DEPARTMENT OF THE INTERIOR
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WATER RESOURCES INVESTIGATIONS
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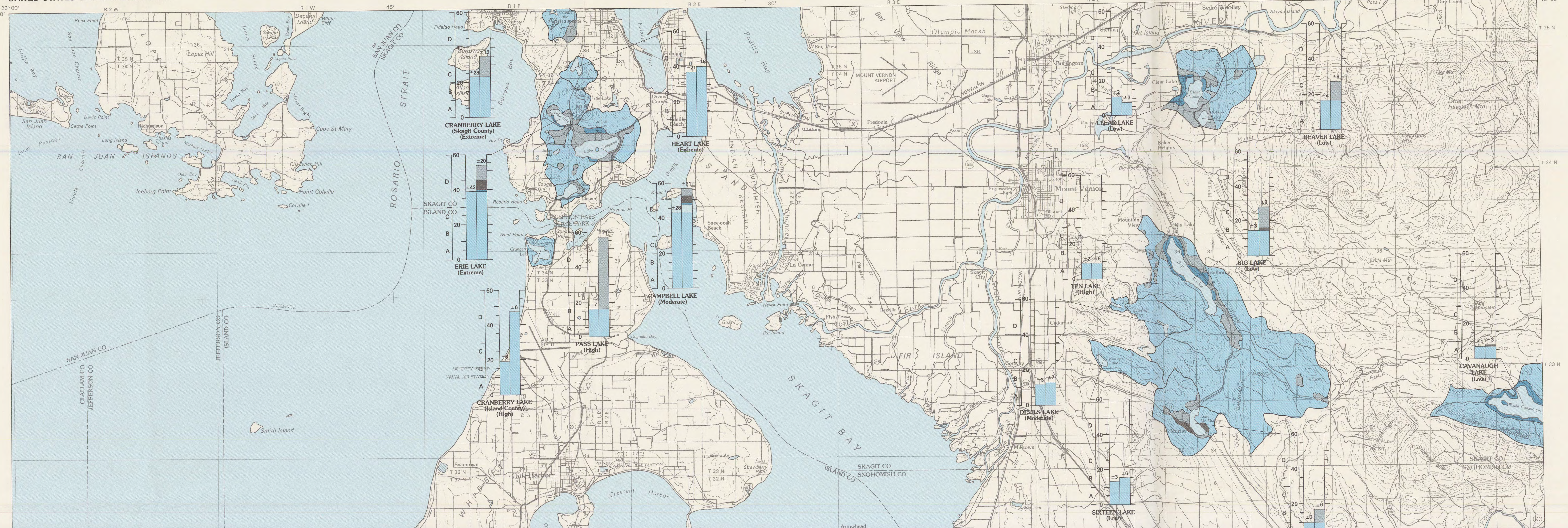

EXPLANATION

The drainage basin boundary for each lake studied has been delineated on the accompanying map. Within each basin, generalized land uses have been depicted. A bar graph accompanying each lake indicates the estimated background (predevelopment) level of phosphorus in the lake, the recently measured phosphorus level, and a proportional breakdown of phosphorus-loading sources. The plus-and-minus values shown above each bar are standard errors of the associated phosphorus-level estimates. Levels of phosphorus have been assigned to water-quality groups A through D which are explained in table 1. Finally, low to extreme ratings of water-quality sensitivity to future increases in phosphorus-loading are indicated for each lake, as derived from the physical characteristics.

Asterisks (*), by Anderson and Cassidy Lakes indicate that evaluations shown for these lakes are of questionable accuracy and should not be relied upon.

WATERSHED LAND USES
(Shown on map areas around lakes)

- Forest and unproductive
- Agriculture
- Residential
- Lake surface
- Basin boundary

PHOSPHORUS LOADING SOURCES
(Shown on right-side bar graph)

- Forest and unproductive-land runoff combined with precipitation on lake surface
- Agricultural-land runoff
- Residential-area runoff
- Nearshore septic-tank systems
- Upstream lakes

WATER-QUALITY SENSITIVITY TO INCREASED PHOSPHORUS LOADING
(Shown in parentheses below bar graphs)

Extreme - 10 kilograms increase in annual phosphorus loading rate results in 20 micrograms per liter or greater increase in concentration.
High - 10 kilograms increase in annual phosphorus loading rate results in a 10 to 20 microgram per liter increase in concentration.
Moderate - 10 kilogram increase in annual phosphorus loading rate results in a 3 to 10 microgram per liter increase in concentration
Low - 10 kilogram increase in annual phosphorus loading rate results in less than a 3 microgram per liter change in concentration.

EXAMPLE

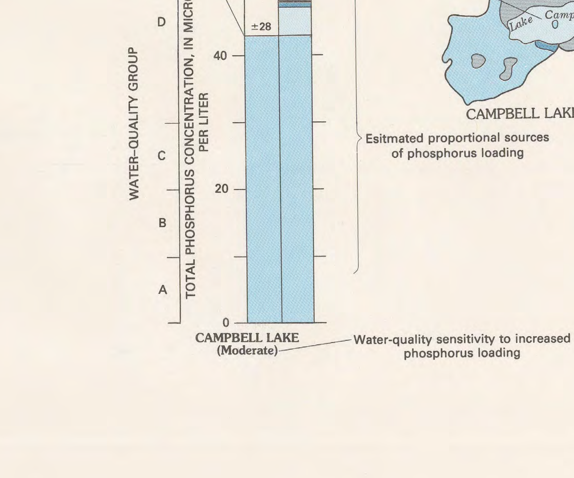

Table 1.--*Selected characteristics of lakes*

Lake	Lake surface area[a] (acres)	Mean depth[a] (feet)	Average annual runoff[b] (inches)
Anderson	67	19	7
Armstrong	30	15	25
Beaver	74	4.9	25
Big	25	14	25
Campbell	370	7.9	3
Cassidy	120	11	20
Cavanaugh	790	43	60
Clear	200	23	25
Crabapple	35	18	12
Cranberry (Island County)	130	13	3
Cranberry (Skagit County)	25	6.9	5
Devils	40	14	30
Erie	110	5.9	3
Goodwin	570	23	12
Goss	47	32	9
Heart	67	8.9	6
Howard	27	29	12
Ki	99	33	12
Loma	22	11	12
Lone	100	8.9	7
Martha	62	33	12
McMurray	160	29	25
Pass	99	15	3
Shoecraft	130	18	12
Sixteen	47	18	25
Stevens	1000	62	20
Sunday	47	7.9	15
Ten	12	32	30
Weallup	22	6.9	12

[a] Bortleson and others (1976a).

[b] Gladwell and Mueller (1967), except for Lakes Campbell, Cranberry (Island County), Cranberry (Skagit County), Erie, Heart, and Pass, which were estimated from Dietrich (1975), and Lakes Goss and Lone, which were estimated from Anderson (1968).

Table 2.--*Generalized characteristics of lakes in water-quality groups based on mean summer phosphorus concentration* (modified from Dillon and Rigler, 1975)

Water-quality group, defined in micrograms per liter (µg/L) of phosphorus	Group characteristics
Group A (0-10 µg/L)	Low algal productivity; high suitability for all recreational uses. Algal blooms are rare and the water is extremely clear, with a Secchi-disk visibility[1] that is usually 15 feet or greater. Summer chlorophyll a[2] concentrations[2] generally average less than 3 µg/L.
Group B (10-20 µg/L)	Moderate algal productivity; generally compatible with all recreational uses. Algal blooms occur occasionally, but generally are of low to moderate intensity. Oxygen depletion is common in the bottom waters and cold-water fish may be endangered in some shallow lakes. In many lakes, however, the fish resources may be enhanced by the increased productivity. Secchi-disk visibility is usually 10 to 15 feet, and average chlorophyll a concentrations range from 2 to 6 µg/L in most lakes.
Group C (20-30 µg/L)	Moderately high algal productivity; still compatible with most recreational uses, but algal blooms are more frequent and intense and oxygen depletion is more serious. This can increase problems for some fish, though total fish productivity may be enhanced. Water clarity is reduced, and Secchi-disk visibility is usually 7 to 12 feet. Average chlorophyll a concentrations usually range from 4 to 10 µg/L.
Group D (greater than 30 µg/L)	High algal productivity; lake suitability for most recreational uses is often impaired by frequent and intense algal blooms, which may form floating scums. The water often takes on a "pea soup" color resulting in extremely murky water. Fish kills may be common, especially in shallow lakes. Secchi-disk visibility is generally less than 10 feet, and chlorophyll a concentration is usually greater than 10 µg/L.

[1] Secchi-disk visibility is a measure of water clarity expressed as the maximum depth at which one can barely see an 8-inch diameter black-and-white disk through the water.

[2] The concentration of chlorophyll a is an indicator of the concentration of algae in lake water.

Table 3.--*Percent standard errors in estimates of phosphorus concentration and loading increases for 14 lakes. Values in parentheses are percent standard errors attainable if standard errors in lake-water P concentrations were reduced to ±10 percent from their present range of ±30 to ±50 percent (see text).*

Lake[1]	Cumulative increase above background level: Concentration increase (micrograms per liter)	Percent standard error (percent of increase)	Percent standard errors in estimated proportions of loading increase attributed to individual sources[2] (percent of attributed increase): Upstream lakes	Residential runoff	Near-shore septic systems	Agricultural land
Anderson	38	70 (30)	-	-	-	70 (30)
Armstrong	9	100 (60)	-	-	200 (200)	200 (200)
Beaver	11	100 (70)	-	-	-	100 (70)
Big	14	70 (50)	100 (60)	-	-	80 (60)
Cassidy	28	60 (40)	-	-	-	60 (40)
Cranberry (Skagit Co.)	28	300 (200)	-	-	-	300 (200)
Howard	15	70 (50)	-	-	70 (50)	-
Loma	10	200 (60)	-	-	200 (60)	-
Lone	211	50 (30)	-	-	-	60 (30)
McMurray	7	100 (60)	-	-	-	100 (70)
Pass	41	100 (30)	-	-	-	100 (30)
Shoecraft	6	90 (70)	-	-	100 (80)	-
Stevens	5	100 (60)	-	40 (40)	200 (100)	-
Weallup	11	100 (60)	100 (60)	-	-	-

[1] Lakes that have estimated present-day P loadings more than 50 percent greater than background.

[2] Standard-error estimates are shown only for loading sources representing more than 25 percent of the total loading increase.

INTRODUCTION

The popularity of lakes in the Puget Sound region for recreational use and as sites for residential development is rapidly increasing with the growing population of the region. The suitability of lakes for these uses is dependent on good water quality. However, the water quality of many of these lakes is threatened by pollutant loadings (inputs) resulting from residential and agricultural land use in their watersheds. Although these land uses may produce a variety of contaminants in the ground and surface water flowing into the lakes, the most serious impact on lakes is usually caused by excessive loading of plant nutrients. Such nutrient enrichment stimulates the growth of algae and other aquatic plants, which accelerates the natural aging, or eutrophication of a lake.

The increased growth (productivity) of algae and rooted aquatic plants that accompanies eutrophication often interferes with recreational uses of lakes. Highly enriched lakes may be characterized by dense algal blooms, floating mats of vegetation, and a murky, "pea soup" appearance. Certain lakes that are degraded by nutrient enrichment can be restored by removing or reducing the sources of the nutrients and by artificially removing nutrients from the lake. However, such restoration measures are not always fully effective (Peterson, 1979), and they are usually very expensive. The great value of lakes, along with the high cost and the uncertainty of success of restoration measures, are strong incentives to control eutrophication before it reaches undesirable levels.

To avoid or control eutrophication, increases in nutrient loadings to a lake must be prevented or reduced. Fortunately, this task is somewhat simplified because, of the many nutrients required by aquatic plants, phosphorus (P) is the growth-limiting nutrient in most lakes (Schindler and Fee, 1974; Rast and Lee, 1978; Schindler, 1978). When P is limiting, more P will cause more growth and less P will cause less growth, regardless of fluctuations in the amounts of other plant nutrients. Therefore, control of P alone often can be used to control eutrophication.

Nutrient enrichment is not the only water-quality impact of land development in lake-drainage basins. Other potentially important contaminants include sediment, pathogenic (disease-producing) organisms, dissolved heavy metals, pesticides, many other toxic compounds, and organic substances that cause oxygen depletion. Fortunately, however, many of the same basic physical principles that govern P loading also govern the production and movement of other pollutants. Therefore, land-use management strategies intended for P control are often good approaches for controlling other pollutants as well.

Identifying and limiting the sources of P loading to a lake are difficult because most P loading usually is from nonpoint (diffuse) sources, such as runoff from residential and agricultural land. These sources are difficult to assess by direct measurement, and the collection and treatment of water from these sources are extremely costly, if not impossible. Avoidance or reduction of eutrophication, therefore, usually requires management of land-use practices to reduce P loading at the source(s).

A critically needed guide for land-use management that is intended to help control eutrophication of a lake is quantitative information on the relationships between land uses in the lake's watershed and P loading to the lake. Without such information, management schemes to improve lake-water quality are likely to be ineffective and based on unrealistic water-quality goals. Unfortunately, the detailed studies necessary to most accurately assess relationships between land uses and P loadings are difficult and expensive. Local and State agencies have been able to finance relatively few such studies, which generally have been limited to unusually important lakes. Recently, however, methods have been developed that can provide a rapid, preliminary evaluation of the amount of P loading to lakes in the Puget Sound region and rough estimates of the amounts attributed to the various land uses. Such preliminary assessments of P loadings and their impacts on lake-water quality can aid in making efficient use of the limited resources that are available by providing information essential for formulating management goals, study priorities, and design of detailed lake studies that may be needed.

The purpose of this report is to provide a preliminary appraisal of the current status (based on mid-1970's data) and causes of eutrophication, as compared to background (predevelopment) levels of eutrophication, for 29 lakes in the Port Townsend quadrangle, Puget Sound region, Washington. This study also serves as a prototype of evaluations that are possible by use of methods for evaluating lake P budgets that have been described in other reports (Gilliom, 1981 and 1982). These methods are based on the types of data that are already available for many lakes in the region.

This map is one of a series being prepared by the U.S. Geological Survey to present earth-science and related information to assist land-use planning, resource development, and environmental protection in the Puget Sound region.

THE LAKES AND MAJOR INFLUENCES

The 29 lakes selected for study generally represent the largest and most widely used lakes in the area of the Port Townsend quadrangle, which contains more than 75 lakes and ponds. The 29 lakes and their drainage basins are shown on the accompanying map, and their physical dimensions and the annual runoffs in their vicinities are given in table 1. The water quality of these lakes, as will be shown, is highly variable. Their quality is strongly influenced by the physical and hydrologic characteristics of the lakes and their basins, and the land uses within their basins. These factors combine to determine the water-quality sensitivity of a lake to P loading and the amount of loading a lake receives.

Factors that Influence Water-Quality Sensitivity

The sensitivity of a lake to water-quality degradation by P loadings depends mainly on the capability of the lake to (a) dilute and "flush out" P, and (b) "trap" P in bottom sediments if it settles along with particulate matter. Depending on the combination of these factors, each lake would generally attain a different average P concentration and associated water quality even if the P loadings to the different lakes were equal. Similarly, each lake would respond differently to the same increase in P loading.

Dilution and flushing are great in a lake with a large volume and a large amount of inflowing water (less sensitive) and are less in a lake with a small volume and a small amount of inflow (more sensitive). The lakes studied have a wide range of volumes, which can be estimated by multiplying their mean depth by their surface area given in table 1. Volumes range from about 150 acre-feet for Weallup Lake to 62,000 acre-feet for Stevens Lake. Annual flow of water into the lakes, which depends mainly on drainage-basin area and annual runoff, also varies widely between the lakes. A large drainage basin and a high rate of runoff result in a large inflow, and a small drainage basin and a low rate of runoff cause a small inflow. Comparison of the variability in drainage-basin areas shown on the map and runoff rates given in table 1 illustrate the wide variability in annual inflows to the lakes studied. These variations in lake volumes and amounts of inflow tend to result in similar variability in water-quality sensitivity between the lakes.

But, the water-quality sensitivity of a lake is also affected by its capability to trap P in bottom sediments, and this depends largely on whether a lake thermally stratifies or not. A lake stratifies if, during the summer season (May-September), cold bottom waters lie beneath much warmer surface waters causing a lack of mixing of bottom and surface waters during the summer growing season for algae. All the lakes studied are evenly mixed from about October through April. Whether or not a lake stratifies depends largely on the depth of the lake. Most of the lakes studied are deep enough to attain stable stratification, but Lakes Beaver, Big, Cambell, Cranberry (Skagit County), Erie, Heart, Lone, Sunday, and Weallup are fairly shallow and appear not to attain stable stratification. In these shallow lakes, P that settles to the lake bottom is likely to be returned to the surface waters, where algae grow, if the lake is mixed by wind action or other turbulence. Such lakes, therefore, tend to be more sensitive to increased P loading than deeper, but otherwise similar lakes.

Factors that Influence Phosphorus Loading

The P loading to a lake, combined with the sensitivity of a lake to loading, largely determines the average concentration of P in a lake and, thus, greatly affects its water quality. The amount of P loading to a lake is influenced by the natural characteristics of its drainage basin and the extent, locations, and types of land uses contained in the basin. The total loading of P to a lake can generally be considered a combination of background loading and increased loading caused by human activities, such as land-use changes, in a lake's drainage basin.

Lakes in undeveloped watersheds receive relatively small amounts of P in water draining from forested land, and by precipitation and dry fallout directly on the lake surface. The ultimate sources of this background loading include dissolved rock and soil particles, leaves and pollen, animal wastes, and atmospheric dust. The total amount of background loading to a lake is mainly determined by the area of the lake and its drainage basin and the rate of runoff characteristic of the lake's basin. The surface area of a lake largely determines the amount of P loading by direct precipitation and fall-out, the drainage-basin area is the potential amount of land contributing P to lake inflow streams, and the rate of annual runoff is a good indicator of how much P will be transported from a given area of land by runoff water (see Gilliom, 1981, for more detail). In general, higher rates of runoff result in higher rates of P yield from a given area of land. Since lake-surface areas, drainage-basin areas, and runoff rates are different for each of the 29 lakes studied, we should expect each to have a different background P loading.

As the population and human activity in the study area have increased over the years, much land in the drainage basins of the lakes in the area has been converted from predominantly forest to residential and agricultural land uses. When such conversions occur, the yield of P from the land is often greatly increased over background levels. The only lakes studied with forested, undeveloped drainage basins are Cranberry (Island County), Devils, Heart, and Ten Lakes, though Cranberry and Heart are in actively used parks. Twenty-five of the lakes studied are in watersheds that contain a significant amount of residential land, agricultural land, or both (see map).

Residential development has tended to start at the lakeshores, commonly as second homes that later are used as full-time residences. The intensity of residential development around the lakes generally depends upon accessibility to urban areas. Most lakes within a 1-hour drive of the Seattle-Everett metropolitan area have concentrated lakeshore development dominated by year-round residences. This is particularly true of Lake Stevens and the "Seven Lakes" area centered around Lake Goodwin. Except for part of the Lake Stevens basin, septic-tank and drainfield systems are the predominant method of sewage disposal for homes around lakes in the study area.

Phosphorus in surface runoff from residential areas is derived from such sources as lawn fertilizers, street dust, grass clippings, leaves, and domestic animal wastes. In addition, P-rich wastewater from septic-tank systems can reach lakes by groundwater seepage or, if failure of the disposal system causes emergence of the waste water at the land surface, in the surface runoff. These sources of P tend to be more important where, as is true for most lakes studied, residential areas are close to a lake or its inflow streams.

Much of the land in the study area that has suitable slope and soil has been cleared and used for agriculture. Most agricultural land in the drainage basins of the lakes studied is pasture for cattle and horses. Much of this pasture land is near the lakeshores or inflowing streams. For example, mapped land uses for Lone, Beaver, Big, and McMurray Lakes show extensive near-shore agriculture. The areas near lakes and their inflows are often the most suitable for agriculture because of low relief and favorable soil conditions.

Phosphorus in runoff from pasture areas is derived mainly from animal wastes, which are rich in P. Particularly large amounts of P may be added to a lake if pasture areas adjoin the lake or its inflows and animals have open access to the water. Fertilizers applied to cropland are also a potential source of P. In general, for equal areas, there is usually more P in runoff from such agricultural areas than from similarly located residential area.

The widespread and increasing conversion of forest land to residential or agricultural land will undoubtedly lead to increasing degradation of lake-water quality in the study area. The results of this study show that such conversion has already seriously affected certain lakes. However, many of the lake basins studied are in early stages of land development, and significant opportunities exist for avoiding water-quality degradation by careful land-use and wastewater management.

EFFECTS OF PHOSPHORUS ON WATER QUALITY

The main effect of increased P levels on lake-water quality is an increased growth of algae and other aquatic plants. Two primary results of high rates of algal growth are (1) decreased water clarity when the algae cloud the water or form a floating scum, and (2) depletion of dissolved oxygen in the bottom waters of the lake that is caused by the decomposition of dead algae. Low concentrations of oxygen commonly cause serious injury to many types of fish, especially cold-water species such as trout. Lake-water P concentrations can be directly related to water clarity and dissolved-oxygen depletion (Dillon and Rigler, 1975; Vollenweider, 1976; Rast and Lee, 1978; Welch and Perkins, 1979; and Walker, 1980); therefore, useful relationships can also be developed between P concentrations and general lake-water quality.

Relationships between lake-water P concentrations and lake-water quality are summarized in table 2 according to four general water-quality groups. Table 2 is useful as a general guide for interpreting the practical meaning of different concentrations of P in Puget Sound region lakes. The reader should note that the water-quality groupings used in table 2 relate only to algal productivity in open water. Productivity, and thus water quality, in embayments may be different. The growth of rooted aquatic plants is also not considered, and excessive numbers of these plants, too, can have undesirable effects on a lake. Table 2 describes some effects of water quality on fish, but does not mention the possible effects on wildlife habitat, which may be enhanced by increased plant productivity in a lake. For example, some highly eutrophic lakes may be more valuable as nutrient-rich habitats than they would be if nutrient levels were reduced to be more amenable to recreation use. Finally, despite the success of using P concentration as an index of the water-quality impacts of increased eutrophication, there are always a few lakes to which that measure, and thus table 2, may not effectively apply. For example, in some lakes other nutrients, such as nitrogen, may be controlling the growth of algae instead of P, or some toxic substance may be inhibiting productivity in spite of abundant nutrients.

EVALUATING THE LAKES

Four main questions concerning the effects that humans may have had on the eutrophication of a particular lake are: (1) What was the lake's water quality before any development had occurred in the drainage basin of the lake, when the lake's P loading was at a background level? (2) What is the present-day water quality of the lake and how does it compare to its background condition? (3) What land uses or other P sources seem to be responsible for observed changes? (4) How would the lake respond to future increases in P loading? The importance of obtaining answers to these questions is discussed below.

Any reliable assessment of the impacts of land development on a lake must be made relative to the background P level of the lake (question 1) because background levels vary substantially between lakes. In this study, measured P concentrations in undeveloped lakes ranged from 9 to 47 µg/L. This fivefold range shows that an assumption of uniform background levels of P in different lakes is likely to cause incorrect assessments of human-related impacts on lake-water concentrations. The wide range in background P also indicates that the application of uniform P standards could result in the establishing of unobtainable water-quality goals.

Estimates of lakes' present-day P concentrations (question 2) are one of our most valuable means of describing their present quality using information such as that given in table 2 of this report. Combined with an estimate of a lake's background concentration, the cumulative effect of land-use changes that have occurred in a lake's drainage basin can also be estimated as the difference between present-day and background concentration.

Specific knowledge about the amount of P-loading increase above background attributable to each individual land use in a lake's drainage basin (question 3) is also necessary because methods for controlling loading may vary greatly for different land-use situations. Though, for example, both agricultural and residential land uses may be present, most loading may come from agricultural areas, and control of residential-area loading may have little effect on lake quality. Estimates of loading increases associated with individual land uses are the most difficult to obtain and have a lower reliability than other assessments in this report. Preliminary estimates of such loadings, however, are necessary for efficient design of the more detailed studies necessary for the more accurate assessments usually required for management decisions.

As discussed earlier, each lake will respond differently to a similar future increase in P loading (question 4) depending on the physical and hydrologic characteristics of the lake and its drainage basin. Knowledge of each lake's sensitivity allows water-quality managers to identify the most sensitive lakes for careful evaluation and perhaps protection, and allows a rapid evaluation of the relative importance of potential land-use change in a lake's drainage basin.

Summary of Methods

The lakes were evaluated using methods developed by the writer for estimating increases in P loadings caused by different land uses. This approach is based on P-concentration measurements and drainage-basin land-use data for many lakes in the Puget Sound region, and a simple mathematical model of the P budget of a lake. The development and use of the methods are discussed in detail in a companion report (Gilliom, 1982). For the purpose of this report, the following provides a brief description of the general application and characteristics of the methods used to evaluate each of the four questions just discussed.

First, the background P levels of the lakes were estimated by assuming that the entire drainage basin of each lake had been undeveloped forest land. Loading of P from the forest land, direct precipitation on the lake, and other lakes (if present), which together make up total background loading, was then estimated as described by Gilliom (1982) and converted to the resulting lake-water P concentration using the lake P-budget model. Necessary data on lake features and drainage-basin size were taken from a report by Bortleson and others (1976a).

Second, the "present-day," mean concentration of P in each lake was determined from measured values. In addition to data collected for this study in August and September 1978, data for calculating mean concentrations were taken from reports from Bortleson and others (1976a), Bortleson and others (1976b), Dion and others (1976), and McConnell and others (1976). Because of the different time spans represented by these data sources, the mean concentrations shown as present-day are usually representative of general lake conditions during the period from 1973 to 1978, and usually are based on data from two separate years during that period.

Third, the amounts of increases in P loading associated with each land-use type were evaluated using the land-use, P-loading relationships described elsewhere (Gilliom, 1982). Land-use data necessary for the analysis were taken from the report by Bortleson and others (1976a) and generally represent land uses in 1973. The loading-increase estimates were converted to equivalent concentration increases (using the lake P-budget model) for display on this map.

Fourth, the predicted response of each lake to forseeable future increases in P loading was evaluated by predicting each lake's P-concentration response to a hypothetical 10 kg/yr (kilograms per year) increase in P loading. These predictions were made using the lake P-budget model. A 10 kg/yr increase was chosen because this amount of increase could easily result from large-scale land-use changes, such as the conversion of 400 acres of forest land to residential land use. The results of this calculation were used to rate lake sensitivity on a relative scale in terms of possible water-quality changes.

A final note on methods is necessary regarding their use for assessing shallow lakes in the study area that do not thermally stratify. These lakes are Beaver, Big, Campbell, Cranberry (Skagit County), Erie, Heart, Lone, Sunday, and Weallup. The methods for P-loading assessment were developed using data for stratified lakes, which, as discussed earlier, may behave differently than lakes that do not stratify. Unstratified lakes may have a reduced capacity to trap P in lake sediments, and great care, or sometimes modification of the lake P model to account for less P retention in sediment, is necessary in use of the method for unstratified lakes. Fortunately, for Beaver, Big, Sunday, and Weallup Lakes, the in-lake retention of P loadings is unimportant relative to loss of P by outflowing water, and no adjustment was necessary for these lakes. For the other shallow lakes, however, empirical adjustment of in-lake P retention was required. The adjustment was made by using the lake P model to "back-calculate" to an estimate of lake P retention for Heart Lake, which is an undeveloped lake. Because Heart Lake is undeveloped, its loading can be estimated independent of the measured concentration in the lake (Gilliom, 1981). This allows calculation of lake P retention from the measured P concentration. The calculation showed that the sediment retention seems to be negligible. In-lake P retention for Campbell, Cranberry (Skagit County), Erie, and Lone Lakes, which are in the same general part of the study area as Heart Lake, was then also assumed to be an unimportant loss of P.

Reliability of Lake Evaluations

All evaluations of lake P concentrations, P loadings, and water-quality groups have important degrees of uncertainty associated with them. Lake-sensitivity ratings are general enough so that possible errors, which average only about ±20 percent in the numerical ratings (Gilliom, 1982), are relatively insignificant. The uncertainties in the other evaluations, which result from a combination of measurement errors, model error, and the inherent variability of lake systems, are involved in every study of natural systems. The resulting potential for error is important to consider when using information in this report for management decisions or for design of other studies.

The uncertainties or, conversely, the reliabilities of evaluations in this report were assessed both qualitatively and quantitatively. Qualitative assessments involve general cautions regarding the variability of a particular relationship, and careful identification of evaluations that do not seem to fit reasonably with theoretical expectations or data for similar lake settings and hydrologic situations. Quantitative assessments involve calculating statistical measures of reliability that indicate the probability, or chance, that a particular estimate under consideration is close to the actual value. The qualitative assessment of reliability was necessary for rating the lakes according to water-quality groups. The main consideration when using water-quality ratings (in addition to specific limitations discussed earlier) is that the rating scale must be considered as a continuous scale, especially for lakes with ratings near one of the arbitrary boundaries between water-quality groups. Numerical lake-quality ratings (P concentrations), and the characteristics of water-quality groups, both have associated uncertainties. For example, a lake rated in the high portion of water-quality group B in table 2 may actually be more like a lake in water-quality group C. Therefore, these general water-quality ratings should be used with due consideration for the possibility of error, particularly in case of borderline P concentrations.

The reliabilities of estimated background P concentrations, present-day P concentrations, and the proportions of loading increase due to all land uses combined and to each individual land use, were statistically evaluated. All reported P concentrations are shown with a plus-and-minus number to indicate the 68-percent confidence limits on the concentration value. This number is referred to as the "standard error" of the estimate. By statistical definition, the true value of the assessed quantity generally has a 68-percent probability, or about a "two-out-of-three" chance of being within one standard error (the plus-or-minus range) of the estimated value. In general, there is also an 84-percent probability that the true mean is greater than the estimated mean minus the standard error, or that the true mean is less than the estimated mean plus the standard error. When the standard error of an estimate is low, management decisions based on a mean value can be made with relatively high confidence, but extra caution is required when the potential for error is high and practical uses of the information may be limited. Standard errors are often expressed as percentages of the estimated values. Most background P concentrations are shown with standard errors in the range of ±20 to ±50 percent of the estimated value. Present-day P concentrations are shown with standard errors ranging from about ±30 to ±50 percent.

INTERPRETING THE MAP

Interpretation of information on the accompanying map requires an understanding of the individual types of information and its reliability for each lake and how this information can be combined for assessments of area-wide patterns and trends and comprehensive assessments of individual lakes. Some unusual results also deserve special mention.

Background Phosphorus Concentrations

Background P concentrations are represented on the map by the left-side bar of the graph near each of the selected lakes. The value of background P concentration and the corresponding water-quality group (described in table 2) are shown by the scales to the left of the graph (see map explanation). For example, the estimated background P concentration for Campbell Lake is 43 µg/L, which corresponds to water-quality group D. Above the background concentration bar in the graph, the standard error of estimate of the concentration value is also given--for Campbell Lake it is ±28 µg/L. This means that there is about a two-thirds probability that the true background P concentration in Campbell Lake was between 15 and 71 µg/L; from 43 minus 28 to 43 plus 28 (see discussion of reliability).

Present-Day Phosphorus Concentrations

Present-day P concentrations and loading sources are shown by the right-side bar on the graph, with the top of the bar indicating the measured concentration. Again, the standard error of the estimated P concentration is indicated above the bar. For example, the measured P concentration in Campbell Lake is shown to be 57±21 µg/L, still within the water-quality group D (table 2). The concentration amount and indication of uncertainty mean that, although the average P concentration in Campbell Lake has most likely increased above background (43±28 µg/L), the increase may be either much less or much greater than the 14 µg/L that is the result of merely subtracting 43 from 57 (see discussion of reliability).

Sources of Phosphorus Loading

The color-coded divisions of the right-side bar of each graph represent the background portion of P loading and the proportions of P-loading increase that are estimated to originate from different land uses. The lake-drainage basins and their land-use patterns are also shown by boundary lines and patterns around each lake. For Campbell Lake, about 75 percent of the present-day P load is shown to be background loading. Of the 25 percent of loading shown to be due to cultural sources, about 9 percent of the increase is estimated to come from agricultural land, about 7 percent each from septic-tank systems and Erie Lake, and about 2 percent from residential-area runoff. Because of the generally high levels of uncertainty in estimates of loading from individual land uses, however, such information may aid only as preliminary guidance for further study.

Table 3 lists standard errors for land-use-related increases in P loadings for each of the 14 lakes that have present-day P concentrations that are more than 50 percent greater than background concentrations. Standard errors of loading increases associated with individual land uses at these lakes are shown for those sources representing more than 25 percent of the total loading increase. The methods used to estimate loadings are highly dependent on estimates of average lake-water P concentration. Therefore, table 3 also shows what the standard errors in loading increases would be if the standard errors in lake-water concentrations were reduced from ±30 to 50 percent as for lakes shown on the map, to a hypothetical ±10 percent by collecting more data. All smaller increases in loading that are not represented in table 3, but are shown on the map, generally have associated standard errors greater than ±100 percent. These small loading sources are difficult to assess by any available approach but, fortunately, are often of relatively minor importance.

Based on general guidelines suggested by Gilliom (1982), estimates with standard errors less than ±50 percent can usually be improved only at a very high cost, and estimates with a ±50 to ±100 percent standard error may be significantly improved only by fairly extensive direct measurements of loadings at the lake being evaluated. Loading estimates with standard errors greater than ±100 percent may sometimes be improved by more general approaches, such as using data for other, more intensively studied lakes in the same region, or by using relationships between land-use and P yield for the entire region that are based on measured P yields from representative land-use areas.

Water-Quality Sensitivity

Water-quality sensitivity ratings are shown below the bar graphs on the map, in parentheses beneath the name of each lake. The ratings are described in the map explanation. Campbell Lake, for example, has a moderate sensitivity rating. This means that a 10 kg/yr increase in the P load would likely cause a 3-10 µg/L increase in P concentration. For Campbell Lake such an increase may not make much difference, but for a lake in water-quality group B and with the same sensitivity (Martha Lake, for example), the impact may be readily visible as increased amounts of algae and reduced water clarity.

Area-Wide Patterns and Trends

Inspection of the map shows that estimated background P concentrations for study-area lakes range from 6 µg/L (group A) to 47 µg/L (group D). The nine lakes in localities with an annual runoff less than 0.3 m (see table 1) had a mean background P level of 25 µg/L (group C), but the remaining 20 lakes had a mean background level of only 12 µg/L (low group B). Cranberry (Island County; 47 µg/L), Devils (13 µg/L), Heart (40 µg/L), and Ten (9 µg/L) Lakes had undeveloped drainage basins at the time of this study. Therefore, the measured P concentrations in these lakes should represent actual background conditions. For comparison, however, model-computed estimates are also shown for the background P levels in these lakes.

Comparison of present-day to background P levels shows that the average increase for lakes in watersheds containing significant residential or agricultural land is 8 µg/L--on the average, a change of about one water-quality group. One extreme case, Lone Lake, was not included in this average; it apparently has increased more than 200 µg/L from the background P level due to increased P loading from agricultural areas. Fourteen lakes have present-day P loadings and concentrations that are greater than 50 percent higher than background (table 3). Many of the drainage basins of these lakes contain agricultural land. In fact, as table 3 shows, this land use seems to have caused most of the large increases in P loading in the study area. Residential use, however, generally causes the greatest relative increases for lakes that are within commuting distance of Everett or Seattle; this includes Stevens Lake and the group of lakes centered around Goodwin Lake (see map).

Most lakes studied have a relatively low or moderate water-quality sensitivity. However, several lakes in the northwestern part of the study area, which is the driest part of the area, are extremely sensitive to even small increases in P loading (see map). This explains their high P levels despite relatively low loadings. In general, lake sensitivity was found to be closely related to annual precipitation and runoff because of the aforementioned influence of these factors on the natural flushing characteristics of a lake.

Individual Lake Assessments

Because of the variations in land use and P levels from lake to lake, an area-wide analysis is sometimes difficult to apply to water-quality management; a careful evaluation of individual lakes is required. Though the information in this report is preliminary, general conclusions are possible for most individual lakes. This type of analysis, using the information shown on the map, is illustrated by the following selected examples:

Big Lake--The bar graph for Big Lake shows that the P concentration in the lake has probably doubled from its background concentration. The increase probably is mainly due to P loading from agricultural activity, with minor contributions from residential development and increased P levels in McMurray Lake, upstream. The estimated loading increase caused by agriculture has a standard error of ±70 percent, which is rated moderately reliable but indicates a substantial chance that the actual loading increase is somewhat greater or less than the estimated value. The estimated P-loading increase has changed the water-quality rating for the lake from the middle of group B, under background conditions, to the upper part of group C at present (see table 2). This change is confirmed by the average 1974 Secchi-disk visibility of about 6 feet (Dion and others, 1976). Because of the potential for error, the water quality of Big Lake may actually tend towards group D.

Even though Big Lake is believed to have a relatively low sensitivity to P loading, the input from extensive agricultural land near the lake and along its inflowing stream apparently has substantially reduced the quality of the lake. The loading analysis and the uncertainty in the loading estimate suggest that, if more detailed study of this lake were to be undertaken, accurate measurement of the P loading from agricultural land should be a primary concern. Table 3 indicates that the uncertainty in the estimate of agricultural-land loading could be reduced to about ±50 percent with better data on lake-water P concentration.

Goss Lake--The bar graph for Goss Lake shows that the background P concentration and the present-day concentration are essentially equal, even though the lake is moderately sensitive and has a cluster of residential development around it. The standard errors in both concentration estimates would mask any increase that may actually have occurred. Any impact would be small, and might not even be measurable in a detailed study. The lack of substantial impact is probably because most homes around the lake are used only seasonally, the home development is relatively recent, and the extent of developed area is relatively small. Goss Lake might be susceptible to future increases in P loading if more of the homes were used for the entire year. This could occur even if the general distribution of land uses in the drainage basin remained the same.

Unusual Results

Despite the relatively large standard errors associated with some of the evaluations in this study, most of the results shown on the map fit well with what we know about lakes and the effects of various land uses on P loading. Results for Anderson, Cassidy, Cranberry (Island County), Cranberry (Skagit County), and Pass Lakes, however, were unexpected in view of the land uses affecting them and in comparison to the other lakes. All these lakes have somewhat higher present-day P concentrations than were expected. These unexpected differences do not necessarily indicate that the methods of assessment are inappropriate, but they illustrate the point that conditions at some lakes do not coincide with the assumptions inherent in the methods. Therefore, the assessment results should not be applied indiscriminately without checking them for a reasonable fit with local conditions and with theoretical expectations. Often, knowledge of limnological processes and the history of land development in the lake's drainage area suggest rational reasons for the differences.

For Cassidy, Cranberry (Island County), and Cranberry (Skagit County) Lakes, the high concentrations may be caused by drainage to the lakes from large marsh areas; such areas sometimes yield relatively large amounts of P. Marsh drainage to Pine Lake, which is in the Puget Sound region but outside the area of this map, was recently found to be a major P source for that lake (Harper-Owes, 1981). If this type of loading is occurring at the above lakes and background loading was underestimated, then the proportion of P loading from agricultural lands to Cassidy and Cranberry (Skagit County) Lakes would be less than has been estimated (because of the method used to assess P-loading increases). This possibility is supported by the finding that Cranberry Lake (Island County), which is also influenced by marsh-area drainage and has a predominantly undeveloped watershed, also has a much higher-than-predicted P concentration (see map).

Both Anderson and Pass Lakes are unusual in that both are now in State parks, and pasture areas near the lakes have not been used since the early 1970's. For Anderson Lake, the present-day P concentration was determined from only one sample taken during 1973. Therefore, as the standard error indicates, the estimated mean could easily be incorrect. But it is also possible that, at the time of sampling, agriculture in the lake's drainage area was supplying considerable P loading, as shown on the map. The lake may or may not have changed substantially since agricultural use was terminated. For Pass Lake, the present-day P concentration that is shown on the map was determined from samples taken in both 1973, when the land was largely in pasture, and in 1978, when it was idle open space. No difference between the sample concentrations was evident. The apparent absence of change in lake concentration since agricultural activity was stopped may have a reasonable explanation. The lake has a very low flushing rate, which means that it takes many years for lake-water concentration to respond completely to changes in P loading. An additional possibility for both Anderson and Pass Lakes is that the background P concentration was underestimated, resulting in an overestimation of the impact of agricultural land use. For all five lakes discussed above, only further studies of each lake can definitively resolve the possible discrepancies.

APPLICATIONS TO WATER-QUALITY MANAGEMENT

As an aid to management of lake eutrophication in the Puget Sound region, this report can be viewed from two perspectives: (1) as a management tool for the area studied, and (2) as a prototype for future similar studies of other areas of the region. As a management tool, it provides basic information and guidance for use by State and local authorities in formulating water-quality goals and priorities for the listed lakes, and it can guide the nature and scope of further studies of those lakes in an efficient manner. As a prototype for other studies, this report is an example of one method of displaying and interpreting data and model estimates such that their meaning is understandable by readers with a wide range of experience in studying lake eutrophication and its causes. The potential uses of this report for water-quality management are discussed in more detail below.

Setting Water-Quality Goals and Priorities

Area-wide or county-wide control of lake eutrophication cannot be fully effective without realistic water-quality goals for individual lakes and the assignment of priorities that indicate which lakes are most important to protect first. A potentially important use of the information in this report is for use by water-quality managers forming such goals and priorities.

Important considerations in setting the goals include: (1) the current condition of a lake in relation to its suitability for desired uses, (2) the changes in P concentration that would be necessary to improve lake quality to various degrees, (3) the background P level (which usually represents the lowest P concentration practically attainable), and (4) the feasibility of controlling the dominant human-related P sources. The information presented in this report on present-day and background P levels (bar graphs), the general relation between these levels and lake-water quality (table 2), and present-day sources of P for each lake (right-side bar of graph), combined with the manager's assessment of the most appropriate uses of a lake, should provide the basis for forming attainable water-quality goals.

Once water-quality goals are established, priorities for further lake-by-lake investigations or implementation of P-loading controls may be assigned. Priorities can be assigned by considering such factors as the present-day severity of water-quality problems in relation to predominant uses of a lake, the location of a lake in relation to regional development patterns, the amount of developable land in a lake's drainage basin, and the sensitivity of a lake to water-quality deterioration should P loading be increased. The main contributions of this report to the process of assigning priorities are a documentation of present-day levels of eutrophication (severity of problems), mapping of recent land uses in the lake basins (development trends), and an evaluation of the general water-quality sensitivity of each lake.

Guidance for Detailed Study

This report can guide future area-wide data collection efforts by showing which lakes are experiencing the most dramatic water-quality and land-use changes, and which lake assessments have the greatest uncertainty. These lakes can then be identified for further monitoring. For most lakes, uncertainty in loading assessments can be most inexpensively reduced by collecting additional P-concentration data. Such a monitoring program may involve sampling each lake three or four times every other year, or every 3 or 4 years, and periodically updating data on land-use changes within the drainage basin. A savings might be achieved by analyzing water samples only for total P concentration, but Secchi-disk, nitrogen, and chlorophyll a analyses would also be useful to check water-quality relationships. Such a data-collection program could greatly reduce the uncertainty in lake evaluations, directly confirm long-term changes in water quality, and provide a valuable data base for developing and testing more sophisticated water-quality models.

On a more specific level, the P-loading analyses shown in this report can aid in the design of detailed studies of individual lakes. The information on the map gives a preliminary indication of which P sources are most important to investigate at each lake. For example, a P-loading study for Lake Howard should certainly be oriented towards accurately evaluating P loading by septic-tank systems, which seem to constitute the dominant source of the human-related increase in P loading from the background level.

Even for lakes for which detailed studies are simply not possible, this report may be of help in guiding selected lake-management decisions. Consider Lone Lake or Beaver Lake, for example. There is little doubt that agriculture is the major P source because of the magnitude of the loading increase above background in relation to the dominant land use in the drainage basins. For these lakes, control of P loading from agricultural land, which was estimated with a moderate reliability for both lakes, is probably the key to reducing lake-water P concentrations. For most lakes, however, the specific relationships between individual land uses and P loadings are far less clear because land-use patterns are complex or the loading increase less dramatic. Detailed study will usually be required before management decisions for individual lakes can be made with confidence.

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LAKE-WATER QUALITY AND LAND-USE RELATIONSHIPS FOR SELECTED LAKES IN THE PORT TOWNSEND QUADRANGLE, PUGET SOUND REGION, WASHINGTON

By
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