localities where the annual runoff does not exceed 1.5 m. Care should be taken if lakes that violate these conditions are to be evaluated. The general methods described in this study for evaluating lake P loading, however, might be successfully used in other natural environments. In addition, there is potential for applying the general approach used in this study to assess human-related sources of phosphorus. The difference between estimated background P concentration and the present P concentration of a developed lake, which approximates the degree of impact of that development on lake-water P concentration, can be converted to equivalent P loading by equation 4. Having been calculated for many lakes with development, the P loadings due to the development can be tested for correlation with specific land-use features of lake basins.

The methods and relationships developed in this study are best applied by persons that are knowledgeable about lakes and their behavior. Ironically, simple models such as the one presented here are perhaps the most commonly misused because they appear simple. However, the natural systems that models represent are usually complex, and the application of a simple model should be accompanied by an analysis of available data and professional insights regarding the reasonableness of simplifying assumptions and estimates from the model. Nevertheless, the approach developed in this study should still be applicable by consultants or technical staff within the planning resource capabilities of many local governments.

DISCUSSION

Although several assumptions are necessary for using the mass-balance, "Vollenweider-type" model of the lake P budget, the most troublesome assumption from a conceptual standpoint is that thermally stratified lakes can be represented as completely mixed. The assumption of complete mixing is necessary because the mass-balance model treats dilution of P in a lake and, therefore, also the amount of P leaving a lake via outflow, as a function of the total volume of water in a lake. This is obviously not an accurate physical description of a lake that is thermally stratified for almost half of each year. However, P loss by lake outflow is reasonably represented for Puget Sound region lakes, because most P loading and loss of P by outflow occurs during periods of highest lake inflow and flushing, when lakes are also completely mixed. In addition, the dilution of P that is in a lake is accurately simulated because the P concentration in a lake's surface waters during stratification is apparently consistently related to the mean, whole-lake concentration. When P loading is calculated from surface-water concentrations of P measured during the summer, the resulting values represent empirical estimates of loading that are proportional to this specific measurement of total-P concentration. The major source of background P loading to lakes, forest-land drainage, was evaluated from such empirical estimates of loading. Therefore, possible problems with the assumption of complete mixing are minimized.

The strong correlation found between forest-land P yield and annual runoff also appears to be conceptually reasonable on the basis of natural processes. The key to evaluating the natural processes that control the yield of P from a drainage basin is to view (1) yield as the combined result of runoff volume and concentration, and (2) concentration as the result of mixed volumes of water from different components of the hydrologic cycle such as precipitation, throughfall (precipitation that has filtered through forest canopy), overland flow, subsurface stormflow (ephemeral ground water), and baseflow ground water. Though the limited scope of this paper does not allow a complete discussion of these processes, some useful observations can be made.

Forest-land P yield can be expressed as the product of the mean concentration of P in the inflow to a lake from its forested drainage basin, and the annual runoff depth in the locality of the lake.

$$FORY = \frac{(\overline{P})_{in} \cdot RO \cdot (WSA-A)}{(WSA-A)} = (\overline{P})_{in} \cdot RO \quad (10)$$

where $(\overline{P})_{in}$ is the annual mean-concentration of P in lake inflow (based on empirically derived P loading), in $\mu g\ L^{-1}$. An arrangement of the last part of equation 10 allows the calculation of $(\overline{P})_{in}$ from FORY and RO, as follows:

$$(\overline{P})_{in} = \frac{FORY}{RO} \tag{11}$$

Equation 11 was used to calculate $(\overline{P})_{in}$ from FORY for each of the lakes in table 1. The mean value of $(\overline{P})_{in}$ for these lakes in 20 $\mu g\ L^{-1}$. By substituting 20 $\mu g\ L^{-1}$ for $(\overline{P})_{in}$ in equation 11, FORY can be calculated for runoff conditions that range from 0.1 to 1.5 m yr^{-1}.

In figure 6, the solution for FORY as a function of a constant, mean-inflow concentration of P is shown compared to the regression solution for FORY as a function of runoff. Figure 6 shows that the variation in P yield from forested drainage basins is largely the result of variations in annual runoff. However, the comparison in figure 6 also indicates that $(\overline{P})_{in}$ may be inversely related to runoff to account for the leveling off of FORY with increased runoff. Causes for this possible relationship are uncertain, but could be related to varying concentrations of P in water in different components of the hydrologic cycle, and the changing contribution of these components to lake inflow in localities with different annual runoff. Solute concentrations in water from different sources tend to be positively correlated with water residence time in earth material (Feller and Kimmins, 1979; Pilgrim and others, 1979), and the magnitide of the effect of residence time on P concentrations is governed mainly by the mineral nature of earth material (Stumm and Morgan, 1970; Lindsey and Vlek, 1977). If inflow to

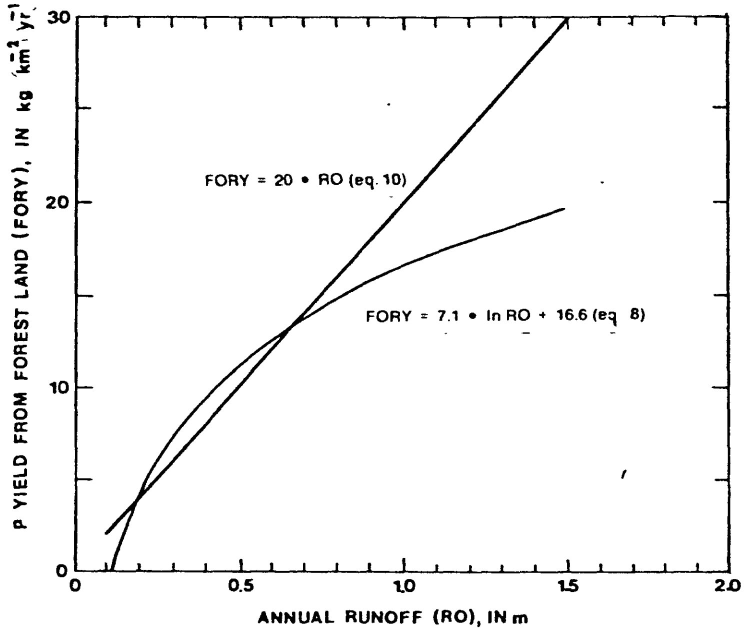

Figure 6. - Comparison of curves for phosphorus yield from forest land as a function of runoff based on, 1.) a constant, mean stream-water concentration (eq. 10), and 2.) the least-squares fit to calculated yields (eq. 8).

lakes in localities that have different annual runoffs is dominated by water originating from different components of the hydrologic cycle, which have different residence times and are in contact with different types of earth material, the chemistry of inflowing water would likely also be different between these lakes.

CONCLUSIONS

1. Phosphorus loading to a lake can be successfully estimated from lake-water concentration using a steady-state, mass-balance model. Loading rates calculated by this method are empirical estimates of loading that are highly dependent on the type (season, depth, and chemical species) of the P-concentration measurement that is used. For this study, loading was calculated from the summertime, total-P concentration in the epilimnion.

2. Phosphorus loading, as calculated in this study, can be quickly evaluated for many lakes in a region with a minimum amount of data. These loading rates can be used to develop simple, empirical relationships to aid in decision making and to direct more detailed studies. Though P loading is usually diffuse and highly variable over time, making it difficult to measure, lake-water concentrations of P, which were used to indirectly calculate loading, are easy to measure and relatively few observations are necessary to characterize a lake.

3. Empirical relationships developed in this study allow the calculation of reliable estimates of background P loading to lakes in the area studied. These estimates can be used in combination with the mass-balance model to calculate the background concentration of P in a lake. The background concentrations calculated by this method are estimates of the mean total-P concentration in a lake's epilimnion during the summer.

4. In lakes that have development in their drainage basins, estimated background-P concentrations can be compared to measured P concentrations in order to estimate the impact of the development on the lake water. These estimates are for summertime P concentrations in a lake's most productive zone and, thus, represent effects on water quality during the period of peak recreational use of lakes.

5. To the disadvantage of the method presented, the empirically derived P loading rates cannot be directly measured to verify calculations, and are not directly equatable with measured loadings of defined chemical species of P. Loading is empirically defined, but not chemically defined. This is a limiting factor for evaluating physical and chemical processes that affect P loading.

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