A METHOD FOR THE RELATIVE CLASSIFICATION OF LAKES IN THE STATE OF WASHINGTON FROM RECONNAISSANCE DATA

U.S. GEOLOGICAL SURVEY, Water Resources Division
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In recognition of a worldwide trend to adoption of the metric system of measurements (SI or System Internationale), metric values are used in this report. However, the following factors are provided for conversion of metric values to English values:

Multiply	By	To obtain
Metres (m)	3.281	feet (ft)
Hectares (ha)	2.471	acres
Square kilometres (km^2)	247.1	acres
	.3861	square miles (mi^2)
Cubic hectometres (hm^3)	811	acre-feet (acre-ft)
Kilograms (kg)	2.205	pounds (lbs)

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ABSTRACT

The classification system developed allows a rapid assessment of the eutrophic potential and condition of more than 750 Washington lakes and reservoirs. The potential for nutrient enrichment from natural sources is evaluated on the basis of the interactions of physical and hydrologic factors that play a role in controlling the trophic condition of lakes, such as: (1) mean depth, (2) volume, (3) bottom slope, (4) shoreline configuration ratio, (5) ratio of drainage area to volume, (6) altitude, and (7) water-renewal time. The potential for nutrient enrichment from cultural sources is evaluated on the basis of (1) total phosphorus loading from nonpoint sources and point sources, (2) volume of water per nearshore home, and (3) percentage of shore developed. Total phosphorus loading for the lakes is calculated using criteria based on phosphorus exports from various nonpoint sources in the lake basin. Indicators of eutrophication and water quality are evaluated from phosphorus and nitrogen concentrations, specific conductance, dissolved-oxygen depletion in the hypolimnion, Secchi-disc visibility, fecal-coliform bacteria, and the abundance of rooted aquatic plants. The classification system, applied to seven Washington lakes, shows that a high enrichment potential from natural and (or) cultural factors is a good indicator of eutrophication and water-quality conditions for the lake.

INTRODUCTION

Purpose and Scope

The State of Washington has more than 7,800 lakes, ponds, and reservoirs (Wolcott, 1964 and 1965), many of which provide for exceptional recreational opportunities and supply water for agricultural, municipal, and industrial purposes. The lakeshores in particular attract ever-increasing recreational development. Use of the land for this purpose, however, is especially conducive to temporary and often inadequate waste-disposal practices. Consequently, degradation of lake-water quality is often a result of lakeshore and lake-basin development unless environmental controls are wisely selected and applied.

Recognizing these needs to assign priorities to lake problems and to provide data for lake-management decisions, in 1970 the State of Washington Department of Ecology entered into an agreement with the U.S. Geological Survey to investigate selected lakes in Washington. Because the program (approximately 25 lakes per year during fiscal years 1970-74) deals with only a small fraction of the total number of lakes in the State, a reconnaissance study involving several hundred lakes was also undertaken to provide preliminary information to guide land-use planning, preservation of lakes, and lake restoration.

The reconnaissance study, in combination with data from the more intensive lake studies, yielded information necessary to structure a classification system for lakes in Washington. The purpose in classifying the lakes was to (1) evaluate actual water-quality and eutrophic conditions, (2) estimate the percentage nutrient contribution from various sources of eutrophication, and (3) evaluate potential nutrient-enrichment sources. This report describes the method devised for classifying lakes in Washington by comparing 24 variables grouped into three categories relating to potential or actual eutrophication. A separate rating scale was developed for (1) factors affecting potential enrichment from natural causes, (2) factors affecting potential enrichment from culturally related causes, and (3) indicators of enrichment based on chemical and biological aspects of water quality. Twenty-five other indicators of natural and cultural enrichment and water quality are considered, but not rated numerically, as supplemental information to guide lake management and restoration measures.

In order to evaluate the cause(s) of eutrophication, a percentage contribution of total phosphorus loading was made for point sources (such as municipal waste and urban storm drainage) and nonpoint sources (such as forest, agricultural, and residential runoff). Total phosphorus contribution to a lake was determined by using criteria developed by Vollenweider (1968) for phosphorus export from various land uses.

The lake-classification criteria described in this report do not apply to saline lakes; separate criteria may be developed after more data are available.

Critical technical reviews of the manuscript by J. F. Ficke and R. C. Averett of the U.S. Geological Survey are gratefully acknowledged.

Occurrence of Lakes in Washington

Lakes in Washington occur under a great variety of geologic conditions. In the Puget Sound Lowland of western Washington most lakes occupy depressions in the surface of glacial drift--the sand, gravel, silt, clay, and till laid down by the Puget lobe of continental glaciers during the ice age. These depressions are either elongate troughs cut by the passing ice sheet or are more circular-shaped kettle lakes formed by the melting of stagnant ice blocks.

In the adjacent foothills of the Cascade Range and Olympic Mountains, most lakes occupy depressions eroded in the bedrock by the passing continental glacier, while lakes in the higher mountains are in basins cut by local alpine glaciers.

In eastern Washington, lakes in the mountainous northern part--Okanogan Highlands--and on the eastern slope of the Cascade Range generally occur in glacier-cut depressions in bedrock. In the semiarid Columbia Plateau, underlain by basalt bedrock, most lakes occupy the more deeply cut parts of some coulees of the channeled scablands. Most of these coulees were cut by gigantic, catastrophic floods (Bretz, 1959) resulting from the breaking of ice dams and rapid emptying of large glacial lakes.

Many lakes have been formed, or increased in size, by man's activities. Numerous reservoirs are located in valleys of the Cascade Range and Olympic Mountains, dammed for a variety of purposes that include municipal water supply, irrigation, electrical-power generation, flood control, and recreation. In the Columbia Basin Irrigation Project area of eastern Washington a number of small lakes have been formed in low areas by seepage and waste water from the irrigation project.

For the purpose of this study, to demonstrate the lake-classification system, seven lakes were selected as representative of some of the foregoing geologic settings and of different cultural and water-quality characteristics.

Eutrophication

Eutrophication involves nutrient enrichment of lake waters from natural or man-induced sources. The changes in the physiochemical conditions and biota in many lakes have been attributed to eutrophication. Normally, increased aquatic-plant productivity results in a significant deterioration of water quality with increased frequency and severity of algal blooms, increased water-treatment problems, decreased recreational values, and other deleterious effects. Limnologists, however, have long recognized that lake productivity is affected by factors other than the concentration of nutrients. Rawson (1939) suggested many interrelations among factors affecting the trophic status of a lake (fig. 1).

The nutrient and mineral load imposed on a lake is a function of the geochemistry of its drainage basin, climate, the hydrology of the region, and other natural conditions. Superimposed on these natural factors may be a variety of human effects, such as runoff from urban and agricultural areas and the amount of domestic sewage discharged directly or indirectly into a lake. The influence of man on the watershed of a lake can result in an increased rate of nutrient input to the lake which will bring about an accelerated rate of generally undesirable chemical, physical, and biological effects. Thus, lakes cannot be regarded as isolated entities because the interactions of the entire watershed must be taken into account.

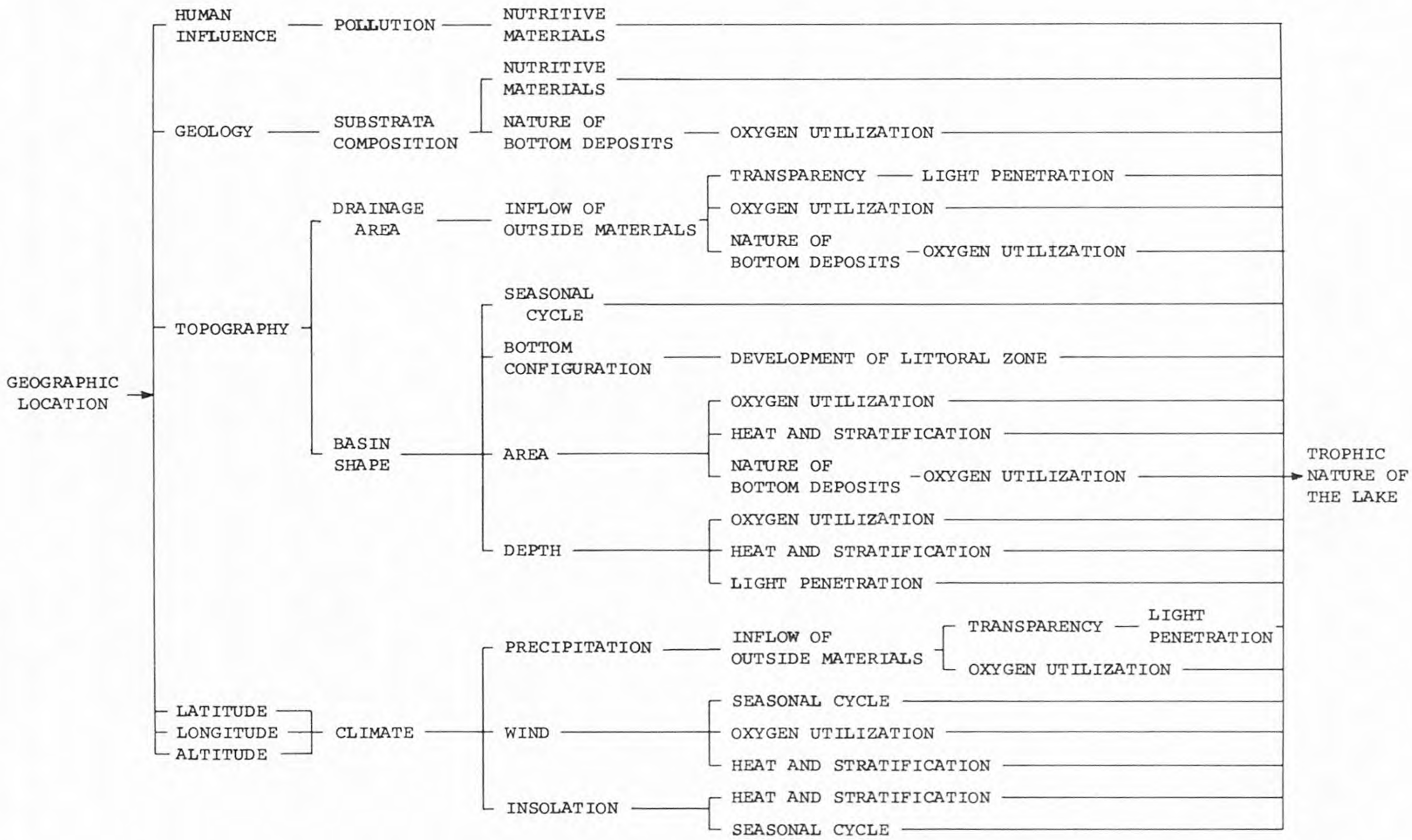

FIGURE 1.--Relations of selected parameters that determine the trophic condition of a lake (modified from Rawson, 1939).

EVALUATING THE LAKES

The criteria used to evaluate the eutrophication potential of the lakes numerically are listed below.

Natural physical factors affecting potential enrichment:
- Mean depth.
- Volume or reservoir capacity.
- Bottom slope
- Shoreline configuration (deviation from circle).
- Ratio of drainage area to lake volume.
- Altitude.
- Water-renewal time.

Culturally related factors affecting potential enrichment:
- Nutrient supply from nonpoint sources in drainage basin.
- Nutrient and waste supply from point sources in drainage basin.
- Volume of water per nearshore home.
- Percentage of nearshore land developed for residential use.

Indicators of eutrophication and water quality:
- Total phosphorus, upper water.
- Total phosphorus, ratio of bottom to upper waters.
- Inorganic nitrogen, upper water.
- Inorganic nitrogen, ratio of bottom to upper waters.
- Organic nitrogen, upper water.
- Specific conductance, upper water.
- Color.
- Secchi-disc visibility.
- Dissolved oxygen, near bottom.
- Water temperature, near bottom.
- Fecal-coliform bacteria.
- Percentage of water surface occupied by emergent macrophytes.
- Percentage of shoreline occupied by emergent macrophytes.

The 24 foregoing criteria are broadly grouped in three categories as follows: (1) seven parameters affecting potential enrichment from natural physical causes, (2) four parameters affecting potential enrichment from culturally related causes, and (3) 13 indicators of existing eutrophication and water quality.

For each lake, each of the 24 criteria is rated separately on a basis of 1 to 5. A value of 1 indicates good water quality or a condition least likely to contribute to eutrophy, whereas a value of 5 indicates a condition observed to contribute to eutrophy or poor water quality. The quantities established for the rating criteria were based on values from limnological literature (Vollenweider, 1968; Lueschow and others, 1970; Schindler, 1971; and Brezonik and Shannon, 1971) and on data from approximately 100 lakes studied in Washington (Collings, 1973; Bortleson and others, 1974; Dion and others, 1974). Thus, a summation of the numerical values assigned to each lake provides an index of the relative quality of a lake in each of the three separate categories. This analysis provides an assessment of water-quality conditions as well as a means to determine the potential natural and cultural influence on lake-water quality.

Although a summation of the ratings may be useful for comparison purposes, lake ecosystems are highly complex and often show integrated patterns of both "poor" and "good" limnological characteristics. For this reason, evaluation of single critical factors is often more useful than a total-score analysis. In order to preserve this sensitivity to critical factors, the ratings for the physical, cultural, and water-quality conditions should not be summed as a "total lake score." Also, to maximize understanding of the aquatic ecosystem, a lake-classification system should emphasize several parameters that should be interpreted individually. The ratings in this report assume that "wanted conditions" embrace a set of generally accepted requirements for human uses of the water resource, such as drinking-water supplies, sports fishing, bathing, and esthetic values.

Twenty-five other indicators of natural or cultural enrichment and water quality are presented in appendix A. Each indicator shown often represents a less desirable limnological condition and is simply checked positively or negatively if its presence or absence is known. These 25 indicators are not evaluated numerically in the relative classification of lakes, but they often provide valuable supplementary data from widely diverse water and land environments.

Natural Physical Factors Affecting Potential Enrichment

Natural physical factors control lake productivity primarily by affecting the distribution, availability, and utilization of nutrients. The physical factors that are used to evaluate the lakes numerically are discussed below. Formulas for some of the physical parameters listed, and limnological terminology, are contained in the glossary (p. 26).

Mean depth is the volume-area ratio--it is determined by dividing lake volume by surface area. Lake depth is the most significant physical feature affecting the ability of a lake to utilize nutrients. In shallow lakes, nutrient-rich bottom water can readily mix with water at the surface, thereby providing more nutrients for aquatic vegetation. Rawson (1955) demonstrated that lakes with a mean depth of less than 20 metres became progressively more productive in plankton, bottom fauna, and fish. Also, the entire lake may have sufficient light penetration for algae and rooted aquatic-plant growth.

Water volume largely determines the ability of the lake to dilute the incoming water and thereby reduces the nutrient concentration. For lakes with a given amount of aquatic-plant production in the epilimnion (surface layer), those with a large hypolimnetic volume tend to have the oxygen concentration depleted to a lesser degree than do those with a smaller hypolimnetic volume.

Bottom slope is a measure of the extent of shallow water and is important to the growth of rooted aquatic plants and the potential for wind mixing of water with bottom sediments. Bottom slope can be represented as the ratio of the maximum depth to the mean diameter of the lake expressed as a percentage. (See glossary for bottom-slope formula.)

Shoreline configuration is a measure of the irregularity of the shoreline in the form of embayments and projections from shore. Shoreline irregularity, reflected in values greater than 1.0 (a perfect circle), results in greater contact of water and land, increased areas of protected bays, and generally areas of shallow water. Shoreline configuration is often an indirect indicator of plant-growth capacity and enrichment potential from nearshore development and runoff. (See glossary for shoreline configuration formula.)

Ratio of drainage area to lake volume is a measure of potential nutrient loading. Generally, for lakes located in similar drainage basins, the quantity of nutrients and other materials entering a lake can be assumed to be roughly proportional to the size of the drainage area. Thus, a lake with a large drainage area with respect to its volume should have a potentially high level of nutrient loading and biological production. Differences in biomass and pollution potential have been explained in terms of ratios of drainage area to volume by Schindler (1971) for Ontario lakes and by Dingman and Johnson (1971) for New Hampshire lakes.

Altitude of the lake is important because of its relation to seasonal temperature and precipitation cycles. Colder water temperatures and shorter growing season generally result in lower aquatic-plant productivity. The altitude of a lake basin also affects the amount of nutrients in solution; as water passes to lower altitudes through streams and additional lakes, the load of soluble minerals and nutrients increases. Pennak (1963) demonstrated basic relations between altitude, lake chemistry, and plant biomass for Colorado lakes.

Water-renewal time is the time necessary to completely replace the water in the lake with inflowing water. A mixed water mass and only surface-water inflow are assumed. Water-renewal time is calculated by dividing the lake volume by the annual runoff from the lake's surface-drainage basin.

The assigned numerical ratings for each of the above described physical factors which affect potential enrichment of Washington lakes are shown in table 1.

TABLE 1.--Ratings assigned to natural physical factors affecting potential enrichment of Washington lakes

[1 indicates the lowest potential for eutrophication; 5 indicates the highest potential]

Physical factors	Rating				
	1	2	3	4	5
Mean depth (m)	>25	>12 ≤25	>6.0 ≤12	>3.0 ≤6.0	≤3.0
Water volume (hm^3)	>62.0	>6.20 ≤62.0	>1.23 ≤6.20	>0.30 ≤1.23	≤0.30
Bottom slope (percent)	>4.0	>2.0 ≤4.0	>1.2 ≤2.0	>0.80 ≤1.2	≤0.80
Shoreline configuration	≤1.15	>1.15 ≤1.30	>1.30 ≤1.50	>1.50 ≤1.80	>1.80
Ratio of drainage area to lake volume (m^2/m^3)	≤0.60	>0.60 ≤1.4	>1.4 ≤3.0	>3.0 ≤9.0	>9.0
Altitude (in metres above msl): Western Washington and Cascade Mountains	>1,100	>750 ≤1,100	>450 ≤750	>200 ≤450	≤200
Altitude (in metres above msl): Eastern Washington	>1,500	>1,200 ≤1,500	>900 ≤1,200	>600 ≤900	≤600
Water-renewal time (years)	≤0.3	>0.3 ≤1.0	>1.0 ≤4.0	>4.0 ≤15	>15

Culturally Related Factors Affecting Potential Enrichment

One of the major considerations in this evaluation is the contamination potential of the lakes' drainage basins, including identification of contamination sources that drain directly or indirectly into the lakes. Waste-disposal methods, the location and density of waste-disposal sites, and the kinds of wastes are critical in governing the type, character, concentration, and dispersal of contaminants in the lake basin and, eventually, in the lake. Factors affecting enrichment from culturally related causes are described below.

Nonpoint sources of nutrients and waste contaminants include all dispersed loading into a lake from natural (base load) and artificial (excess load) sources in the drainage basin. Some natural nonpoint sources of nutrients are unfertilized forests, wetlands and meadows, rainfall, leaves and pollen, and fauna. Artificial nonpoint sources of nutrients include runoff from cultivated croplands, pasture, and residential and industrial areas. However, because of man's complex intervention with nature it is often difficult to distinguish between natural and artificial loads.

Evaluations of the potential impact of nonpoint sources of nutrients and estimations of the percentage contribution from various land uses can be made on the basis of generalized land-use patterns, respective nutrient runoff contributions, and the surface area of the lake in question. Many elements and compounds serve as a food supply for aquatic plants; however, nitrogen and phosphorus concentrations usually are considered the most important in evaluating the ability of a body of water to produce plant organisms. Several studies have indicated that there is a positive correlation between amounts of nitrogen and phosphorus originating in the watershed and the enriched state of the lake (Lee and others, 1966; Vollenweider, 1968; Brezonik and Shannon, 1971; Patalas, 1972). For the purpose of evaluating the lakes in this study, phosphorus loading was used because (1) phosphorus is often considered the most likely limiting element in lake waters which are low-to-moderate in nutrient concentration (Bartsch, 1972; Schindler, 1974); (2) compared to phosphorus, sources of nitrogen in the aquatic environment are more varied and complex; and (3) most phosphorus reaches waterways from surface runoff.

A formula for estimating total phosphorus loading is

$$L_t = \frac{D_n}{A_o} (A_1L_1+A_2L_2 \ldots\ldots\ldots\ldots A_nL_n) ,$$

where

- L_t = total phosphorus loading, in kilograms per square kilometre of lake surface area per year;
- D_n = terrestrial drainage area including lake surface area, in square kilometres;
- A_o = area of the lake surface, in square kilometres;
- A_n = decimal fraction of total drainage area in a particular land use; and
- L_n = export of phosphorus from a particular land use (that is, forest, agricultural, and so forth),in kilograms total phosphorus per square kilometre of land per year.

Nonpoint sources of phosphorus runoff from forests, fallow land, and rainfall were considered the natural base load; runoff from other land uses was considered an artificial or excess load. The estimated quantities of phosphorus, expressed in kilograms per square kilometre of land surface area per year, from various nonpoint sources are presented in table 2. Example calculations for seven lakes using the above formula are shown in appendix B.

TABLE 2.--Factors for estimating phosphorus contributions from nonpoint sources

Source	Phosphorus ($kg/km^2/yr$)	Reference
Agricultural[a]-------------	50	Vollenweider (1968)
Forest[b]-------------------	10	Vollenweider (1968)
Cultural:		Vollenweider (1968)
Rural and suburban[c]---	100	
Urban[d]----------------	140	
Rainfall[e]-----------------	20	Ellsworth and Moodie (1964); Gessel (written commun., 1974)

[a]Agricultural land use includes cropland and grazing.

[b]Forest land use includes unproductive cleared areas, meadows, and wetlands.

[c]Rural and suburban land use includes parks and recreation areas. Assumed are (1) a population density of 2,500 persons per km^2 with a loading of 2.25 grams of phosphorus per capita per day, and (2) an annual loss of 5 percent of the total phosphorus to lakes.

[d]Urban land use includes commercial, industrial, and land areas with a high percentage of streets and roads. Assumed are (1) a population density of 3,330 persons per km^2 with a loading of 2.25 grams of phosphorus per capita per day, and (2) an annual loss of 5 percent of total phosphorus to lakes.

[e]Based on 0.027 mg/l total phosphorus in rainfall and 76 centimetres rainfall per year.

Point sources include nutrients and waste contaminant that discharge directly into a lake or into a stream feeding a lake at a specific location. Point sources include municipal sewage plants, industrial waste discharges--such as canneries, dairies, and papermills--urban storm drainage, agricultural feedlots, and irrigation return flows. The localized nature of point-source discharges sometimes facilitates their remedial treatment. An inventory of discharge points compiled by the State of Washington Department of Ecology was used to evaluate these point sources of surface- and ground-water disposal. An example of the calculation of total phosphorus loading to a lake from a point source is given in appendix C.

Volume of water per nearshore home is an important relation because in many areas domestic wastes are dispersed through septic-tank systems and ground water contaminated with septic-tank effluent has become a principal source of nutrients for lakes with populated shorelands. Conditions most likely to result in enrichment of lake waters by contaminated ground water are those where bedrock or impervious glacial till are shallow, slopes are steep, ground water gradients are high, and disposal systems are near shore and closely spaced.

Percentage of nearshore land developed for residential use is both an expression of potential nutrient loading and management options available for the nearshore community.

The assigned numerical ratings for the above-described cultural factors which affect potential enrichment of Washington lakes are shown in table 3.

TABLE 3.--Ratings assigned to cultural factors affecting potential enrichment of Washington lakes

Cultural factors	Rating				
	1	2	3	4	5
Point sources of domestic sewage (kg total phosphorus per km^2 lake surface per year)[a]	No known point sources of waste disposal	101-200	201-350	351-800	>800
Nonpoint sources (kg total phosphorus per km^2 lake surface per year)	<100	100-200	201-350	351-800	>800
Volume of water per nearshore home (hm^3)	>1.2	0.19-1.2	0.061-0.18	0.030-0.060	<0.030
Percentage of nearshore land developed for residential use	0-10	11-20	21-50	51-70	71-100

[a]Based on a mean value of 2.25 grams total phosphorus per capita per day loading from treated and untreated domestic sewage (Vollenweider, 1968). Equivalent comparisons of domestic sewage, industrial wastes, urban storm drainage, irrigation return flow, and feedlot wastes are made on a population equivalent flow basis of 300 litres per capita per day; an example of a calculation for a point-source loading to a lake is shown in appendix B.

Indicators of Eutrophication and Water Quality

An increase in nutrients in a lake is generally considered the causal mechanism of eutrophication, but the consequences or effects of nutrient enrichment are usually measured and expressed by a set of physical, chemical, and biological indicators relating to plant and animal production. Some general characteristics which are often used to define water quality are (1) nutrient concentrations, (2) Secchi-disc visibility, (3) aquatic plant and animal production, (4) fecal-coliform bacteria, and (5) dissolved oxygen in the hypolimnion.

The indicators of eutrophication and water quality used in evaluating the lakes and as listed on page 6 are discussed below.

Phosphorus, which is an essential element for aquatic plants, in natural waters is often low enough in concentration to limit algal growth (Lee, 1973). Experimental data indicate generally that a total phosphorus concentration of about 20 µg/l (micrograms per litre) may be regarded as the lower concentration limit critical to development of nuisance plant growths (Sawyer, 1947; Vollenweider, 1968).

Total phosphorus concentration ratios, of bottom water to upper water, often show that concentrations increase in deeper waters (Bortleson and others, 1974). In stratified eutrophic lakes, there is often a considerable accumulation of phosphorus below the metalimnion. Differences in phosphorus concentration with depth are often less marked in waters of low productivity.

Inorganic nitrogen includes nitrate, ammonia, and nitrite nitrogen. Nitrogen is an essential element to plant growth. Nitrate is one of the most soluble compounds and is quickly leached out of soils and into the ground water or surface water. An empirical correlation has been shown between excessive plant production and inorganic nitrogen concentrations in excess of 300 µg/l (Vollenweider, 1968).

Inorganic-nitrogen concentration ratios, of bottom water to upper water, show that concentrations of nitrogen (especially as ammonia) increase in the deeper waters and that there is a potential exchange of nutrients from bottom to overlying waters. The proportionate difference between surface- and deep-water concentrations tends to increase in eutrophic lakes (Bortleson and others, 1974).

Organic nitrogen is an indicator of plant biomass in the lake. Lueschow and others (1970), studying Wisconsin lakes, found that a lake having an annual mean organic-nitrogen concentration of less than 200 µg/l probably would not have algae or other plankton nuisances, but a lake having an annual mean total organic-nitrogen concentration of more than 800 µg/l would probably have numerous blooms during most of the growing season.

Specific conductance is a measure of the lake water's ability to conduct an electric current and is used as a measure of dissolved solids in the water. An increase in dissolved-solids concentration in a lake often results in increased plant and animal production because more dissolved minerals are available for plant utilization (Moyle, 1956; Rawson, 1951; Ryder, 1964).

Color is an important water-quality characteristic because it shares a role in determining light transmission through water. A significant source of color to some brown-water lakes is natural organic material derived from soil and vegetation. Even though the total nitrogen and phosphorus concentrations are often high in brown-water lakes, algal blooms may be limited because "organic-bound" nitrogen and phosphorus are not easily available for plant growth (Golterman, 1973).

Secchi-disc visibility is a measure of the lake water's transparency or its ability to allow light transmission. Because changes in biological production can cause changes in the color and turbidity of a lake, transparency is often related to the quantity of aquatic flora and fauna present--or the lake's "biomass" (Brezonik and Shannon, 1971; Patalas, 1972).

Dissolved oxygen is one of the more significant chemical elements in natural waters. It is both a regulator of life processes and an indicator of lacustrine conditions. Of special biological significance is the amount of dissolved oxygen in deep water during midsummer. The organisms in the lighted upper layers of water produce organic matter which settles to the bottom layers where bacteria consume oxygen to degrade the organic materials; thus dissolved-oxygen content in the hypolimnion is reduced. The hypolimnetic-oxygen deficit is frequently related to the biomass or plant growth in the upper waters (Hutchinson, 1957). Also, the exchange of nutrients between sediment and water is closely associated with the oxygen depletion near the sediment surface (Mortimer, 1971).

Water temperature affects the growth and seasonal succession of aquatic plants. Of special significance is the temperature of the deep water during midsummer because (1) temperature stratification and water circulation affect the vertical distribution of nutrients, and (2) water temperatures affect the potential of cold-water fisheries. Deep lakes become thermally stratified (warmer layers overlying colder layers) and the nutrients which sink into the hypolimnion are usually not recirculated into the upper layers.

Fecal-coliform bacteria are a particular group of bacteria that are present in the gut of warm-blooded animals. Their presence in water is generally accepted as an indicator of recent fecal-waste contamination. The recommendation for primary-contact recreation, such as swimming, is that the standard count does not exceed 200 colonies per 100 ml (millilitres), based on a minimum of not less than 5 samples for a 30-day period, and that not more than 10 percent of the total samples in any 30-day period exceed 400 colonies per 100 ml (U.S. Department of Interior, 1968, p.12). According to State of Washington Department of Ecology (1973), the median value of the total count of coliform bacteria (both fecal and nonfecal), when associated with any fecal source, should not exceed 240 total coliform colonies per 100 ml of water and less than 20 percent of samples should not exceed 1,000 colonies per 100 ml of water.

Macrophytes are large-leafed, rooted aquatic plants which are a relatively long-lived, bulky part of the plant community. Probably one of the more important characteristics of shallow lakes is the large part of the lake bottom supporting rooted-aquatic plant growth. Macrophyte abundance often is a function of bottom composition of the beach and nearshore areas (Bortleson and others, 1974), as well as nutrient concentrations, lake shape, and wave action. Abundant rooted-plant growth is often associated with nuisance conditions for boating, swimming, and esthetics. The percentages of the water-surface area and of the shoreline length occupied by emergent macrophytes are indicators of the total quantity and distribution of rooted plants.

The numerical ratings assigned for the above described eutrophication and water-quality factors for Washington lakes are shown in table 4.

DATA COLLECTION

Field data were collected to aid in classifying lakes according to the rating criteria described above. Collection techniques described here were devised to allow rapid assessment of many lakes. All information was collected during the summer seasons (June-September) of 1973 and 1974.

Aerial Photographs

Black and white aerial photographs at a scale of 1:12,000 were obtained from the State of Washington Department of Natural Resources, if available for the lakes studied. Additional aerial photographs, in color and at a scale 1:4,800, were taken of selected lakes in the populated, 10-county Puget Sound area and of other selected lakes throughout the State. The 1:12,000-scale photographs were used to determine basin conditions and population densities, whereas the larger scale photographs were used to define details of shoreline development and to estimate the extent of emergent plant growth in the lake.

TABLE 4.--Ratings assigned to eutrophication and water-quality factors for Washington lakes

[1 is the best rating; 5 the poorest]

Indicators	Rating				
	1	2	3	4	5
Total phosphorus, upper water (µg/l)---	<5	5-10	11-20	21-30	>30
Total phosphorus, ratio of bottom to upper waters --------	<1.0	1.0-1.5	1.6-3.0	3.1-10	>10
Inorganic nitrogen, upper water (µg/l)---	<100	100-200	201-300	301-650	>650
Inorganic nitrogen, ratio of bottom to upper waters---------	<1.0	1.0-1.5	1.6-3.0	3.1-10	>10
Organic nitrogen, upper water (µg/l)---	<100	100-200	201-400	401-800	>800
Specific conductance (micromhos at 25°C)--	<20	20-50	51-100	101-500	>500
Color (Pt-Co units)----	0-10	11-20	21-40	41-60	>60
Secchi-disc (m)--------	>8.0	5.1-8.0	3.1-5.0	1.0-3.0	<1.0
Dissolved oxygen near bottom (mg/l)--------	>8.0	5.1-8.0	2.1-5.0	0.5-2.0	<0.5
Water temperature near bottom (°C)-----	<5.0	5.0-7.0	7.1-10.0	10.1-15.0	>15.0
Fecal-coliform bacteria (colonies per 100 ml; mean value)----------	<1	1-5	6-50	51-240	>240
Percentage of lake surface occupied by emergent rooted aquatic plants-------	<1	1-10	11-25	26-50	>50
Percentage of shoreline occupied by emergent rooted aquatic plants---------------	<10	10-25	26-50	51-75	76-100

Reconnaissance and Sampling

Drainage-basin characteristics, nearshore land development and other environmental information were determined for each lake by helicopter reconnaissance. Rooted aquatic-plant abundance was assessed according to the percentage of the lake area occupied by emergent and (or) floating plants and the percentage of the shoreline occupied by emergent rooted aquatic plants.

From helicopters fitted with pontoons or from boats, vertical profiles of temperature and dissolved-oxygen concentration were measured in situ in the deepest part of each lake. Multiple sites were sampled on lakes with areas greater than 2,500 hectares and on irregular-shaped lakes. Secchi-disc visibility was also determined. Water samples were collected for color, nutrient, and specific-conductance analyses at depths 1.0 metre below the water surface and 1.0-1.5 metres above the lake bottom. The nutrient analyses were performed in U.S. Geological Survey laboratories, using procedures described by Brown, Skougstad, and Fishman (1970).

Near the shore at a depth of 0.3 metre below the water surface, samples for fecal-coliform bacteria were collected in sterilized 0.25-litre glass bottles. The samples were iced, filtered, and placed on growth media usually within 1 to 8 hours after collection. The fecal-coliform tests were performed according to U.S. Geological Survey procedures described by Slack and others (1973).

Bathymetric Maps

Bathymetric (bottom-contour) maps were available for about one-third of the lakes investigated. The other lakes were sounded and charted with a continuous-recording fathometer. Using the aerial photographs and lake depths the data were digitized by the U.S. Geological Survey and transferred to computer cards which served as input to a contouring program that generated a bathymetric map. Morphometric parameters such as lake volume, mean depth, and length of shoreline were computed from these same data.

RELATIVE CLASSIFICATION OF SEVEN LAKES IN WASHINGTON

Seven Washington lakes with different physical, cultural, and water-quality characteristics were chosen to illustrate the classification system. The assigned ratings of one through five are summed as an individual score for each of the three lake and drainage-basin categories: (1) natural physical factors, (2) cultural factors, and (3) indicators of eutrophication and water quality, as shown in table 5.

To evaluate the causes of eutrophication, a percentage contribution of total phosphorus loading was estimated for point sources (such as municipal waste and urban storm drainage) and for nonpoint sources (such as runoff from forest, agricultural, and residential areas). The estimated percentages are shown in table 6. The degree of confidence is given for each estimate and is based primarily on the complexity of the population and land-use patterns and to a lesser extent on the availability of background data. A sample calculation of the percentage contribution of phosphorus from various nonpoint sources is given in appendix D.

Some of the more salient characteristics of the lakes classified are as follows:

Boren Lake shows poor water quality and strong cultural stresses. Because of the large size of the lake drainage area relative to the lake volume, the potential nutrient load to this lake is high.

Diamond Lake shows intermediate characteristics for physical, cultural, and water-quality conditions.

Hancock Lake shows good qualities in all three categories. Nutrients are particularly low.

Harts Lake shows that, despite the fairly low cultural impact and moderately rated physical qualities, the lake has poor water-quality characteristics. However, the nonpoint-source impact, mainly from agriculture, is fairly high.

Mason Lake shows moderate to good qualities in all three categories.

Summit Lake, a high altitude lake, shows excellent qualities with the exception of the long water-renewal time. The total phosphorus input to the lake is derived mainly from rainfall.

Wye Lake shows a high cultural impact combined with poor natural physical factors. Most of the total phosphorus input to the lake is from residential sources. However, on the basis of its water-quality conditions, the lake appears to be capable of assimulating these cultural stresses reasonably well.

TABLE 5.--Relative classification of seven lakes in Washington

Rating factors	Boren King Co. T.24 N.,R.5 E.	Diamond Pend Oreille Co. T.30 N.,R.44 E.	Hancock King Co. T.24 N.,R.9 E.	Harts Pierce Co. T.16 N.,R.3 E.	Mason Mason Co. T.21 N.,R.2 W.	Summit Pierce Co. T.18 N.,R.8 E.	Wye Kitsap Co. T.19 N.,R.5 W.
Natural physical factors:							
Mean depth	4	3	3	3	2	2	5
Volume	4	2	2	3	2	3	4
Bottom slope	2	4	4	3	4	1	4
Shoreline configuration	2	4	2	1	5	1	5
Ratio of drainage area to lake volume	4	3	3	3	2	1	4
Altitude	5	4	3	5	5	1	5
Water-renewal time	1	3	1	2	3	4	1
Maximum possible rating: 35	22	23	18	20	23	13	28
Cultural factors:							
Nonpoint phosphorus sources (cultural and natural)	5	3	3	4	2	1	4
Point phosphorus sources	1	1	1	1	1	1	1
Volume of water per nearshore home	5	3	2	2	3	1	5
Percentage of shore developed for residential use	4	5	2	1	5	1	5
Maximum possible rating: 20	15	12	8	8	11	4	15
Indicators of eutrophication and water quality:							
Total phosphorus, upper water	4	3	2	5	2	2	2
Total phosphorus, ratio of bottom to upper waters	1	3	3	4	2	2	3
Inorganic nitrogen, upper water	5	2	2	5	1	1	1
Inorganic nitrogen, ratio of the bottom to upper waters	2	2	1	3	2	2	2
Organic nitrogen, upper water	3	4	1	1	2	1	3
Specific conductance, upper water	4	3	1	4	2	1	1
Color	3	1	1	3	1	1	1
Secchi-disc visibility	4	2	2	4	3	1	3
Dissolved oxygen, near bottom	4	4	2	5	2	1	1
Water temperature, near bottom	3	4	2	2	3	1	5
Fecal-coliform bacteria	3	2	2	2	2	1	2
Percentage of water surface occupied by emergent macrophytes	2	2	2	2	1	1	2
Percentage of shoreline occupied by emergent macrophytes	3	2	4	5	1	1	1
Maximum possible rating: 65	41	34	25	45	24	16	27

TABLE 6.--Sources of artificial and natural loading of total phosphorus, expressed as an estimated percentage contribution

Lakes	Estimated percentage contribution of nonpoint-source loading, and confidence in estimate[a]					
	Urban	Rural-suburban	Agricultural	Forest or unproductive	Rainfall	Confidence in nonpoint-source evaluation
Boren	[b]N	71	7	20	2	Moderate
Diamond	N	12	37	44	7	Moderate
Hancock	N	2	N	87	11	High
Harts	N	6	50	39	5	Moderate
Mason	N	24	N	65	11	Moderate
Summit	N	N	N	47	53	High
Wye	N	71	N	25	4	Moderate

[a]Point sources (waste effluent) such as untreated domestic, untreated municipal, primary and secondary treatment, and industrial wastes; urban storm sewer; irrigation return and flow are negligible.

[b]Negligible contribution.

GLOSSARY

Algal bloom. A large abnormal population of phytoplankton which often forms objectionable scums and odors upon decomposition. Usually a bloom comprises 0.5 to 1 million cells per litre.

Biomass. The existing amount (standing crop) of organisms present in a lake. Biomass is expressed as weight per unit area or volume.

Bottom slope. The slope profile of a lake bottom, expressed as a percentage ratio of the maximum depth to the mean diameter (referred to by Hutchinson, 1957, p. 167, as relative depth), given as

$$\text{bottom slope} = \frac{\text{maximum depth} \times 50 \times \sqrt{\pi}}{\sqrt{A}} ,$$

where A is the area of the lake.

Cultural eutrophication. The acceleration of the natural process of nutrient enrichment in a lake as a result of man's activities.

Emergent plant. A rooted aquatic plant with parts extending above the water surface.

Eutrophication, eutrophic. The enrichment of water, a natural process that may be accelerated by the activities of man; pertains to waters in which primary productivity is high as a consequence of a large supply of available nutrients.

Epilimnion. The upper, relatively warm, circulating zone of water in a thermally stratified lake.

Hypolimnion. The lower, relatively cold, noncirculating zone in a thermally stratified lake.

Land-use categories:

Urban. Predominant use is by single-family residences in city-lot sizes where apartment complexes and commercial or industrial activities also may be present.

Suburban and rural. Predominant use is single-family residences with lot sizes usually one hectare or less. Where residentially developed land and highway right-of-ways jointly use shoreland, the dominant use is residential. Parks and recreational areas are included.

Land-use categories--continued

Agricultural. Pasture or cropland.

Forest or unproductive. Public and private forest lands and tree farms. Lands may include cleared or fallow unproductive land, meadows, wetlands, and recreational areas.

Commerical. Retail sales and business offices, shopping centers, and related commercial enterprises.

Industrial. Manufacturing and fabrication industries.

Macrophyte. Large plant of macroscopic size (easily visible to the naked eye) and usually rooted to lake bottom.

Mean depth. The volume of the lake divided by its area.

Metalimnion. The middle layer of water in a thermally stratified lake in which temperature decreases rapidly with increasing depth.

Muck. Highly decomposed organic material in which the original plant material is not recognizable. It is normally darker than peat and contains more mineral matter.

Nearshore development. In this report, refers to residences located on and near lake shoreline, within about 150 metres of the shoreline.

Nutrient. Any chemical element, ion, or compound that is required by an organism for the continuation of growth, reproduction, and other life processes. In this report, nutrients usually mean phosphorus and nitrogen.

Plankton. The community of suspended or floating organisms which drift passively with water currents.

Population equivalent. A basis for comparing industrial wastes with domestic sewage. Comparisons to the average values for domestic sewage can be made on the basis of chemical concentrations or flow.

Primary productivity. The rate at which radiant energy is stored by photosynthetic and chemosynthetic activity of producer organisms (chiefly green plants) in the form of organic substances which can be used as food materials (Odum, 1971, p. 43).

Production. The total amount of living matter produced in a lake per unit time regardless of the fate of the living organic matter.

Secchi disc. A white and black, circular disc which is lowered into the water on a calibrated line to measure the transparency of the water.

Shoreline configuration (sometimes referred to as "development of shoreline"--a misleading term). A dimensionless ratio of the length of shoreline divided by the circumference of a circle having an area equal to the area of the lake, given as:

$$\text{shoreline configuration} = \frac{\text{length of shoreline}}{2\sqrt{\pi A}},$$

where A equals the area of the lake.

Submergent plant. An aquatic macrophyte that lives and completes its life cycle entirely below the surface of the water.

Thermal stratification. The layering of water in a lake or reservoir owing to different densities as a function of temperature; the layers are the epilimnion (upper), the metalimnion (middle), and the hypolimnion (lower).

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APPENDIX A.--Lake and drainage-basin factors evaluated

Natural physical factors affecting potential enrichment:

Mostly sedimentary or meta-sedimentary rocks in drainage basin.
Absence of surface-water outflow channel.
Beach composition mostly muck or silt and muck.
Little or no beach.
Upland slope greater than 30 percent.
Drainage infiltrating peat deposits.
Evidence of unstable water levels.
Lake fed from upstream lake.
Development of volume greater than 0.50 (deviation from cone shape).
Known large resident-waterfowl population on lake.

Culturally related factors affecting potential enrichment:

Perennial surface-water streams draining residential, urban, agricultural, or developed lands.
Waste disposal from nearshore residential units other than sewerage system.
Less than 30 metres of shoreline per nearshore home.
Mostly permanent residences near shore.
Major land-use alterations near shore.
Proximity to large urban center (<30 km).
Road access to lake drainage basin.
Public access to lake.
Heavy in-lake recreational activities.

Indicators of actual lake eutrophication and water quality:

Ratio of total nitrogen to total phosphorus (N_T/P_T) less than 15, with P_T >20 µg/l.
Observed growth of submergent macrophytes covering most of lake bottom.
Floating logs or debris.
Submerged logs or debris.
Algal bloom.
Hydrogen sulfide in hypolimnion.

APPENDIX B.--Data for calculation of total phosphorus loading of seven Washington lakes from nonpoint sources, and results

Lake	$\frac{D_n}{A_o}$ [a]	Urban			Rural-suburban			Agricultural			Forest			Rainfall			Summation of loading	Total phosphorus loading
		A_1 [b]	L_1 [c]	A_1L_1	A_2 [b]	L_2 [c]	A_2L_2	A_3 [b]	L_3 [c]	A_3L_3	A_4 [b]	L_4 [c]	A_4L_4	A_5 [d]	L_5 [c]	A_5L_5	A_nL_n	L_t [e]
Boren---	38	0	140	0	0.242	100	24.2	0.050	50	2.5	0.680	10	6.8	0.026	20	0.52	34.0	1,292
Diamond-	14	0	140	0	.022	100	2.2	.129	50	6.5	.783	10	7.8	.066	20	1.3	17.8	249
Hancock-	20	0	140	0	.002	100	.20	0	50	0	.938	10	9.4	.060	20	1.2	10.8	216
Harts---	19	0	140	0	.012	100	1.2	.194	50	9.5	.742	10	7.4	.052	20	1.0	19.1	363
Mason---	13	0	140	0	.032	100	3.2	0	50	0	.891	10	8.9	.077	20	1.5	13.6	177
Summit--	3.2	0	140	0	0	100	0	0	50	0	.638	10	6.4	.362	20	7.2	13.6	43.5
Wye-----	17	0	140	0	.212	100	21	0	50	0	.733	10	7.3	.055	20	1.1	29.4	500

[a] $\frac{D_n}{A_o}$ = drainage area (including lake-surface area) divided by lake-surface area.

[b] $A_{1,2,3,4,5}$ = decimal part of total drainage area in a particular land use.

[c] $L_{1,2,3,4,5}$ = export of total phosphorus from a particular land use, in kilograms of total phosphorus per square kilometre of land per year. (See table 3.)

[d] Decimal part of total drainage area that is water-surface area.

[e] L_t = total phosphorus loading to a lake in kilograms per square kilometre of lake surface per year.

APPENDIX C.--Calculation of total phosphorus loading of a lake from a point source

Known quantities:

Lake-surface area = 0.89 square kilometre.

Sewage discharge to lake = 1.1×10^{6} litres per day.

Assumption:

7.5×10^{-6} kg total phosphorus (P) per litre of sewage.

Calculation:

Kilograms of total phosphorus per square kilometre of lake surface per year =

$$1.1 \times 10^{6} \frac{\text{litres P}}{\text{day}} \times 7.5 \times 10^{-6} \frac{\text{kg P}}{\text{litre}} \times \frac{1}{0.89 \text{ km}^2} \times \frac{365 \text{ day}}{\text{year}} = 3,380.$$

APPENDIX D.--Data for calculation of percentage phosphorus contribution from nonpoint sources, and results

Lake	$\sum A_nL_n$[a]	Urban		Rural-suburban		Agricultural		Forest		Rainfall	
		A_1L_1[b]	Per-cent[c]	A_2L_2[b]	Per-cent[c]	A_3L_3[b]	Per-cent[c]	A_4L_4[b]	Per-cent[c]	A_5L_5[b]	Per-cent[c]
Boren------	34.0	0	0	24.2	71.1	2.5	7.3	6.8	20.0	0.52	1.5
Diamond----	17.8	0	0	2.2	12.4	6.5	36.5	7.8	43.8	1.3	7.3
Hancock----	10.8	0	0	.20	1.85	0	0	9.4	87.0	1.2	11.1
Harts------	19.1	0	0	1.2	6.28	9.5	49.7	7.4	38.7	1.0	5.23
Mason------	13.6	0	0	3.2	23.5	0	0	8.9	65.4	1.5	11.0
Summit-----	13.6	0	0	0	0	0	0	6.4	47.1	7.2	52.9
Wye--------	29.4	0	0	21	71.4	0	0	7.3	24.8	1.1	3.74

[a] Summation of total phosphorus loading.

[b] $A_{1,2,3,4,5}$ = decimal part of total drainage area in a particular land use.

$L_{1,2,3,4,5}$ = export of total phosphorus from a particular land use, in kilograms of total phosphorus per square kilometre of land per year.

[c] Percentage contribution from nonpoint sources $\left(\text{that is, } \frac{A_1L_1}{\sum A_nL_n}\right)$.