EPA 910-R-05-002

United States
Environmental Protection
Agency

Region 10
1200 Sixth Avenue
Seattle WA 98101

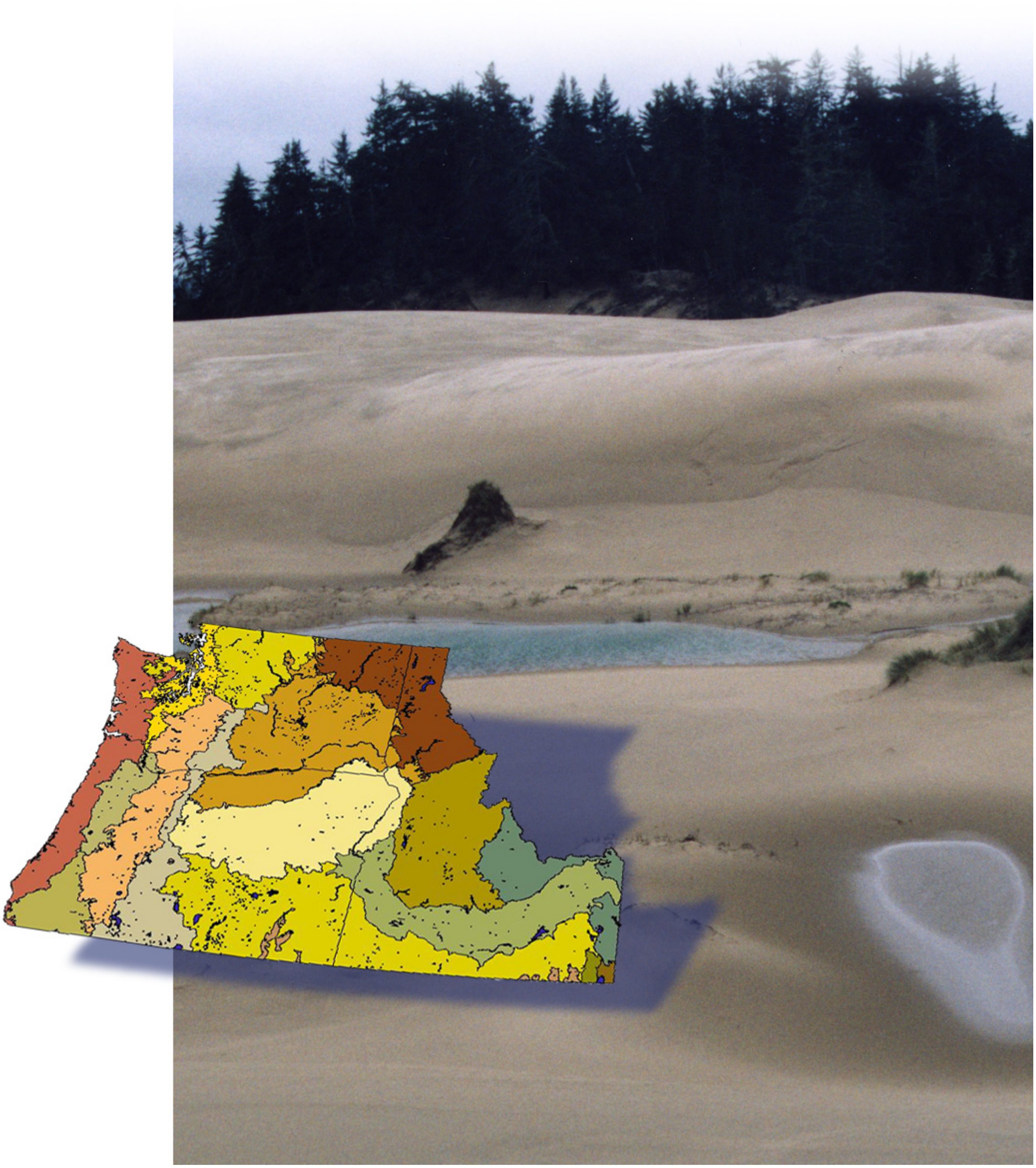
Alaska
Idaho
Oregon
Washington

Office of Water & Watersheds

December 2005

EPA

A Classification of Lakes in the Coast Range Ecoregion with Respect to Nutrient Processing



EPA 910-R-05-002
December 2005

A CLASSIFICATION OF LAKES IN THE COAST RANGE ECOREGION WITH RESPECT TO NUTRIENT PROCESSING

R.M. Vaga, US Environmental Protection Agency, Office of Water and Watersheds, Region 10, 1200 Sixth Ave. Seattle, WA 98101

R.R. Petersen, M.M. Sytsma and M. Rosenkrantz, Environmental Sciences and Resources, Portland State University, Portland Oregon, 97202

A.T. Herlihy, Department of Fisheries and Wildlife, Oregon State University, 104 Nash Hall, Corvallis, OR 97331

DISCLAIMER

The information in this document has been funded wholly or in part by the United States Environmental Protection Agency. It has been subjected to the Agency's peer and administrative review and it has been approved for publication as an EPA document. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

(Cover photo: An unnamed dune lake on the Southern Oregon coast. Photo by R.M. Vaga)

TABLE OF CONTENTS

ABSTRACT

This report presents one methodology to classify natural lakes with respect to nutrient processing. Lakes in the Coast Range Ecoregion were inventoried and lakes greater than 4 ha in surface area were chosen as the target population. A methodology was then developed based upon "expert opinion" to categorize lakes in the ecoregion based upon basic limnological principles. The categories were developed without recourse to nutrient data.

Analysis of total P, total N, chlorophyll and Secchi was carried out for 1) the Coast Range lakes as a whole and 2) for each lake category. Results suggest that these parameters have inherently different variability among lake categories which affects their utility in developing numeric nutrient criteria.

Stratification of lakes was also performed using Level IV Ecoregions. Although a rough correlation appeared to exist between lake category and ecoregion, data were insufficient to draw any conclusions.

Two empirical methods are described whereby numeric nutrient criteria can be derived in relation to beneficial uses.

CHAPTER 1. INTRODUCTION

This report presents the results of a study conducted in the Coast Range Ecoregion in support of the nutrient criteria development effort in Region 10 EPA. The goals of this study were to 1) define the population of lakes and reservoirs in the Ecoregion, 2) classify the lakes with respect to nutrient processing based on limnological principles, 3) analyze water quality data to characterize the lake categories and 4) explore methods to derive numeric criteria for the nutrient criteria variables (Total P, Total N, chlorophyll and Secchi) in relation to designated uses.

The approach used in this study was adapted from methods described in the Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs (EPA 2000). Figure 3-1 presents a flow chart of the methodology used for deriving numeric nutrient criteria for lakes in the Coast Range Ecoregion. Lakes were inventoried (Chapter 2) and lakes greater than 4 hectares in surface area were considered the population for which categories were to be derived. A methodology to categorize lakes based upon "expert opinion" and basic limnological principles was developed for this population. The categories were developed without recourse to nutrient data. As a result seven categories were developed as described in Chapter 3.

Analysis of Total P, Total N, chlorophyll and Secchi depth was carried out for 1) the Coast Range Ecoregion as a whole and 2) for lake categories. Results show that the categories roughly defined different trophic conditions. In addition an analysis of variance components in the historical data is also presented. Results suggest the different parameters have inherently different variability which affects their utility in developing numeric criteria.

Stratification of lakes by category was compared to Level IV Ecoregions. There appeared to be a rough correlation between Level IV Ecoregion and lake category but there have been too few lakes categorized to draw any firm conclusions.

Two empirical methods to develop numeric criteria in relation to beneficial uses are presented in Chapter 5. The illustrations show that while empirical descriptions of reference lake types are possible, the development of numeric criteria for Total P vis-a-vis beneficial uses requires specific interpretation of the definition of the beneficial use and judgement regarding how protective to make the criterion.

In this report we demonstrate that for certain Ecoregions, stratification of lakes at the Level III and even Level IV Ecoregion is not sufficient for classification purposes with respect to nutrient processing. The use of non-codified, unpublished information, e.g. local and 'expert judgement' are a source of information of significant value in lake classification.

CHAPTER 2. DEFINING THE LAKE POPULATION

2.1 Methods

The Coast Range Ecoregion extends from the tip of the Olympic Peninsula in Washington State to the Oregon-California border and approximately 50 miles inland from the Pacific Ocean (Omenik, 1986) (Fig. 2-1). Spatial data on lakes and reservoirs in the Coast Range Ecoregion used in this report were obtained from various sources. The spatial data were checked and corrected using topographic maps for Oregon and Washington (Delorme 1998,2001). A complete description of the procedure used to verify the spatial data is described in Vaga and Herlihy (2004). Lakes greater that 4 ha in surface area were defined as the target population of lakes. This size of lake was selected because it is readily identifiable on the topographic maps used in the verification process.

2.2 Results

There are a total of 353 named lakes in the Coast Range Ecoregion (Appendix Table 1). Of those, there are 171 lakes greater than or equal to 4 hectares in surface area and 182 less than 4 ha (Table 2-1). Of the 171 features greater than 4 hectares that were identified as existing on the landscape, most were confirmed to be lakes. It was not possible to determine from maps whether 16 features were actually lakes. However, they were included in the population. For purposes of this report, the lake population in the Coast Range Ecoregion is therefore defined as the set of 171 lakes.

Lakes are found in the Coast Range Ecoregion from southern Oregon to the tip of the Olympic Peninsula in Washington (Fig. 2-1). The highest density of lakes is found on the southern Oregon Coast where many of the lakes are right on the Pacific Coast, e.g.

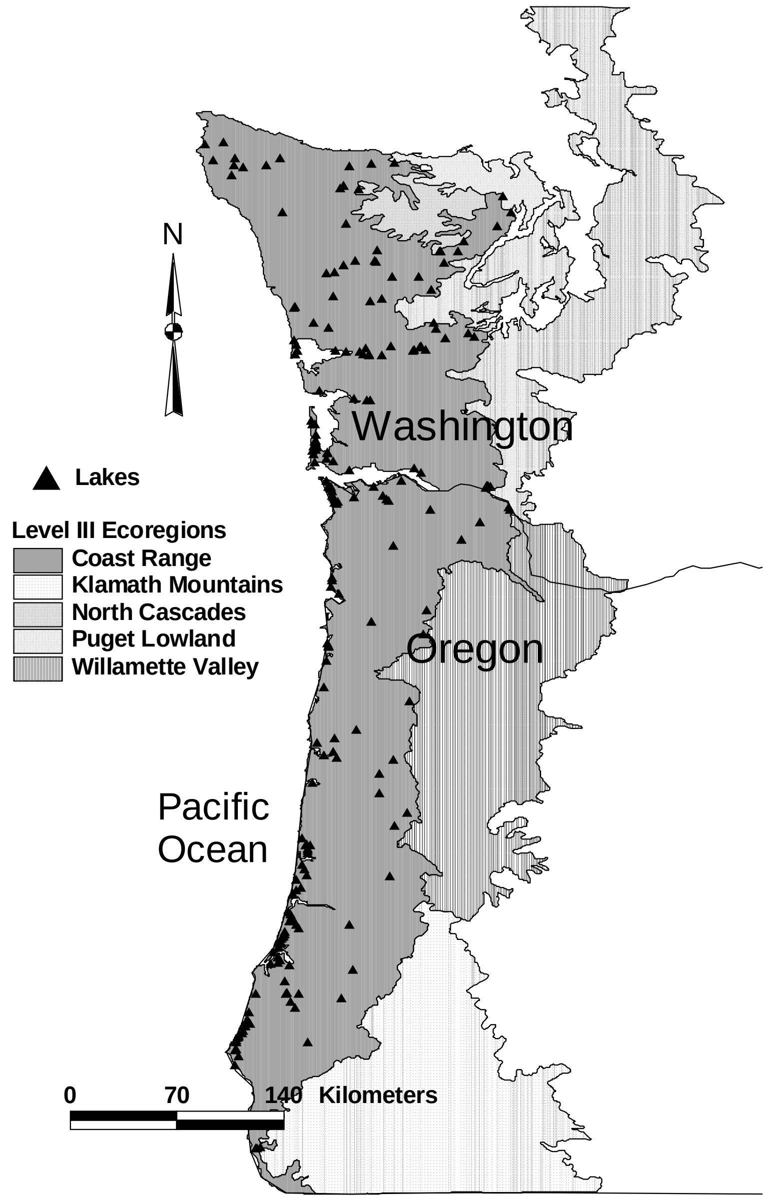


Figure 2-1. Location of the 171 lakes ≥ 4 ha in surface are in the Coast Range Ecoregion.

dune lakes. There are no lakes north of Grays Harbor in Washington that are truly coastal, i.e. right on the coast. Most of the lakes in Washington are inland (Fig. 2-1).

The cumulative distribution of lakes ≥ 4 ha in the Ecoregion with respect to surface area is presented in Figure 2-2. About half of the lakes (n = 86) are less than 11 hectares in surface area.

The total lake surface area of the 353 lakes is 156.3 km^2. The171 lakes ≥ 4 hectares accounted for 153.9 km^2 or over 98% of total lake area in the Ecoregion.

Very few lakes account for a large percentage of the total surface area of lakes. Just over fifty percent of the total lake area in the Ecoregion is accounted for by only 5 lakes (Lake Ozette, Lake Crescent, Lake Cushman, Lake Quinault, Siltcoos Lake) (Fig. 2-3). There are 30 lakes larger than 50 ha and these account for 89% of the total surface area (Appendix Table 2). Lake Ozette (3,007 ha) is the largest lake in the Ecoregion and alone accounts for 19.3% of the total surface area.

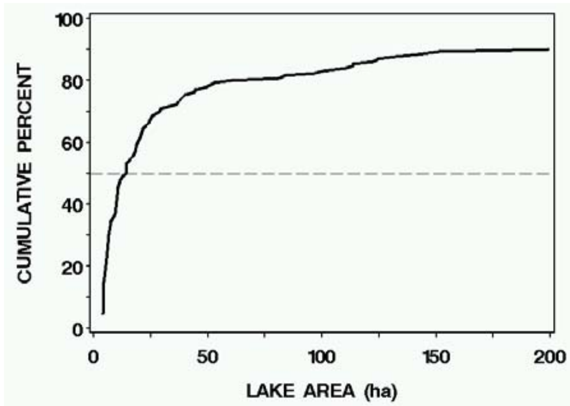


Figure 2-2. Cumulative distribution of lake surface areas of lakes in the Coast Range Ecoregion (≥ 4 ha). About half of the lakes are less than 11 ha in surface area.

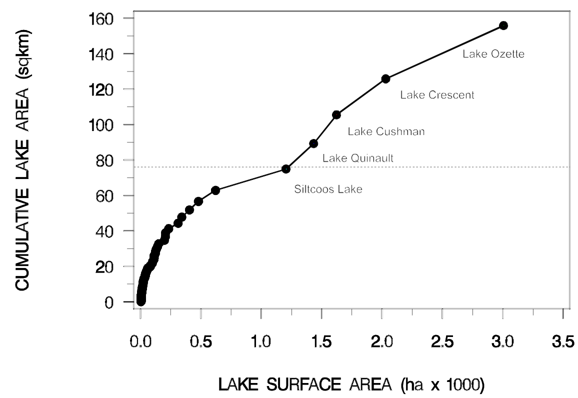


Figure 2-3. Cumulative disbribution of total lake surface area in the Coast Range Ecoregion by lake size. The five largest lakes in the region account for one-half of total lake surface area.

Table 2-1. The number of lakes in Coast Range Ecoregion < 4 ha and ≥ 4 ha in surface area. The number of lakes ≥ 4 ha in the Coast Range Ecoregion accounts for only 48% of the Total Number of lakes but 98% of the total lake surface area.

Total Number of Lakes	Total Number (< 4ha)	Total Area (< 4ha) (sq km)	Total Number (≥ 4 ha)	Total Area (≥ 4 ha) sq km	% Numb (≥4ha)	% Area (≥ 4ha)	Density No/sq km x 100
353	182	2.4	171	153.9	48	98	0.05

CHAPTER 3. CLASSIFICATION OF LAKES IN THE COAST RANGE ECOREGION

3.1 Introduction

The EPA National Nutrient Strategy calls for setting water body specific nutrient criteria for lakes and reservoirs. Documentation provided by EPA suggests a number of approaches for setting nutrient criteria for individual lakes. (EPA, 2000). Importantly, the Manual recommends segregating lakes by Ecoregion (Omernik) and identifying lakes thought to be representative of undisturbed conditions ("Reference Lakes"). Implicitly, these recommendations recognize the necessity of assigning lakes to categories of similar limnological character to allow setting realistic and useful criteria for nutrients. Indeed, the Technical Guidance Manual explicitly recommends the development of …"a classification scheme for rationally subdividing the population of lakes in the State" . A classification scheme for the lakes in the Coast Range Ecoregion is presented as a step toward setting criteria that are neither unrealistically permissive for several large, very oligotrophic lakes nor impossibly restrictive for many smaller lakes heavily influenced by wetlands.

3.2 History of the concept of lake classification or lake tyopology

Lake classification or lake tyopology has a long history in limnology. The most important of the early (1900 to 1920) effort on lake classification was work by August Thienemann in Germany and Einar Nauman in Sweden, who together introduced the now generally accepted scheme of oligotrophy to eutrophy to describe the general patterns of variation in lakes (Moss et al. 1994). Indeed, the trophic classification system became a central paradigm in modern limnology. Other systems of classification were developed based on geological origin of lake basins (Hutchinson, 1957) or annual temperature stratification patterns (Hutchinson and Loeffler, 1956).

Naumann and his successors continued with constructing ever more elaborate lake tyopology schemes. The belief in the utility of the approach reached its apex when lake tyopology (*Seetypenlehre*) was the major topic of the International Congress for Limnology in Finland in 1956 (Moss et al. 1994). However, Moss et al. (1994) point out in their review that the "concept of lake types was flawed and attention [turned] to processes in lakes." Beginning in the 1960s, it was recognized that each lake was unique and that lakes vary continuously along many variables. Moss et al. conclude their historical review with: "But the concept of discrete types is dead…".

Nevertheless, Moss et al (1994) return to the issue of lake classification as a means to deal with cultural eutrophication and environmental regulations meant to cope with the problem. They recommend a scheme based on three "major axes" (roughly, morphometry, major ions and nutrients) as a method for the classification of individual lakes while avoiding "…a tyopology with named units defined by preconception". Their intent is to describe lakes in their present condition and to provide a framework for estimating the prior condition of each lake before the onset of cultural eutrophication. Nevertheless, in the end, they adopt a set of discrete categories because continuous variation leads to "…an infinity of possibilities not practicable in a scheme intended for use by statutory regulatory authorities." In short, the concept of *Seetypen* (Lake Tyopology) has been abandoned but the classification of lakes in some manner has reemerged as a necessary component of setting realistic criteria for nutrients in lakes.

3.3 Current research in lake classification

A current approach to develop lake classifications is to use multivariate statistical methods based on the structure of the data collected from the lakes themselves, or as stated by Thierfelder (2000): "… a supplemental approach to lake classification is conceivable. With exploratory methods of multivariate statistical analysis, relatively objective analyses of empirically observed data are facilitated."

Thierfelder demonstrated such an analysis using data collected from 76 Swedish lakes sampled monthly over a period of 5 years. He based his analysis on pH, alkalinity, conductivity, hardness, color, Secchi depth and Total Phosphorus data. Data for each parameter were linearly transformed to approximately suitable statistical distributions. Theirfelder then analyzed the data by principal components analysis, obtaining just two principal components that efficiently described most of the data structure. The first principal component could be represented by hardness alone (pH, alkalinity and conductivity were highly correlated with hardness), and the second principle component could be represented by color alone (Secchi depth was highly correlated). The result was a 2 dimensional framework, one dimension for inorganic characteristics (hardness) and a second for organic characteristics (color) for the classification of individual lakes (his figure 4). Individual lakes were then plotted on the resulting framework based on their individual water quality characteristics. Thierfelder concludes:"…the base is well suited for the chemometric lake water classification in accordance with the objectives set."

Toivonen and Huttunen (1995) also use multivariate statistical methods for lake classification using TWINSPAN, followed by ordination with detrended correspondence analysis (DCA) and canonical correspondence analysis (CCA). They compare the results with two *a priori* classification systems: the trophic classification system and the traditional Finnish botanical lake classification system. For their analysis they included data on altitude above sea level, lake area, maximum depth, pH, conductivity, Secchi depth and color. (They assume that conductivity is a good overall parameter for the general nutrient status.) They used data from 57 small lakes in southern Finland collected over several years. Using the *a priori* classification systems, they described six groups of lakes based on trophic conditions and dystrophic influences. The multivariate methods, applied to data on the species composition of the macrophytes collected from the lakes, produced much the same groupings. They conclude: "Most of the final …clusters constitute more or less recognizable lake groups, which match to a great extent the *a priori* groupings." Nevertheless, Toivonen and Huttenen note a common difficulty: …"some of the lakes are difficult to place [into *a priori* groupings]." In this regard, the dichotomous classification produced by TWINSPAN (their figure 4) is based on objective criteria and doesn't require the sometimes arbitrary designation of borderline lakes under the *a priori* classification systems.

A third very useful example is a classification method suggested for northern Wisconsin lakes by Emmons et al (1999). They also note that the uniqueness of individual lakes poses a challenge to management approaches, since effective management requires some generalization. To this end, they observe: "Classification systems that account for ecologically meaningful variation provide a way to group lakes into units in which similar ecological processes operate and similar responses to anthropogenic impacts or management strategies can be expected." They examined two alternative classification procedures for the nearly 15000 individual lakes in Wisconsin, one a familiar use of multivariate methods and the second an iterative dichotomous splitting of the lakes to form a hierarchical classification tree. Their objective was to compare a cluster and discriminate analysis approach with a tree-structured classification approach with data from Wisconsin lakes. The data (originally reported in Lillie and Mason, 1983) consist of morphometric parameters (lake area, maximum depth, drainage basin area), inorganic chemistry (calcium, magnesium, alkalinity, chloride, pH), nutrients (Total Phosphorus, Total Nitrogen), Secchi transparency, turbidity, and chlorophyll a for a total of 667 lakes sampled during 1979. They first describe a multivariate method of classification that uses cluster analysis (k-means) to form lake groups and discriminate function analysis to assign individual lakes to the clusters (following methods of Schupp, 1992). They also discuss some of the weaknesses of multivariate approaches, notably that the results are often difficult to interpret and to explain for management purposes. As an alternative, they proposed using tree-structured methods, know as classification and regression tree analysis (CART). They argue that the tree-structured methods …"may provide a powerful tool for classifying ecological units in a reliable and interpretable framework", in part because such methods recognize the often hierarchical data structure of lakes. A significant problem with tree-structured approaches is that they require group membership to be known in advance. In the end, the authors adopt a method that combines aspects of both approaches. "We propose combining some of the advantages of tree-structured methods with cluster analysis into an approach that forms groups and models group membership. We take advantage of the recursive nature of classification trees to include variable interactions, hierarchical relationships, and reduction of dimensionality while avoiding some of the potential pitfalls of more traditional multivariate techniques." As a final result, they identify six clusters of lakes (their figure 3) based on familiar limnological parameters. The lakes were first split into two large groups based solely on alkalinity (more or less than 55 mg/l), with subsequent splits based on morphometric characteristics (depth, area) or nutrients and water clarity. In the authors words: "This results in a more accurate and interpretable classification with fewer variables…".

In summary, although lake tyopology may have fallen into disuse, the need to classify lakes for management purposes persists. As part of an effort to implement realistic nutrient criteria, some system of classification is necessary. On the one hand, the great variety of limnological conditions must be recognized by any system for setting criteria, but in the end, criteria must be established for individual lakes to have any management value. It is of interest that the three examples cited make use of the latest multivariate statistical methods yet arrive at classification schemes that can be described in terms of familiar and traditional limnological characteristics: water color and clarity, lake morphometry, major ion chemistry and of course nutrient concentrations. It is also worth noting that each of the three examples was based on the analysis of a very large database. Unfortunately such data are not generally available for lakes in the Coast Range Ecoregion.

3.4 Coast Range Ecoregion Lake Classification: "Expert Opinion"

As part of an effort to gather data for the development of lake nutrient criteria for lakes in EPA Region 10, data were collected during 1999 and 2000 for 24 lakes, all in the Coast Range Ecoregion (Omernik 1986). The lakes were selected randomly from a database of all known lakes in the Ecoregion using a procedure developed for the Environmental Monitoring and Assessment Program (EMAP) Northeast Lake Survey (Larsen et al. 1994), and can therefore be interpreted as a representative sample of all the lakes in the Ecoregion.

Lake categories were constructed based on this sample of 24 following the recommendations in the EPA Nutrient Criteria Technical Guidance Manual (EPA, 2000). The categories were developed without reference to nutrient data, i.e. characteristics other than trophic state were used to define a category. They were developed by the authors with input from local experts. The categories are based on how the lake might be described by the author to a local limnologist who is not familiar with the particular lake. The categories may be thought of as a "thumbnail sketch" of the lakes. The categories are explicitly not meant to represent a gradient of disturbed to pristine. Rather, the categories are based on the overall character of the lakes. A flow chart of the categorization scheme is presented in Figure 3-1. Within the various categories are lakes that are nearly pristine or partially disturbed by human influence. The possible interaction between degree of disturbance and lake category is discussed below. Thus the categories presented here were constructed based on what appeared to be significant characteristics influencing their limnological character.

All lakes in the sample are from the Coast Range Ecoregion. It is recognized that the sample size is not sufficient to justify a proper statistical description of the various categories. Instead, the categories are suggested based on the notion of "expert opinion" suggested in the EPA manual. While not sufficient to develop a statistically sound lake classification, the results do suggest that designation of lakes by ecoregion alone will not be sufficient to recommend appropriate nutrient criteria for the entire Ecoregion. The results suggest that morphometric characteristics such as mean depth and exposure to the direct influence of coastal winds, dissolved humic substances (color), and major ion chemistry can influence lake characteristics and should be reflected in appropriate nutrient criteria designations. Clearly, additional random sampling would be necessary to extend the list and construct similar categories for other Ecoregions within EPA Region 10.

3.5 Lake Categories

Seven lake categories were identified in the Coast Range Ecoregion. The lakes were assigned to categories according to their overall appearance, or as noted above, how they might be described to a local limnologist. Characteristics that appear significant include the effects of wetland drainage (dissolved humic substances), mean depth, wind exposure, and surrounding soil type (sand versus other soil types). The conceptual scheme for this classification is presented in Figure 3-1 and defines seven categories. Category 7 is composed of unique lakes which are not subject to classification based upon this scheme. The location of each of the lakes is presented in Figure 3-2.

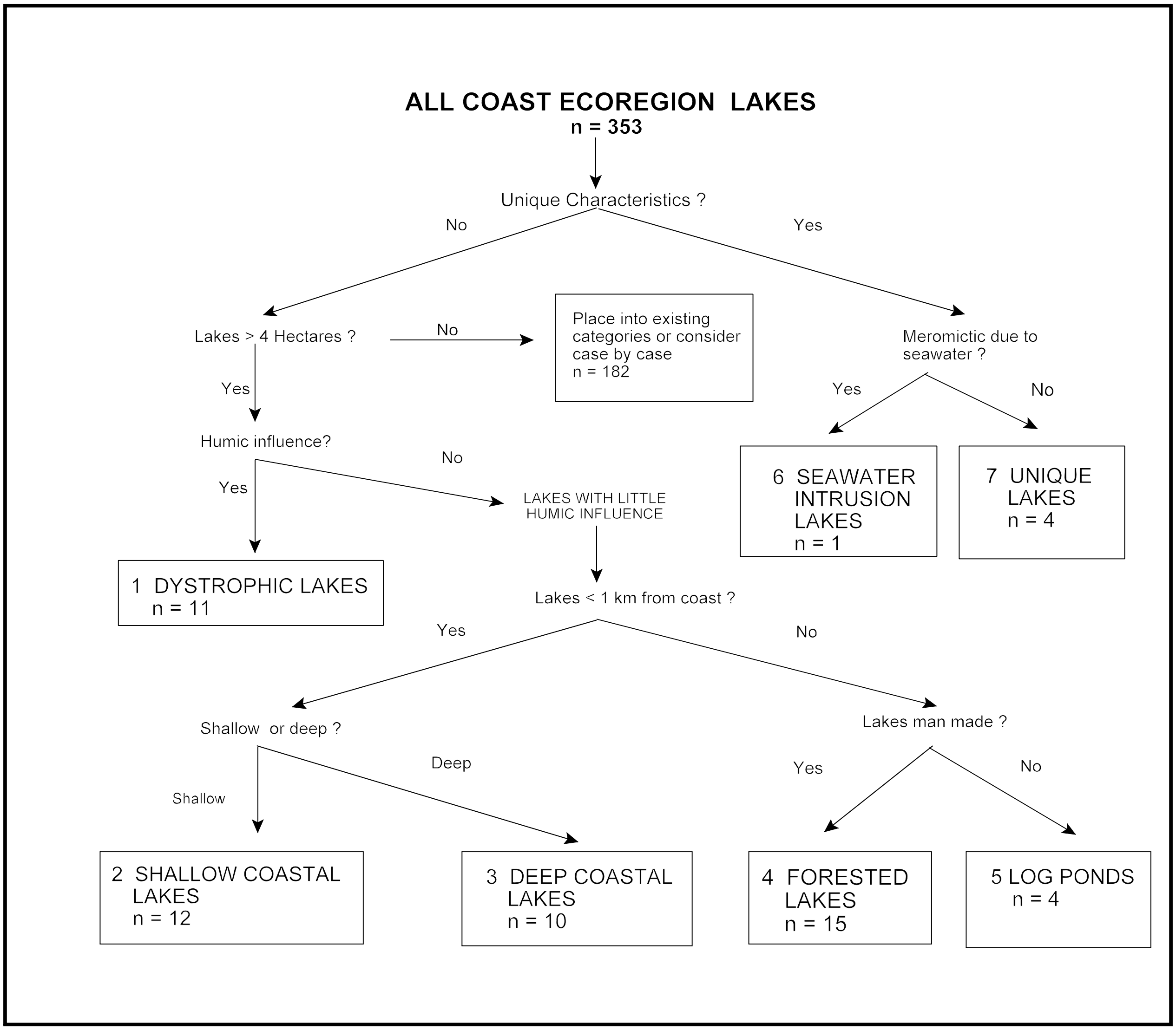


Figure 3-1. Schematic illustrating the characteristics used to categorize lakes in the Coast Range Ecoregion. The number of lakes in each category is also shown. See text for explanation.

Category 1: **Lakes with significant dystrophic influence.**

Lakes in this category are relatively small and have a watershed with a significant amount of wetlands (Table 3-1). The primary causal factor of the designation is the presence of large to moderate concentrations of dissolved "humic" materials. The immediate effect of the humic materials is to limit water transparency, although other effects may also be important (Williamson et al. 1999). For some of the lakes (Cullaby, Clam) this lack of transparency is almost certainly sufficient to bring about light limitation of primary production. The remaining lakes may be less prone to light limitation in spite of the presence of significant dissolved organic matter as a consequence of their very shallow depth.

These lakes are also characteristically shallow (maximum depth of 7 meters or less). Cultural eutrophication influences vary from very little to strong. These lakes can be either strongly dystrophic (highly colored, e.g. Clam Lake, Creep and Crawl Lake, Cullaby Lake, Long Lake or have a somewhat lower dystrophic influence (colored, e.g. Freshwater Lake, Island Lake, Sunset Lake, Failor, Wentworth).

There is some tendency for loss of oxygen near the bottom of each of these lakes, i.e. clinograde oxygen profiles. It is likely that the tendency for low oxygen at depth is a result of decomposition of the relatively high concentration of dissolved organic matter.

Category 2: Shallow Coastal Lakes.

The defining characteristics of these lakes are their shallow mean depth, large surface area and frequent exposure to strong coastal winds, resulting in polymixis (Table 3-1, Fig. 3-2). Mean depth ranges from 1 to 3 meters. The lakes mix frequently and are stratified only weakly and for short periods. Not surprisingly, they remain well oxygenated from top to bottom. Water transparency, as measured by the Secchi disk, is sufficient that light limitation of primary production is not probable in these shallow lakes.

Cultural eutrophication influences vary from slight to moderate.

Category 3: Deep Coastal Lakes.

Lakes in this category have a large surface area and are sufficiently deep (mean depth greater than 4 meters) to stratify during the summer and are accordingly designated "Deep Coastal Lakes". Each of these lakes lies in a basin formed by sand dunes (still

Figure 3-2. Location of lakes in the Coast Range Ecoregion that were placed into one of the seven lake categories.

Table 3-1. List of lake categories, number of lakes in each category (n) and mean lake area ± 1 sd.

No	Lake Category	n	Mean Area (ha)
1	Dystrophic Lakes	11	32.1 ± 34
2	Shallow Coastal Lakes	12	293.6 ± 280
3	Deep Coastal Lakes	10	158.4 ± 122
4	Inland/Forested Lakes	15	114.6 ± 123
5	Log Ponds	4	16.5 ± 10
6	Seawater Intrusion Lakes	1	53.1 ± -
7	Unique Lakes	5	2123.5 ± 577

active in some cases). Each of the lakes in this category develops pronounced thermal stratification during the summer. The depth of the thermocline at the height of summer stratification is conspicuously related to the degree of exposure to the typical coastal northwest wind. The most protected of the lakes, Laurel Lake, develops a thermocline at about 4 or 5 meters, as do the central and northern basins of Collard Lake. The southern basin of Collard Lake and Sutton Lake are more exposed and each develops a thermocline at about 7 meters. The most wind-exposed lake, Woahink Lake, develops a thermocline at 16 to 17 meters.

The watershed of each of the lakes includes a number of residences although eutrophication effects are not obvious.

Category 4: **Inland and Forested Lakes**

Lakes in this category are located in the Coast Range of Oregon and the Olympic Peninsula of Washington and are typically surrounded by hills covered with native forest, mostly second growth (Fig 3-2). Most are not directly influenced by coastal winds. Surface area varies widely (Table3-1).

There are many residences on the immediate shore of Triangle Lake and Pleasant Lake but few or no residences in the watershed of the others. Rink Creek and Ollala are water supply reservoirs, and experience changes in surface elevation depending on precipitation and demand for water. Because of the considerable number of residences around Triangle Lake, it might be anticipated that this lake would be more eutrophic than the other lakes.

Category 5: **Log Ponds.**

Each of these lakes is actually an abandoned log pond. They were originally constructed by excavation and dike construction, resulting in small shallow basins. Although they owe their origin to their use as log ponds, none have been used for that purpose for many years. The ponds are still cluttered with debris from their original use: scattered logs and branches. Each is shallow, weedy and surrounded by re-grown alders.

These ponds are small and too shallow to stratify, but nevertheless oxygen was sometimes depleted (Table 3-1). At the time of sampling, Johnson Log Pond was less than 50% saturation throughout the water column. Lake Creek exhibited very low oxygen in the deepest half meter of water, and Vernonia Pond was about 25% less than saturation from top to bottom.

The ponds are now used by anglers, but without any "official" developed boat ramp. Currently there is no evidence of activities in the watershed that might contribute high nutrient concentrations in water flowing into the lakes. However, each receives considerable use by anglers and all show evidence of a history of heavy impact from their prior use as a log pond.

Category 6: **Sea water intrusion.**

This category consists of a single lake, Garrison Lake, which contains a very high concentration of sea water from a recent intrusion during a winter storm. (The lake would probably be grouped with Category 3 without the seawater intrusion.) The intrusion of salt water has produced a meromictic lake with predictable consequences. The monimolimnion is anoxic and highly saline. Depending on the date of sample collection, the chemocline may be supersaturated with oxygen or under saturated.

In terms of its location and morphology, Garrison Lake could be expected to share the same characteristics as "category 2", or more likely, "category 3" lakes (Fig. 3-2). Indeed, data from earlier years suggest such an assignment. However, a major winter storm overtopped the dunes bordering the western side of the lake, introducing a large amount of seawater into the lake. The seawater remains in the deeper northern basin of the lake as a very heavy deep layer, or monimolimnion, at the bottom of the lake. For the last 2 years, the lake has not destratified at any time, and is therefore clearly an example of a monomictic lake. The very strong stratification and the presence of a chemocline have introduced a novel influence to the lake and make it distinctive among the lakes in this sample. The monimolimnion is completely anoxic. Oxygen profiles are sometimes positive heterograde, with a considerable supersaturation (with respect to surface atmospheric pressure) accumulating in the chemocline. Nutrient values in the monimolimnion are apparently very high. No data are available on the presence of reduced chemical species such as sulfide or ferrous iron, but it is likely that such species are accumulating. The present meromictic condition is likely to persist for a very long time, with the accumulation of more reduced chemicals in the monimolimnion.

Based solely on water quality characteristics of the mixolimnion, Garrison Lake could be described as mesotrophic, and similar to lakes in "Category 3". However, the presence of the very high nutrient concentrations in the monimolimnion and very high oxygen and chlorophyll, at times, in the chemocline defy such a classification. Any reasonable designation useful for setting nutrient criteria for the lake will need to take the present meromictic character of the lake into account.

Category 7: Unique, Very Large Lakes

These lakes are lakes that cannot be placed into any of the other six categories due to their unique nature, primarily large surface area and depth (Table 3-2). For example, Lake Crescent (2,004 ha) has a mean depth of 92.8 meters and Secchi transparencies that typically exceed 15 meters. Lake Ozette (3007 ha) has a mean depth of 38.4 meters but due to dystrophic influences Secchi transparency seldom exceeds 3.5 meters.

CHAPTER 4. ANALYSIS OF WATER QUALITY DATA

4.1 Introduction

We combined data for Coast Range lakes collected in the 1999 - 2000 sampling with the large 1,000+ site historical database for Region 10 lakes described in an earlier report (Vaga and Helihy 2004).

For regional analysis of the lake data, a single value was created, the summer lake index value, for each lake and parameter. Only surface data collected between May and October (inclusive) were used. For a given parameter a lake index value was calculated by first taking the median for the parameter for each year and for each unique lake sample location in each lake. A median value for each sample location was calculated by taking the median across all the yearly medians. The final lake summer index value was then taken as the median of all the median site location values for all sites on each lake. For lakes with only one sample site, the index value is simply the median of all the yearly median surface May-October data. Medians were used instead of means to minimize the influence of large outliers. By taking yearly and station medians at each lake we minimized the influence of large sample sizes in just one year or one particular sampling location.

To investigate relationships among parameters, a monthly median parameter value for each lake was calculated by taking the median across all lake stations by year and month (Appendix Table 3). Lakes from the historical data set were classified into one of the seven categories described in Section 3 (57 of 71 lakes).

4.2 Ecoregional Patterns

Median Ecoregional values of water quality parameters were indicative of mesotrophic conditions. For the 71 lakes for which water quality data exist, median Total P was 15 µg/L, Total N 270 µg/L, Secchi depth 3.4 m and chlorophyll 4.9 ug/L (Table 4-1). Interquartile ranges were small, as compared with the median values.

There were strong relationships between parameters across lakes (Table 4-2). Regressions of log-transformed monthly means were highly significant in all cases.

Total N increased with Total P across all lakes (Fig. 4-1). Total P ranged from <1 ug/L to over 100 ug/L and Total N from less than 20 ug/L to over 1 mg/L. Monthly median chlorophyll increased with Total P concentrations across lakes but there was large amount of scatter in the data (Fig. 4-2). There was a strong decrease in Secchi depth with increasing chlorophyll concentrations (Figs. 4-3).

There was also a strong relationship between and Secchi depth and Total P

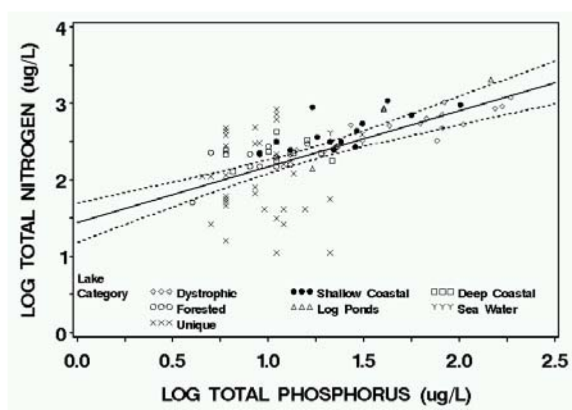


Figure 4-1. Relationship of monthly median Total N and Total P across all lake categories. There was a clear increase in Total N with Total P. Regression is for all data. Dashed lines are ± 95% confidence envelope.

Table 4-1. Summary of summer index 25th percentile, median and 75th percentile values for all lakes in the Coast Range Ecoregion and lakes in each lake category. The number of lakes (No) refers to the Total Number of lakes having Total P data. For comparative purposes 25th percentile values Ambient Water Quality Criteria Recommendations are also presented for the Western Forested Mountains and Coast Range Ecoregions (Level III) (EPA 2000).

Cat	Category Name	No	Total P (ug/L)			Total N (ug/L)			Chl (ug/L)			Secchi (m)		
			25th	Med	75th	25th	Med	75th	25th	Med	75th	25th	Med	75th
	All Lakes	71	10.0	15.0	26.0	180	270	520	2.2	4.9	10.3	2.0	3.4	4.2
1	Dystrophic	11	71.8	81.0	159.3	530	650	940	7.7	16.6	25.5	0.6	0.9	1.3
2	Shallow Coastal	12	15.0	22.8	26.8	250	320	638	0.8	6.1	7.8	1.9	2.0	2.5
3	Deep Coastal	10	9.8	11.5	18.0	160	220	230	2.2	2.4	4.2	4.0	4.5	5.6
4	Inland/Forested	15	9.5	10.0	15.0	150	225	280	2.1	4.6	7.3	3.0	3.9	4.2
5	Log Ponds	4	27.5	39.0	92.0	495	875		7.6	7.6	7.6	1.0	1.0	2.0
6	Sea Water Intrusion	1	-	30.0	-	-	365	-	-	3.3	-	-	3.2	-
7	Unique	4	8.4	9.6	11.3	64	105	140	0.4	1.1	10.2	3.8	10.1	17.4
Western Forested Mtns.		296	8.8	-	-	100	-	-	1.9	-	-	4.5	-	-
Coast Range Ecoregion		71	10.0	15.0	26.0	180	270	520	2.2	4.9	10.3	2.0	3.4	4.2

* Values from Table 2, Reference conditions for Nutrient Ecoregion II lakes, Western Forested Mountains. (EPA 2000).
** Values from Table 3a, Reference conditions for Level III ecoregion I, Coast Range Ecoregion. (EPA 2000).

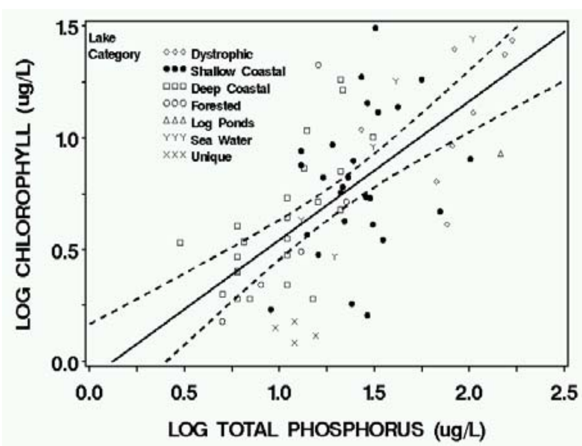


Figure 4-2. Relationship of monthly median chlorophyll to Total P across all lake categories. There was significant scatter of the data.

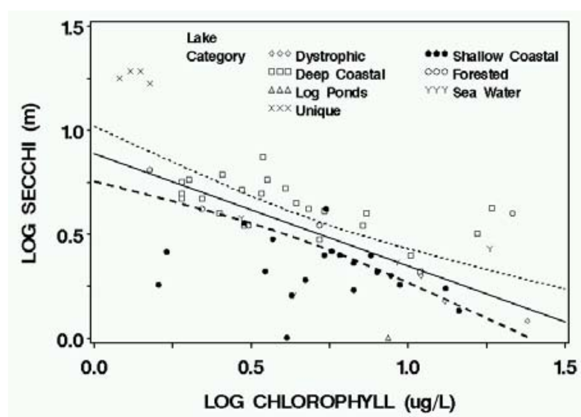


Figure 4-3. Median monthly Secchi versus Total P. There was a general decrease in Secchi with increasing Total P. Data for Deep Coastal lakes tended to fall above the line whereas Shallow Coastal lakes fell well below the line.

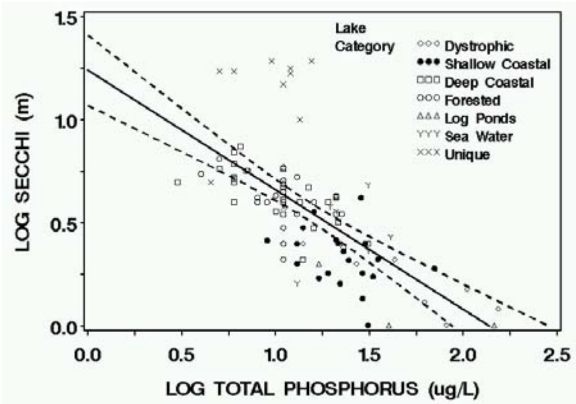


Figure 4-4. Median monthly Secchi versus Total P across lake categories. Secchi generally decreased with increasing Total P. Shallow Coastal lakes tended to fall below the line.

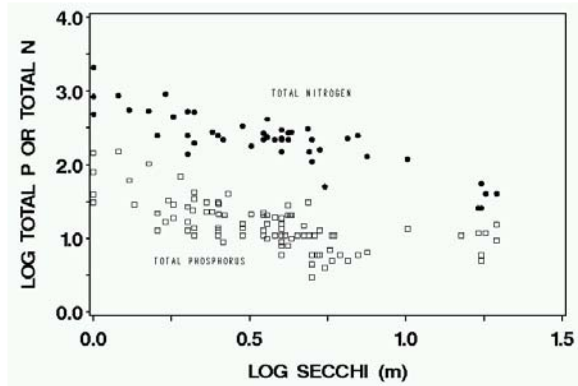


Figure 4-5. Relationship between Secchi Total P and Total N. Sechhi decreased in a similar fashion with both nutrients.

Table 4-2. Regression statistics for log-transformed water quality parameters. Values are monthly means. * - intercept not significantly different from zero. All slopes significant ($p < 0.001$).

Dep Var	Ind Var	N	slope	int	r^2
LogTN	Log TP	63	0.558	1.77*	0.68
LogChl	LogTP	68	0.58	0.04*	0.45
LogSecchi	LogTP	113	-0.55	1.12	0.63
LogChl	LogSecchi	114	-0.45	0.76	0.42
LogChl	LogTN	51	0.68	-0.92	0.2
LogSecchi	LogTN	45	-0.71	2.22	0.56

(Figure 4-4). It should be noted that all of the high Secchi depth readings (≥ 15 m) come from Crescent Lake in Olympic National Park and are definitely outliers in the TP-Secchi plot in Figures 4-3, 4-4. Interestingly, while they are at the extreme end of the TN-Secchi plot in Figure 4-5, the high Secchi depth Crescent Lake data fit right on the line with the rest of the data. This is most likely due to the fact that the Total P concentrations are actually much lower than reported, i.e. detection limits were reported. In that event the Total P data would fall onto the TP - Secchi line.

4.4 Patterns in Coast Range Lake Categories

In Chapter 3 a lake categorization scheme was proposed for lakes in the Coast Range Ecoregion. We classified each of 71 lakes into one of the seven categories and looked at how the nutrient parameters varied among categories. The seven categories along with how many sample lakes we had in that category are given in Table 4-1.

In analyzing patterns across lake categories we used Lake Crescent to represent the Unique category, since it represents a truly unique water body.

There were clear differences in median Total P values among lake categories, as well as in the range of values (Fig. 4-6). Total P

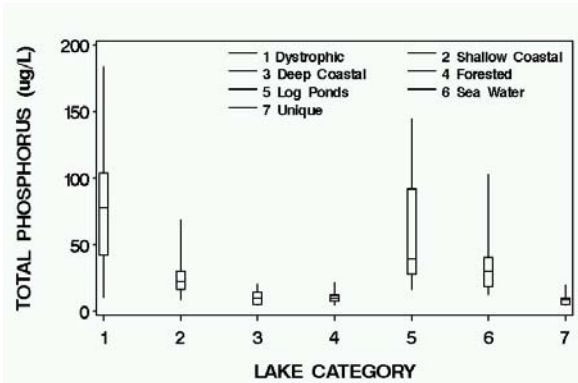


Figure 4-6. Distribution of summer index Total P values by lake category. There were clear differences among the categories.

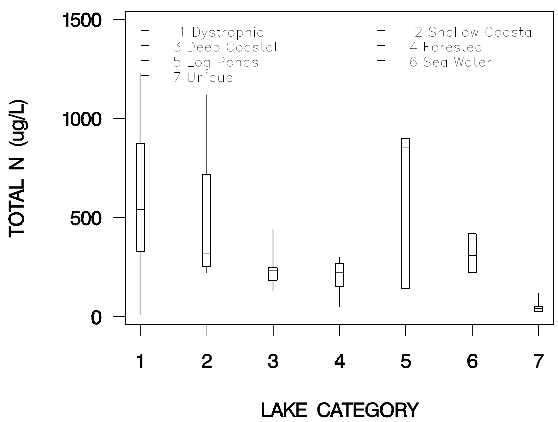


Figure 4-7. Distribution of summer index Total N values by lake category. There are clear differences among lake categories.

values were lowest in the Category 7, i.e. Lake Crescent. The Deep Coastal and Forested categories had slightly higher median Total P values but virtually all the lakes in these groups had TP < 30 µg/L. Shallow Coastal lakes had intermediate Total P concentrations and occasionally values over 50 ug/L. Lakes in the Dystrophic and Log Pond category had the highest TP concentrations and a much larger range. Lakes in these categories vary from oligotrophic to hypertrophic, i.e.

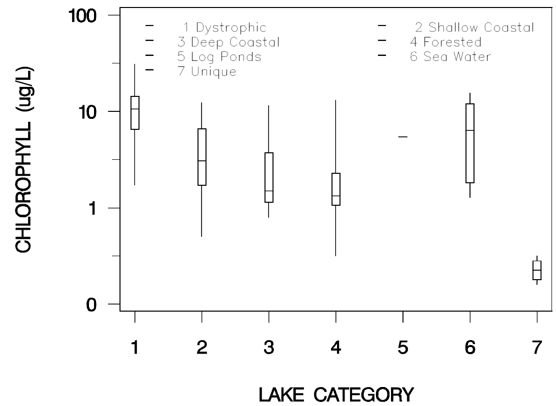


Figure 4-8. Distribution of summer index Chlorophyll values by lake category. The differences among lake categories are not as distinct as for nutrients.

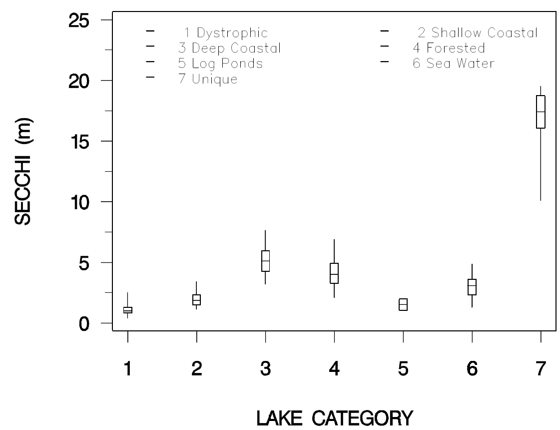


Figure 4-9. Distribution of summer index Secchi depths by lake category. There are clear differences among lake categories which rougly correspond to catetory nutrient levels.

Total P concentrations ranged from less than 20 ug/L to over 150 ug/L.

Total N values showed a pattern similar to that for Total P (Fig. 4-7).

Chlorophyll concentrations roughly approximated nutrient concentrations among the lake categories but the differences were not as distinct (Fig. 4-8).

Category 7 (Lake Crescent) had very low chlorophyl concentrations whereas Dystrophic lakes had the highest. It is interesting to note that Dystrophic lakes had the highest chlorophyll concentrations even though these lakes have the lowest water transparency due to humic materials.

As would be expected given these patterns in nutrient levels, Secchi depths were highest in Lake Crescent (Fig. 4-9). The next highest Secchi depths were in the low nutrient Deep Coastal and Forested categories. Secchi depths in the Dystrophic and Log Pond classes were low, mostly between 0.5 and 2.5 m. This is likely due to the colored water associated with the dystrophy/logging history of these categories. In general the Shallow Coastal lakes had slightly higher levels of nutrients than the Deep Coastal lakes and a shallower Secchi depth. The latter may be a function of the shallowness of these lakes.

Total N to Total P ratios generally were greater than 10 (by mass) for most lakes categories (Fig. 4-10). Interestingly Dystrophic lakes and Lake Crescent (category 7) showed some evidence of nitrogen limitation. Even if Total P concentrations were reported at a detection limit of 10 ug/L for Lake Crescent, a value of 5 ug/L Total P would still put that lake on the border of nitrogen limitation.

In order to test whether the nutrient-stressor relationship was consistent across categories, we regressed the same parameters as for the entire Ecoregion by lake category. Generally, there too few data to draw any conclusions within any lake category. For those categories that had sufficient data, regression statistics were similar to those for the Ecoregion as a whole. However, additional data may show that lakes in different categories do show differences in these statistic, as indicated by relationships in Figure 4-4.

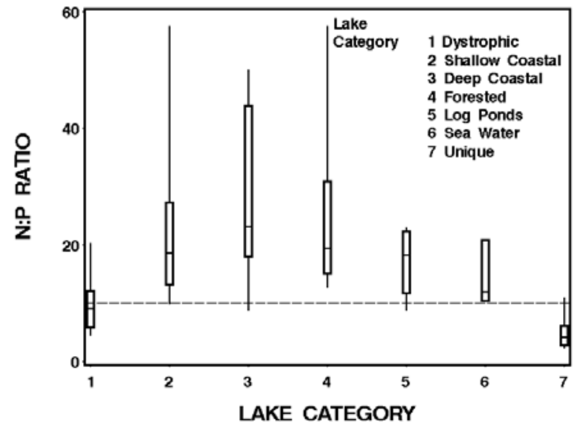


Figure 4-10. Total N to Total P ratios by lake category. The horizontal line represents an N:P ratio of 10 by mass.

4.2 Temporal Variability in 1999-2001 Lake Data

As part of the probability lake study in the Coast Range Ecoregion, some of the lakes were visited more than one time during the 1999-2000 sampling and during additional visits in 2001. We can use this information to quantify temporal variability in lake nutrient parameters that will be useful in calculating the power of classifying groups and in trend detection. We restricted the analysis to surface water chemistry samples collected between May and October as that is the data that we are using to index lake conditions. To quantify the temporal variability, we calculated a grand mean, pooled standard deviation and coefficient of variation (CV) using all the lakes that had multiple visits. The pooled standard deviation is calculated by calculating a mean and variance for each individual lake based on all the revisit data, summing all the individual lake variances together, dividing by the appropriate degrees of freedom and then taking the square root to get a standard deviation. The grand mean is just the mean of all the individual lake means and the CV is the pooled standard deviation divided by the grand mean expressed as a percent. TP and chlorophyll-a had the most variability with CV of 63% and 55% (Table 4-3) and the pooled standard deviation for TP was 9.6 µg/L. TN had the lowest CV (7%) whereas Secchi depth had a CV of 23% based on a pooled standard deviation of 1.2 m. If the concentrations observed in the repeat data are around the concentration of interest, the pooled standard deviation is a good indicator of the amount of variability that is likely to be found in taking one measurement as an index of site conditions.

Table 4-3. Pooled standard deviation and coefficient of variation for data collected from sample lakes with repeat visits in the 1999-2001 probability survey. Only water chemistry data collected from the top depth and data collected during May-October were used in calculations. No - number of lakes, sd - standard deviation, cv - coefficient of variation.

Variable	No	Grand Mean	Sd	CV
TotalP (ug/L)	10	17.5	9.6	55%
Total N (ug/L)	5	272	19.2	7.1%
Secchi (m)	8	5.03	1.16	23%
Chlorophyll-a (µg/L)	10	5.46	3.41	63%
Maximum Profile DO (mg/L)	15	9.81	2.2	23%
Maximum ProfileTemp (°C)	16	19.1	1.48	7.7%

4.3 DISCUSSION

Value of Lake Categories

Data presented here suggest that Level III Ecoregion is not always sufficient as a stratification variable in the development of numeric nutrient criteria for lakes. The distributions of nutrient criteria parameters (Total P, Total N, Secch and chlorophyll) in all lake categories were substantially different than the values derived for either the Nutrient Ecoregion or the Level III Coast Range Ecoregion (Table 4-1). Although future investigation may permit the combining of certain lake categories, different lake types with respect to basic limnological character and processing of nutrients should be taken into account in any such effort. For example, Total P and chlorophyll values were similar for Shallow and Deep Coastal lakes but water transparency was much different (Figs. 4-6, 4-8, 4-9. This difference was mostly likely due to the nonalgal turbidity in Shall Coastal lakes that results from wind driven mixing and subsequent resuspension of sediment.

The pooled standard deviation for nutrient variables suggests that within any given lake category variability may be relatively small (Table 4-3). Thus the sample sizes required to test whether any given lake deviates from the observed distributions for nutrient parameters may be relatively small.

The need for developing Total N criteria may also be lake category dependent. Only two categories (1 and 7) indicated the possibility for nitrogen limitation (Fig. 4-10).

On the other hand, the diversity of lakes found in the Coast Range Ecoregion may not hold for other Ecoregions. For example, Vaga and Herlihy (2004) found that in several Ecoregions, nutrient concentrations in lakes were quite consistent. For example, there are a total of 455 lakes ≥ 4 ha in surface area in the North Cascades Ecoregion. In a sample of 189 lakes the median Total P concentration was found to be 11.3 ug/L (25th percentile of 2.6 and 75th percentile of 11.3 ug/L) (Vaga and Herlihy 2004). Thus the hereogenity of lake types should be investigated by Ecoregion prior to determining their nature regarding nutrient processing.

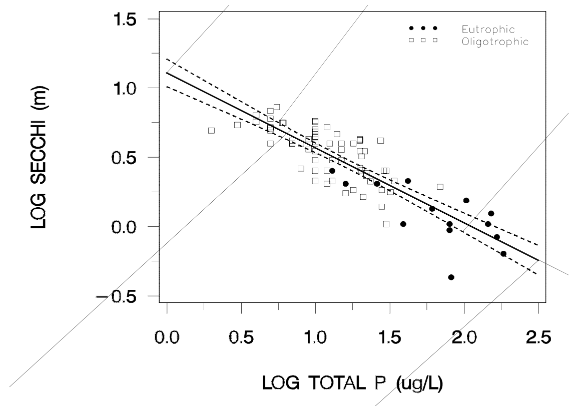


Figure 4-10. Relationship of median monthly Secchi to total P (log-log) for lakes that are clearly meso-oligotrophic and lakes that are eutrophic. The data tend to fall on the same line but segregate according to trophic group.

Evaluation Lake Category versus Trophic Status

The lake categories have been constructed based on a subjective impression of overall limnological character. The extent to which the trophic conditions in the lakes are correlated with those subjective categories can be evaluated by comparing the various limnological measures of trophic conditions collected from each of the lakes. The EPA manual identifies a number of "candidate variables" (Chapter 5 of Manual) for evaluating lake trophic status. The candidate variables include: phosphorus and nitrogen species, chlorophyll, water transparency (Secchi disk depth), hypolimnetic oxygen concentration and mixing type. The lake categories identified here can be compared across these candidate variables as a means of testing the validity of such categories. If the categories have any value, they should serve to predict, in some sense, the range of conditions across the variables, independently of degree of human disturbance. If the categories prove useful in this sense, the results would suggest that lake category should be considered in setting nutrient criteria for monitoring lakes for undesirable impacts. As a means of comparison, the data available are listed for each of the suggested lake categories.

Again, it is important to recognize that the amount of data available is insufficient to conduct any proper statistical test of the differences among the categories. The evaluation is attempted only in the sense of using local "expert opinion" as a means of identifying lakes which might serve as illustrating "reference conditions" and "water body categories".
In summary, it may be seen that trophic status of the lakes in this sample might be predicted to some extent based on "Lake Category". It is of course obvious that the categories suggested here are clearly arbitrary in that they were created based on the sample of less than 50 lakes. However, the descriptions of the "categories" are related to more fundamental lake characteristics such as mean depth or concentration of allochthonous organic matter that might be employed for establishing a more objective lake classification.

The seven lake categories were found to be generally in accordance with expectations regarding trophic state. By any measure, Dystrophic lakes (category 1) are eutrophic. Nutrient concentrations are very high (characteristic Total Phosphorus of 81 ug/L, Total Nitrogen of 650 ug/L), chlorophyll is relatively high (characteristic value of chlorophyll a of 16.6 ug/L) and water

transparency is limited (characteristic Secchi depth of 0.9 meter) . However, the eutrophic status of these lakes occurs without, in most cases, direct evidence of cultural eutrophication. Freshwater Lake, Clam Lake, Creep and Crawl Lake, Long Lake, Failor Lake and Island Lake are nearly pristine, with very little human disturbance of their watershed, and only low impact recreational use. There are several residences on the shore of Cullaby Lake, however, those residences are served by a sewer and treatment plant that diverts effluent away from the lake. Only Sunset Lake is subjected to the direct impact of cultural eutrophication. Many residences, served by septic tanks, are located along the western shore of the lake on a very porous substrate (a relict sand dune), and much of the eastern shore of the lake is bordered by a golf course that is fertilized and irrigated. It can be seen in the data that Sunset Lake does not stand out among the Category 1 lakes in spite of a notably higher level of human disturbance in its watershed.
Shallow Coastal lakes (category 2) are mesotrophic. Nutrient concentrations, chlorophyll a concentrations, water transparency, and oxygen concentration all indicate the same interpretation (Table 4-1). Each of these lakes is a popular recreation lake, but impact is apparently relatively light. There is very little motorboat traffic on Smith Lake and Coffenbury Lake, whereas Lake Lytle and South Tenmile Lake are more heavily used. Only South Tenmile Lake has a significant number of residences in its watershed. The watershed of Tenmile Lake is also modified by recent logging and ongoing agricultural activities. Differences among the lakes appear to be slight. Since none of these lakes could be argued to be pristine, their "natural" trophic condition remains undefined. However, given their shallow depth, their mesotrophic status is not surprising.

In overall appearance, Deep Coastal and Forested (categories 3 and 4) are the most nearly oligotrophic group of the lakes. The concentrations of phosphorus (Total P, 10 - 11.3 ug/L) and nitrogen (Total N, 220 - 225 ug/L) suggest a mesotrophic status, and are lower than other lakes. Chlorophyll concentration (characteristic values, 2.4 - 4.6 ug/L) and water transparency (characteristic Secchi disk depth, 3.9 - 4.5 meters) also suggest a mesotrophic status for these lakes (Table 3-1). There are a number of residences located within the watershed of many of the lakes, although the potential impact on the lakes has not been evaluated. The distinctly clinograde oxygen profile that develops in each of these lakes would seem to suggest possible impacts on the lakes and that the trophic status of the lakes may be more eutrophic than indicated by other characteristics. However, similar lakes in the region (not included in this survey) that have no housing in their watershed and very little human disturbance of any kind have also been observed to develop clinograde oxygen profiles. Given the very porous soils (relict sand dunes) bordering some of these lakes, it is likely that groundwater moves relatively freely into the lakes and may be in part responsible for the clinograde oxygen profiles. In this case, the clinograde oxygen profiles are *not* considered to indicate eutrophic conditions.

The Inland/Forested lakes (category 4) and Log Ponds (category 5) are mesotrophic (characteristic Total P, 39 ug/L, characteristic Chl a , 7.6 ug/L; characteristic Secchi depth, 1 m). There is a tendency for loss of oxygen with depth. There is not a consistent pattern of stratification for this group of lakes, e.g. Ollala Reservoir and Town Lake are polymictic and Rink Creek Reservoir and Triangle Lake are warm monomictic. Given their history, it is not surprising that these ponds are eutrophic, or in the case of Johnson Pond, hypertrophic. The ponds are very shallow and overgrown with macrophytes in places. Nevertheless, the ponds are popular fishing spots. They lack any "official" boat ramps or other developments but nevertheless attract anglers. There are no residences in the drainage basin of any of these ponds, and no other significant source of disturbance other than the disruption from boat launching where no suitable ramp is available.

The Seawater Intrusions lakes (category 6) represent a unique limnological condition. As such this category is useful primarily for segregating out such water bodies from the scheme depicted in Figure 3-1.

The Unique lakes represent a category that defies classification. These lakes are those that have characteristics that obviously make them unique. Lake Crescent is an example. Not only is its limnological character unique (maximum depth 195 m, Secchi 20 m), there are two endemic trout species in the lake.

Human Disturbance versus Lake Category

Several of the lakes in the overall sample could be described as "pristine" in that there is very little evidence of significant human disturbance of the lake or its watershed. Lakes that could be so described include Clam Lake, Creep and Crawl Lake, Freshwater Lake, and Island Lake. Other lakes are apparently subject to only light disturbance, such as Long Lake, Coffenbury Lake, Smith Lake (McGruder), Sutton Lake, or Town Lake. The lakes which have the most potential for nutrient enrichment from residences in their watershed are Sunset Lake and Triangle Lake. Other lakes with residences in their watershed but probably lesser nutrient enrichment include Cullaby Lake, Lake Lytle, South Tenmile Lake, Collard Lake, Laurel Lake. Lake Pleasant and Woahink Lake. Ollala Reservoir and Rink Creek Reservoir have no residences in their watershed but are likely affected by frequent changes in surface elevation with consequent erosion of their shoreline. The four log ponds, Johnson, McCleary, Vernonia and Lake Creek, are not presently influenced by human disturbance other than fishing but exhibit the effects of their history. Garrison Lake is the only meromictic lake in the sample.

Unfortunately, with the exception of South Tenmile Lake, no quantitative data are available to indicate nutrient loading to any of the lakes. (More extensive studies would be needed to develop a quantitative nutrient budget for the lakes, including the loading that is attributable to human disturbance.) However, the relationship between nutrient concentration observed in the lakes can be compared with the general description in the paragraph above. It is immediately evident that lake "category" is at least equal to human disturbance in predicting nutrient concentration in a particular lake. For example, some of the most "pristine" lakes, Clam Lake and Creep and Crawl Lake, have the highest phosphorus concentration. On the other hand, Triangle Lake, which has at least 50 residences immediately on the lake, has among the lowest phosphorus concentration, and Woahink Lake, with a significant number of residences in its watershed, had the lowest phosphorus concentration.

The most eutrophic lakes, "Category 1", are the lakes with significant dystrophic influence, including some lakes subject to human disturbance but several that can be described as pristine. Less surprising is eutrophic status of the "Category 5" lakes: relict log ponds. Among the most transparent lakes in this sample, Woahink Lake and Triangle Lake, are lakes that are clearly subject to some nutrient enrichment from human disturbance. In short, it seems apparent that trophic status among the lakes in this sample is largely determined by factors not related solely to human disturbance. There is considerable variation among the lakes, all from the same Level III Ecoregion.

It must be acknowledged that the "categories" of lakes described here are arbitrary, and developed based on the overall appearance of each lake and its watershed. It is probable that such a subjective procedure will be influenced by circular reasoning. For example, Sunset Lake was placed among "Category 1", humic influenced lakes, where its concentration of phosphorus and chlorophyll and water transparency are characteristic values among the lakes in the category. The placement was based on the concentration of organic matter in the lake. Had Sunset Lake been placed with "Category 2", shallow coastal lakes, it would be the most eutrophic lake in the category. Arguably, the organic matter could be attributed to autochthonous sources resulting from the nutrient enrichment from the surrounding residences and the golf course. Nevertheless, it should be apparent that for this sample of lakes, location in a particular Level III Ecoregion is not a sufficient predictor of expected trophic status in the absence of human disturbance. Setting protective nutrient criteria standards will require recognition of the important natural influences on lake trophic status independent of the effects of human disturbance.

Lake Category versus Level IV Ecoregion

All of the lakes in this study are in the Level III Coast Range Ecoregion. Recently Level IV Ecoregions have been developed that refine Level III Ecoregions (Ref). There are nine Level IV Ecoregions in the Coast Range Ecoregion (Fig. 4-11).

There appears to be some correspondence between lake category and Level IV Ecoregion (Table 4-5). However, there are too few lakes that have been assigned a category to ascertain any general pattern. However, it is clear that even Level IV Ecoregions contain more than one lake type. For example, the Coastal Lowlands contain representatives of all lake categories (Table 4-4, Fig. 4-11).

Nevertheless the Level IV Ecoregions do provide a geographic structure with which to segregate lake types for further investigation. For example, Ecoregion 1a (Coastal Lowlands) has the greatest density and number of uncategorized lakes (Table 4-4). It apparently also has the highest diversity in lake type. This suggests that this Level IV Ecoregion would provide the greatest benefit from further effort in lake categorization.

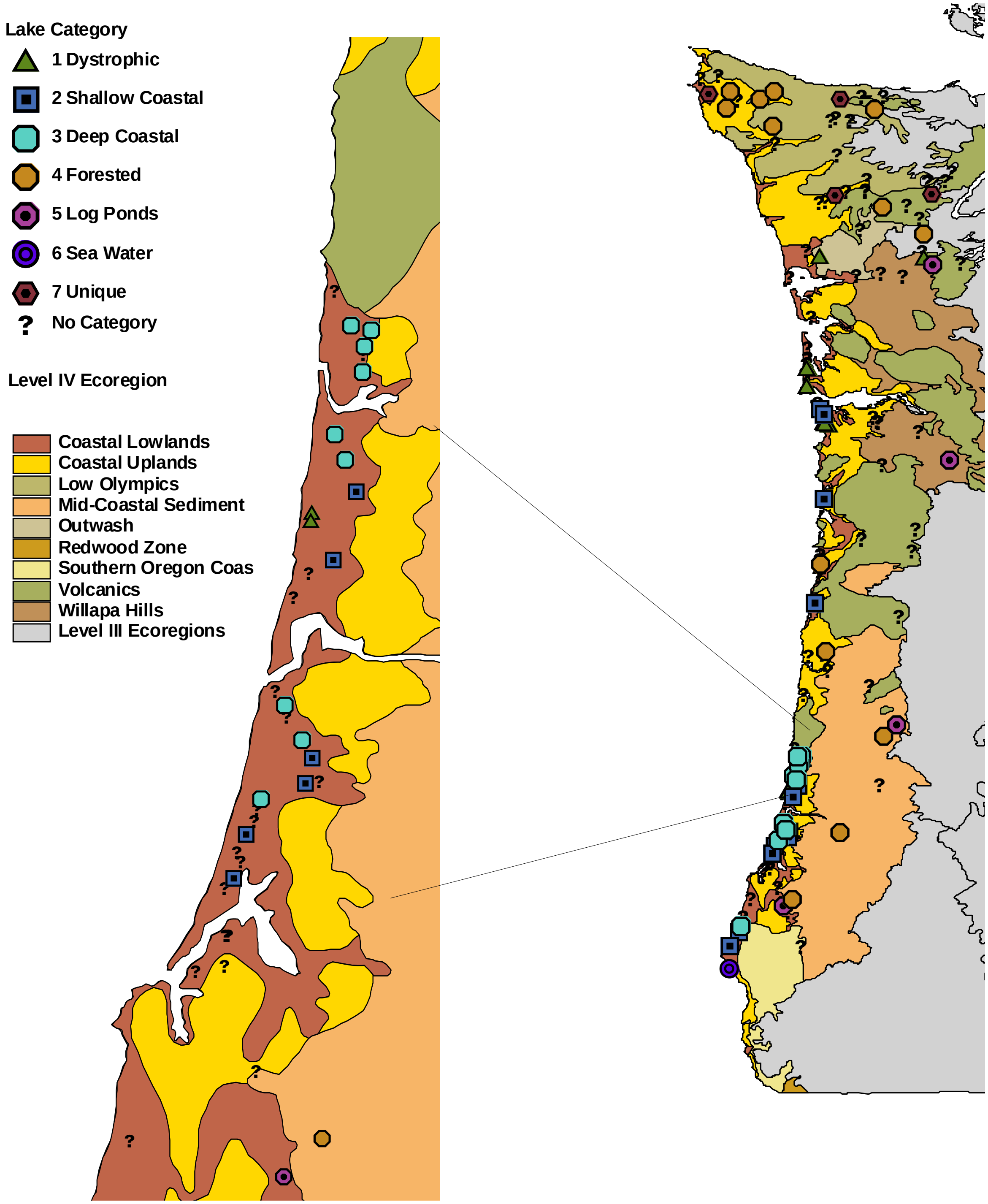


Figure 4-11. Locations of lakes by category in the Coast Range Ecoregion. Level IV Ecoregions are also shown. Most lakes have yet to be categorized. The inset shows detail of three different lake categories (and uncategorized lakes) in the Coastal Lowlands Ecoregion.

Table 4-4. Total Number of lakes in each Level IV Ecoregion and number of lakes in each lake category by Level IV Ecoregion. The areas (sq km) of Level IV Ecoregions and density of lakes are also given. Most lakes in this Level III Ecoregion have yet to be assigned a category. N - number of lakes, Dn - lake density (N/sqkm x 1000).

Level IV Ecoregion	Area	N	Dn	1	2	3	4	5	6	7
Coastal Lowlands	2531	96	37	8	11	10	1	1	1	1
Coastal Uplands	6739	27	4.0	-	1	-	4	-	-	1
Low Olympics	4361	13	2.9	-	-	-	4	-	-	1
Volcanics	9265	17	1.8	-	-	-	-	-	-	1
Outwash	917	4	4.4	1	-	-	1	-	-	-
Willapa Hills	5258	12	2.3	1	-	-	-	2	1	-
Mid-Coastal Sed	9675	12	1.2	-	-	-	3	1	-	-
So Oregon Coast	1793	1	0.6	-	-	-	-	-	-	-
Redwood Zone	81	0	-	-	-	-	-	-	-	-

5. NUMERIC NUTRIENT CRITERIA DEVELOPMENT AND BENEFICIAL USES

5.1 Introduction

EPA guidance recommends using Total P, Total N, chlorophyll and Secchi to set numeric nutrient criteria (EPA 2000). In the preceding chapters lakes in the Coast Range Ecoregion were inventoried according to location and size, classified according into seven types based upon basic limnological principles and then characterized with respect to nutrients, chlorophyll and Secchi transparency.

In this chapter we illustrate two potential ways in which the classification scheme, coupled with water quality data, could be linked to designated uses to develop numeric criteria. The following discussion is meant to be illustrative only, i.e. not an exhaustive exploration of the various ways in which lake categories, numeric nutrient criteria and beneficial uses can be linked. The illustration shows that numeric nutrient criteria cannot be developed on the basis of empirical models alone. Development of such criteria require judgements as to how protective to make the standards.

5.2 Beneficial Uses

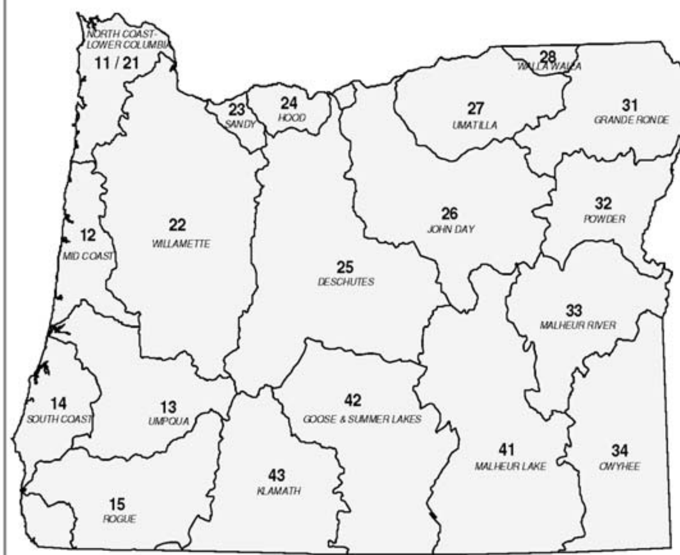
To illustrate the development of numeric criteria we will use the lake classification scheme presented in Chapter 3, beneficial uses defined in Oregon's water quality standards (OAR Chapter 340) and available water quality data. Table 5-1 lists the beneficial uses for estuaries, adjacent marine and all streams in the North Coast-Lower Columbia Basin. By implication lakes and reservoirs are included in the streams category. There are four regulatory basins in Oregon that overlap the Coast Range Ecoregion (Fig. 5-1). All of those basins have the same beneficial uses for lakes and reservoirs. Thus all lakes in the Coast Range Ecoregion have essentially all beneficial uses.

5.3 Reference Condition Approach

One approach suggested in the Technical Guidance Manual is that of a reference condition approach (EPA 2000). In this method a standard for Total P is developed relative to a reference condition. The reference condition is defined as a percentile of Total P concentrations in a set of reference lakes (least impacted).

The 25^{th}, median and 75^{th} percentiles for summer index Total P, Total N, chlorophyll and Secchi were calculated (as described in Chapter 4) for all the lakes in the Coast Range ecoregion and by lake category (Table 4-1, Figs. 4-6,9). It is evident that medians and percentile values for most parameters for each lake category are different from those of the lake population as a whole. Therefore using all lakes to define reference values would not be justified. The same conclusion holds for using values derived for Aggregate Nutrient Ecoregion II (Western Forested Mountains) (Table 4-1). For example, the 25^{th} percentile for Total P (8.8 ug/L) would be appropriate for only two of the six categories (leaving out the unique lakes). Therefore for purposes of setting reference conditions in this Ecoregion, the use of percentiles (or any other statistic) necessitates consideration of differences among lake categories.

Figure 1: Oregon Basin Index Map



Basin Name	Basin #	OAR #
DESCHUTES	25	340-41-0130
GOOSE & SUMMER LKS	42	340-41-0140
GRANDE RONDE	31	340-41-0151
HOOD	24	340-41-0160
JOHN DAY	26	340-41-0170
KLAMATH	43	340-41-0180
MALHEUR LAKE	41	340-41-0190
MALHEUR RIVER	33	340-41-0201
MID COAST	12	340-41-0220
NORTH CST-LWR COL	11-21	340-41-0230
OWYHEE	34	340-41-0250
POWDER	32	340-41-0260
ROGUE	15	340-41-0271
SANDY	23	340-41-0286
SOUTH COAST	14	340-41-0300
UMATILLA	27	340-41-0310
UMPQUA	13	340-41-0320
WALLA WALLA	28	340-41-0330
WILLAMETTE	22	340-41-0340

Figure 5-1. Map showing basins used to designate beneficial uses in the State of Oregon. Basins corresponding to the Coast Range Ecoregion all have the same beneficial uses (OAR 340-41-0230).

Assuming that the lakes included in this analysis are relatively undisturbed (and therefore can be called reference lakes), the 75^{th} percentile of the four parameters could be used as a starting point to set criteria for a given lake category. The 25^{th} percentile appears to be too restrictive for many lakes in this Ecoregion where the reference lakes are largely unimpacted (Table 4-1).

The simplest way to assign corresponding values for the various beneficial uses for each parameter would be to define them *ipso facto*. Thus all the beneficial uses in Table 5-1 would be met as defined by the 75^{th} percentile values in Table 4-1.

Compliance with the standard could then be tested using simple statistical tests for each parameter, e.g. t-test. For example, the difference between median Total P values during the growing season in a given lake can be compared with the 75^{th} percentile of the reference population of lakes.

$$\Delta_i = [(P_{(ref)})-(P_{(lake)})]_i$$

where $P_{(lake)}$ is the median summer index Total P concentration in the

Table 5-1. Beneficial uses in the North Coast basin of Oregon. Essentially all beneficial uses apply to all fresh water in this basin, as well as in all of the Coast Range Ecoregion (OAR 340-41-0230).

Beneficial Uses	Estuaries & Adjacent Marine Waters	All Other Steams & Tributaries Thereto
Public Domestic Water¹		X
Private Domestic Water¹		X
Industrial Water Supply	X	X
Irrigation		X
Livestock Watering		X
Fish & Aquatic Life²	X	X
Wildlife & Hunting	X	X
Fishing	X	X
Boating	X	X
Water Contact	X	X
Aesthetic Quality	X	X
Hydro Power		
Commercial Navigation	X	
¹ With Adequate pretreatment (filtration & disinfection) and natural quality to meet drinking water standards.		
² See also Figures 230A and 230B for fish use designations for this basin.		

lake being tested, $P_{(ref)}$ is the 75th percentile of the summer index Total P concentrations in the reference lakes and (i) the lake category. The value of Δ_i can take on values less than or equal to zero. The criterion, i.e. the value of $P_{(ref)}$, could then be set for the most sensitive beneficial use.

To illustrate this we define a Total P standard for one lake category and one beneficial use: Resident Fish & Aquatic Life Use in Deep Coastal Lakes. In other words, what is the largest value of Δ_i that still protects Resident Fish & Aquatic Life Use in Deep Costal Lakes (Table 5-1). Perhaps the most direct effect of increased nutrient loading on resident aquatic life in a lake is an increase in the areal hypolimnetic oxygen demand (AHOD). The increase in (AHOD) results from the increase in algal biomass and subsequent decay of organic matter in the hypolimnion and sediment surface. In lakes that do not naturally experience periods of anoxia in the sediments, development of anoxia will profoundly change the species composition of the benthos.

In this example if Δ must be $\geq$ 0 zero then the median seasonal Total P (or Total N, Secchi and chlorophyll) in any given lake in this category could not be significantly greater than the 75th percentile of the reference population medians. However, lakes naturally eutrophy so a less restrictive criterion may be more appropriate. Thus an increase of 25% in median seasonal Total P over reference levels might be an appropriate criterion for these lakes, since a change of this magnitude would begin to affect the areal hypolimnetic oxygen deficit.

The size of Type I and Type II error can be defined by the sample size used in the test to determine if diff is significantly different from the 75th percentile. (The power of the statistical test can be made arbitrarily stringent. However the accuracy of the test will be influenced by how well the lake categories have been defined.) This would include specifying the number of samples, frequency, season, etc. For example, the test must be based on 10 Total P samples taken during the growing season not less than two weeks apart.

It is apparent that the relevance and magnitude of Δ_i is dependent upon lake category. Thus for dystrophic lakes which naturally experience prolonged periods of sediment anoxia, the measure of AHOD would be meaningless as a way to link nutrient concentrations to aquatic life use. For polymicitic lakes AHOD would also be of little use, since physical mixing reoxygenates the sediments. In contrast, oligotrophic lakes that thermally stratify are sensitive to increases in nutrient loading so the value of Δ_i should be relatively small.

Lakes in this ecoregion have a Total P to Total N ratio of about 20. Therefore, unless there is a potential for downstream effects, a criterion for Total N may be unnecessary.

5.4 Stressor-Response Approach

An alternative manner in which to set numeric Total P criteria is using a stimulus-response model such as linear regression equations of chlorophyll *a* versus Total P (Fig. 4-2). Table 4-2 provides regression coefficients for four different lake types in the ecoregion. In the example of Resident Aquatic Life in Deep Coastal Lakes, the Total P standard could be set so as to prevent a 25% increase in median chlorophyll concentrations (from 4.3 to 5.4 ug/L) (Fig. 4-2). The lower 95th percentile confidence envelope corresponding to a median chlorophyll concentration of 5.4 ug/L is a Total P concentrations of 15 ug/L.

This equation could also be used to define Total P standards with respect to the aesthetic beneficial use, i.e. water transparency. Similar equations can be developed for Secchi and chlorophyll or Secchi and Total P to further refine the Total P standard. This approach would not be useful in dystrophic lakes where water transparency is largely not affected by chlorophyll concentrations. It would be of greater use in lakes where water clarity is largely a function of chlorophyll concentrations.

The beneficial uses of downstream waters must be protected. If it is assumed that the standards are protective of the in situ beneficial uses the downstream waters in all probability will also be protected, i.e. the given lake is functioning normally in the landscape.

For Unique Lakes the use of epilimnetic Total P concentration will not be sufficient to protect beneficial uses in those lakes because these lakes are so large that significant changes in Total P loading could go undetected. Thus a nutrient criterion based upon epilimnetic concentrations would have little meaning for lakes such as these. A near shore criterion that reflects more immediate impacts of nutrient loading (including periphyton chlorophyll) would be more appropriate for these unique lakes.

5.5 Limitations of Empirical Approaches

These empirical procedures for defining numeric nutrient criteria are straightforward in that they define whether a lake is significantly different from the reference population. However, they do not necessarily reveal whether a beneficial use is not being supported. The explicit definition of a nutrient standard with respect to beneficial uses cannot be derived from descriptions of reference conditions alone. This is because lakes degrade with respect to eutrophication along a gradient. Therefore where to set the numeric nutrient criterion (the magnitude of diff in this example) involves a judgement as to how conservative to be with respect to the eutrophication gradient for each beneficial use.

5.6 CONCLUSIONS

The results of this study have several implications for the development of numeric nutrient criteria in Region 10 lakes. First, a more thorough inventory of the water bodies should be undertaken so the this resource can be better defined. Second, it appears that at least in some Level III ecoregions a lake classification scheme needs to be developed according to how they process nutrients. Lakes included in this study exhibit characteristics that suggest that ecoregion alone is not a sufficient predictor of lake trophic status for the purpose of setting nutrient criteria. Additional factors that influence natural lake trophic status include the concentration of dissolved organic matter, lake and watershed morphology, and location of the lake with respect to the type of geological terrain. Therefore without such categorization, the development of ecologically meaningful nutrient criteria is problematic.

Third, long-term water quality sampling should be carried out across the Region with the goal of refining lake classification schemes. A potentially useful method for collecting such data is to combine nutrient TMDL's for many different systems by water body type, define reference systems for those listed systems, and then collect water quality data on the reference systems. Such data could be used to define nutrient assimilative capacity for the listed systems as well as be used to begin to develop numeric nutrient criteria for all systems of that type.

Finally, work needs to be undertaken to systematically define numeric criteria for each lake category corresponding to relevant beneficial uses for lakes in that category. Such definitions require judgements to be made that are nonscientific in nature, i.e. how protective a criterion should be for a given beneficial use.

Acknowledgments. We thank Dave Flemer and George Gibson for their comments on an earlier draft of this report.

5. REFERENCES

Delorme Mapping 1998. Washington Atlas and Gazetteer. 3nd Edition.

Delorme Mapping 2001. Oregon Atlas and Gazetteer. 3nd Edition.

Emmons, E.E., M.J.Jennings, and C. Edwards. 1999. An alternative classification method for northern Wisconsin lakes. Can. J. Fish. Aquat. Sci. **56**:661-669.

EPA 2000. Nutrient Criteria Technical Guidance Manual: Lakes and Reservoirs. EPA-822-B00-001

Hutchinson, G.E. and H. Loeffler. 1956. The thermal classification of lakes, Proc. Nat. Acad. Sci. **42**:84-86.

Larsen, D.P., D. L. Stevens Jr., A.R. Selle, S.G. Paulsen. 1991. Environmental monitoring and assessment program, EMAP-surface waters: a Northeast lakes pilot. *Lake and Reservoir Management* 7:1-11.

Larsen, D.P., K.W. Thornton, N.S. Urquhart, S.G. Paulsen. 1994. The role of sample surveys for monitoring the condition of the Nation's lakes. *Environmental Monitoring and Assessment* 32:101-134.

Lillie, R.A. and J.W. Mason. 1983. Limnological characteristics of Wisconsin lakes. Wis. Dep. Nat. Resour. Tech. Bull. No. 138.

Moss, B., P. Johnes, and G. Phillips. 1994. August Thienemann and Loch Lomond--an approach to the design of a system for monitoring the state of north-temperate standing waters. Hydrobiologia **290**:1-12.

Omernik, J.M. 1987. Ecoregions of the conterminous Unites States. Map (scale 1:7,500,000). *Annals Assoc. Am. Geographers* 77:118-125.

Schupp, D.H. 1992. An ecological classification of Minnesota lakes with associated fish communities. Minn. Dep. Nat. Resour. Invest. Rep. No. 417.

Thierfelder, T.K. 2000. Orthogonal variance structures in lake water quality data and their use for geo-chemical classification of dimictic, glacial/boreal lakes. Aquatic Geochemistry **6**:47-64.

Toivonen, H and P. Huttunen 1995. Aquatic macrophytes and ecological gradients in 57 small lakes in southern Finland. Aquatic Botany **51**:197-221.

USEPA. 2000. *Nutrient Criteria Technical Guidance Manual Lakes and Reservoirs,* EPA-822-B00-001, U.S. Environmental Protection Agency: Washington, DC.

Vaga, R. M. and A. T. Herlihy. 2004. A GIS inventory of Pacific Northwest lakes/reservoirs and analysis of historical nutrient and water quality data. EPA 910-R-04-009.

Williams, C.E., D.P.Morris, M.L.Pace, O.G.Olson. 1999. Dissolved organic carbon and nutrients as regulators of lake ecosystems: Resurrection of a more integrated paradigm. Limnology and Oceanography **44**: 795-803.

APPENDIX

Table 1. List of the 349 lakes identified in the Coast Range Ecoregion. Lake area and Level IV Ecoregion are also provided.

LAKENAME	HECTARES (ha)	Ecoregion No	ECOREGION NAME
Aaron Mercer Reservoir	18.8	1d	Volcanics
Aberdeen Reservoir	5.4	1e	Outwash
Ackerley Lake	3.2	1a	Coastal Lowlands
Alder Lake	0.6	1f	Willapa Hills
Astoria Reservoir	12.2	1f	Willapa Hills
Barney Reservoir	81.3	1d	Volcanics
Beale Lake	20.7	1a	Coastal Lowlands
Beaver Lake	14.7	1c	Low Olympics
Bebe Pond	1.4	1f	Willapa Hills
Big Creek Reservoir No. 2	25.6	1b	Coastal Uplands
Big Jones Lake	5.8	1b	Coastal Uplands
Black Lake	11.5	1a	Coastal Lowlands
Blackwood Lake	6.3	1c	Low Olympics
Bluebill Lake	5.9	1a	Coastal Lowlands
Bogachiel Lake	0.5	1c	Low Olympics
Boulder Lake	3.7	1c	Low Olympics
Bradley Lake	9.6	1a	Coastal Lowlands
Breaker Lake (1)	2.9	1a	Coastal Lowlands
Breaker Lake (2)	1.4	1a	Coastal Lowlands
Briscoe Lake	4.8	1a	Coastal Lowlands
Bunch Lake	4.7	1d	Volcanics
Butterfield Lake	5.1	1a	Coastal Lowlands
Camp 7 Pond	1.2	1f	Willapa Hills
Carlisle Lake (1)	1.4	1a	Coastal Lowlands
Carlisle Lake (2)	2.0	1a	Coastal Lowlands
Carlisle Lake (2)	0.4	1a	Coastal Lowlands
Carlisle Lakes (3)	0.8	1a	Coastal Lowlands
Carter Lake	13.4	1a	Coastal Lowlands
Case Pond	0.9	1b	Coastal Uplands
Cemetery Lake	3.2	1a	Coastal Lowlands
Clam Lake	3.4	1a	Coastal Lowlands
Clear Lake	4.1	1a	Coastal Lowlands
Clear Lake	60.5	1a	Coastal Lowlands
Clear Lake	5.8	1a	Coastal Lowlands
Cleawox Lake	40.0	1a	Coastal Lowlands
Coffenbury Lake	21.8	1a	Coastal Lowlands
Cohassett Lake	0.7	1a	Coastal Lowlands
Collard Lake	14.7	1a	Coastal Lowlands
Crabapple Lake	9.4	1a	Coastal Lowlands
Cranberry Lake	7.3	1a	Coastal Lowlands
Crescent Lake	7.5	1b	Coastal Uplands
Croft Lake	28.7	1a	Coastal Lowlands
Daley Lake	5.4	1a	Coastal Lowlands
Damon Lake	4.7	1a	Coastal Lowlands
Deer Lake	2.5	1a	Coastal Lowlands
Deer Lake 1	3.4	1c	Low Olympics
Deer Lake 2	0.4	1c	Low Olympics

LAKENAME	HECTARES (ha)	Ecoregion No	ECOREGION NAME
Devils Lake	233.5	1a	Coastal Lowlands
Devils Lake	4.5	1d	Volcanics
Dickey Lake	208.3	1b	Coastal Uplands
Dragon Lake	2.4	1c	Low Olympics
Dry Bed Lakes 2	1.8	1d	Volcanics
Dry Beds 1	2.8	1d	Volcanics
Duck Lake	100.6	1a	Coastal Lowlands
Eagle Lakes 1	0.1	1c	Low Olympics
Eagle Lakes 2	0.3	1c	Low Olympics
Eagle Lakes 3	0.5	1c	Low Olympics
Edna, Lake	14.5	1a	Coastal Lowlands
Eel Lake	151.3	1a	Coastal Lowlands
Elbow Lake	6.5	1a	Coastal Lowlands
Elk Lake	20.6	1b	Coastal Uplands
Elk Lake	3.7	1d	Volcanics
Elk Lake	4.2	1d	Volcanics
Elk Lake - Upper	1.5	1d	Volcanics
Elochoman Lake	2.0	1d	Volcanics
Esmond Lake	6.5	1g	Mid-Coastal Sediment
Fahys Lake	9.9	1a	Coastal Lowlands
Failor Lake	24.5	1e	Outwash
Fishhawk Lake	29.6	1f	Willapa Hills
Floras Lake	113.7	1a	Coastal Lowlands
Fourth Creek Reservoir	3.4	1a	Coastal Lowlands
Freshwater Lake	3.1	1a	Coastal Lowlands
Fulton Lake	0.1	1d	Volcanics
Gile Lake	7.5	1a	Coastal Lowlands
Happy Lake	1.0	1c	Low Olympics
Helmicks Pond	1.0	1f	Willapa Hills
Hidden Lake	2.1	1c	Low Olympics
Hobuck Lake	3.3	1b	Coastal Uplands
Hoquiam Water Works Reservoir	0.5	1e	Outwash
Horsfall Lake	132.1	1a	Coastal Lowlands
Huttula Lake	4.8	1f	Willapa Hills
Intermittent Lake	4.7	1c	Low Olympics
Intermittent Lake	2.4	1f	Willapa Hills
Intermittent Lakes (1)	0.4	1a	Coastal Lowlands
Intermittent Lakes (2)	2.2	1a	Coastal Lowlands
Intermittent Lakes (3)	0.4	1a	Coastal Lowlands
Irely Lake	10.8	1b	Coastal Uplands
Island Lake	21.5	1a	Coastal Lowlands
Jefferson Lake	4.9	1d	Volcanics
Jefferson Lake - Upper	1.9	1d	Volcanics
Jordan Lake	1.2	1a	Coastal Lowlands
Jupiter Lakes 1	0.6	1d	Volcanics
Jupiter Lakes 2	0.6	1d	Volcanics
Jupiter Lakes 3	2.9	1d	Volcanics
Jupiter Lakes 4	1.3	1d	Volcanics
Klickitat Lake	14.9	1g	Mid-Coastal Sediment
Klone Lakes (1)	3.1	1d	Volcanics

LAKENAME	HECTARES (ha)	Ecoregion No	ECOREGION NAME
Klone Lakes (2)	1.8	1d	Volcanics
Klone Lakes (3)	0.3	1d	Volcanics
Kurtz Lake	0.5	1c	Low Olympics
Lake Aberdeen	21.1	1a	Coastal Lowlands
Lake Armstrong	2.5	1d	Volcanics
Lake Connie	2.1	1c	Low Olympics
Lake Dilly	3.9	1c	Low Olympics
Lake Haven	6.1	1d	Volcanics
Lake Mills	0.1	1c	Low Olympics
Lake Pleasant	199.1	1b	Coastal Uplands
Lake Success	0.3	1c	Low Olympics
Lake Sundown	1.6	1c	Low Olympics
Lake Sutherland	142.0	1c	Low Olympics
Lang Lake	1.5	1a	Coastal Lowlands
Laurel Lake	16.1	1a	Coastal Lowlands
Lena Lake - Lower	20.6	1d	Volcanics
Lily Lake	7.2	1a	Coastal Lowlands
Lily Lake	0.6	1c	Low Olympics
Litschke Lake	6.0	1a	Coastal Lowlands
Lizard Lake	0.8	1c	Low Olympics
Long Lake	4.7	1a	Coastal Lowlands
Loomis Lake	60.6	1a	Coastal Lowlands
Loon Lake	96.9	1g	Mid-Coastal Sediment
Lords Lake	24.1	1d	Volcanics
Lost Lake	7.8	1a	Coastal Lowlands
Lost Lake	3.4	1a	Coastal Lowlands
Lost Lake	4.5	1d	Volcanics
Lower Empire Lake	9.4	1a	Coastal Lowlands
Lyons Reservoir	1.8	1a	Coastal Lowlands
Lytle, Lake	18.8	1b	Coastal Uplands
Makenzie Head Lagoon	2.7	1a	Coastal Lowlands
Manmade Pond	20.6	1a	Coastal Lowlands
Manmade Pond	7.3	1a	Coastal Lowlands
Manmade Pond	32.8	1a	Coastal Lowlands
Manmade Pond	9.2	1a	Coastal Lowlands
Manmade Pond	6.3	1a	Coastal Lowlands
Manmade Pond	3.1	1a	Coastal Lowlands
Manmade Pond	10.2	1f	Willapa Hills
Marie, Lake	6.1	1a	Coastal Lowlands
McGravey Lake	0.5	1c	Low Olympics
McGwire Reservoir	51.4	1d	Volcanics
Middle Empire Lake	11.0	1a	Coastal Lowlands
Middle Lake	4.6	1f	Willapa Hills
Mildre Lakes 2	4.6	1c	Low Olympics
Mildred Lakes 1	17.1	1c	Low Olympics
Mildred Lakes 3	3.4	1c	Low Olympics
Miles Lake	5.9	1a	Coastal Lowlands
Mink Lake	4.1	1c	Low Olympics
Moose Lake	1.6	1f	Willapa Hills
Mountain Spring Reservoir	0.7	1b	Coastal Uplands

LAKENAME	HECTARES (ha)	Ecoregion No	ECOREGION NAME
Mountain Springs Ranch Reservoir	2.0	1d	Volcanics
Munsel Lake	37.1	1a	Coastal Lowlands
Myrtle Point Log Pond	11.2	1a	Coastal Lowlands
New Lake	44.3	1a	Coastal Lowlands
North Fork Reservoir	2.5	1d	Volcanics
North Tenmile Lake	342.2	1a	Coastal Lowlands
Oakhurst Ponds (1)	0.1	1f	Willapa Hills
Oakhurst Ponds (2)	0.1	1f	Willapa Hills
Oakhurst Ponds (3)	0.0	1f	Willapa Hills
Olalla Reservoir	40.3	1b	Coastal Uplands
Old Mill Pond	1.0	1a	Coastal Lowlands
Oneal Lake	3.9	1a	Coastal Lowlands
Pauls Lake	6.8	1a	Coastal Lowlands
Pine Lake	3.1	1d	Volcanics
Pope Lake	2.9	1b	Coastal Uplands
Powers Pond	7.4	1h	Southern Oregon Coas
Quinault Lake		1b	Coastal Uplands
Radar Ponds No. 1	1.3	1b	Coastal Uplands
Raymond City Reservoir	0.5	1b	Coastal Uplands
Reflection Lake	0.5	1c	Low Olympics
Reservoir	0.4	1a	Coastal Lowlands
Reservoir	0.7	1a	Coastal Lowlands
Reservoir	0.6	1a	Coastal Lowlands
Reservoir	3.1	1b	Coastal Uplands
Reservoir	4.3	1b	Coastal Uplands
Ring Lake	0.9	1c	Low Olympics
Rink Creek Reservoir	4.5	1g	Mid-Coastal Sediment
Riverside Lake	1.8	1a	Coastal Lowlands
Roaring Creek Slough	2.8	1b	Coastal Uplands
Roaring Ponds No. 2	1.1	1b	Coastal Uplands
Round Lake	1.1	1c	Low Olympics
Ryderwood Pond	1.8	1f	Willapa Hills
Sandpoint Lake	36.2	1a	Coastal Lowlands
Sarviniski Lakes (1)	1.7	1f	Willapa Hills
Sarviniski Lakes (2)	1.0	1f	Willapa Hills
Sarviniski Lakes (3)	0.8	1f	Willapa Hills
Satsop Lake No. 1	1.1	1d	Volcanics
Satsop Lake No. 2	0.9	1d	Volcanics
Satsop Lake No. 3	0.1	1d	Volcanics
Satsop Lake No. 4	0.6	1d	Volcanics
Satsop Lake No. 5	0.7	1d	Volcanics
Saunders Lake	18.1	1a	Coastal Lowlands
Seafield Lake	7.1	1b	Coastal Uplands
Shag Lake	1.8	1a	Coastal Lowlands
Shye Lake	3.3	1a	Coastal Lowlands
Skating Lake	10.7	1a	Coastal Lowlands
Skookum Lake	15.9	1d	Volcanics
Slusher Lake	8.1	1a	Coastal Lowlands
Smith Lake	18.1	1a	Coastal Lowlands
Smith Lake	9.2	1b	Coastal Uplands

LAKENAME	HECTARES (ha)	Ecoregion No	ECOREGION NAME
Snag Lake	14.2	1a	Coastal Lowlands
Soapstone Lake	3.4	1b	Coastal Uplands
Solduck Lake	11.4	1c	Low Olympics
South Bend City Reservoir	0.5	1a	Coastal Lowlands
Spider Lake	7.3	1d	Volcanics
Spring Lake	3.6	1b	Coastal Uplands
Stanley Lake	3.9	1a	Coastal Lowlands
Stump Lake	11.0	1f	Willapa Hills
Summit Lake	206.7	1d	Volcanics
Sunset Lake	44.5	1a	Coastal Lowlands
Sutton Lake	40.4	1a	Coastal Lowlands
Sylvia Lake	11.5	1f	Willapa Hills
Tahkenitch Lake	621.8	1a	Coastal Lowlands
Tape Lake	3.5	1a	Coastal Lowlands
Tarheel Reservoir	8.1	1a	Coastal Lowlands
Taylor Lake (Carnahan Lake)	3.5	1a	Coastal Lowlands
Teal Lake	2.9	1a	Coastal Lowlands
Tenmile Lake	479.9	1a	Coastal Lowlands
Three Horse Lake	1.6	1c	Low Olympics
Three Lakes 2	0.1	1c	Low Olympics
Three lakes 1	0.4	1c	Low Olympics
Three lakes 3	0.1	1c	Low Olympics
Threemile Lake	28.8	1a	Coastal Lowlands
Thunder Lake	4.4	1b	Coastal Uplands
Tinker Lake	4.2	1a	Coastal Lowlands
Triangle Lake	110.5	1g	Mid-Coastal Sediment
Unnamed Lake	0.1	1a	Coastal Lowlands
Unnamed Lake	1.5	1a	Coastal Lowlands
Unnamed Lake	1.9	1a	Coastal Lowlands
Unnamed Lake	1.1	1a	Coastal Lowlands
Unnamed Lake	0.7	1a	Coastal Lowlands
Unnamed Lake	1.0	1a	Coastal Lowlands
Unnamed Lake	1.0	1a	Coastal Lowlands
Unnamed Lake	2.2	1a	Coastal Lowlands
Unnamed Lake	0.9	1a	Coastal Lowlands
Unnamed Lake	0.6	1a	Coastal Lowlands
Unnamed Lake	1.4	1a	Coastal Lowlands
Unnamed Lake	1.1	1a	Coastal Lowlands
Unnamed Lake	3.9	1a	Coastal Lowlands
Unnamed Lake	0.2	1a	Coastal Lowlands
Unnamed Lake	0.5	1a	Coastal Lowlands
Unnamed Lake	0.4	1a	Coastal Lowlands
Unnamed Lake	1.0	1a	Coastal Lowlands
Unnamed Lake	0.4	1b	Coastal Uplands
Unnamed Lake	1.0	1b	Coastal Uplands
Unnamed Lake	0.1	1b	Coastal Uplands
Unnamed Lake	0.2	1c	Low Olympics
Unnamed Lake	0.3	1c	Low Olympics
Unnamed Lake	0.4	1c	Low Olympics
Unnamed Lake	1.4	1c	Low Olympics
Unnamed Lake	0.8	1c	Low Olympics

LAKENAME	HECTARES (ha)	Ecoregion No	ECOREGION NAME
Unnamed Lake	1.8	1c	Low Olympics
Unnamed Lake	3.8	1c	Low Olympics
Unnamed Lake	1.2	1c	Low Olympics
Unnamed Lake	2.8	1c	Low Olympics
Unnamed Lake	11.0	1c	Low Olympics
Unnamed Lake	0.6	1c	Low Olympics
Unnamed Lake	0.5	1c	Low Olympics
Unnamed Lake	0.4	1e	Outwash
Unnamed Lake	0.2	1d	Volcanics
Unnamed Lake	0.4	1d	Volcanics
Unnamed Lake	0.4	1d	Volcanics
Unnamed Lake	1.2	1d	Volcanics
Unnamed Lake	0.3	1f	Willapa Hills
Unnamed Lake	0.1	1f	Willapa Hills
Unnamed Lake	0.7	1f	Willapa Hills
Unnamed Lake	2.6	1f	Willapa Hills
Unnamed Lake	1.2	1f	Willapa Hills
Unnamed Lake	0.1	1f	Willapa Hills
Unnamed Lake	0.6	1f	Willapa Hills
Unnamed Lake	0.5	1f	Willapa Hills
Unnamed Lake	2.6	1f	Willapa Hills
Unnamed Lake	1.4	1f	Willapa Hills
Unnamed Lake	0.4	1f	Willapa Hills
Unnamed Lake	0.1	1f	Willapa Hills
Unnamed Lake	0.1	1f	Willapa Hills
Unnamed Lake	0.5	1f	Willapa Hills
Unnamed Lake	0.4	1f	Willapa Hills
Unnamed Lake	6.5	1a	Coastal Lowlands
Unnamed Lake	5.9	1a	Coastal Lowlands
Unnamed Lake	6.2	1a	Coastal Lowlands
Unnamed Lake	8.4	1a	Coastal Lowlands
Unnamed Lake	2.5	1a	Coastal Lowlands
Unnamed Lake	5.9	1a	Coastal Lowlands
Unnamed Lake	4.5	1a	Coastal Lowlands
Unnamed Lake	4.7	1a	Coastal Lowlands
Unnamed Lake	22.9	1a	Coastal Lowlands
Unnamed Lake	6.0	1a	Coastal Lowlands
Unnamed Lake	5.2	1a	Coastal Lowlands
Unnamed Lake	8.4	1a	Coastal Lowlands
Unnamed Lake	4.8	1a	Coastal Lowlands
Unnamed Lake	7.9	1a	Coastal Lowlands
Unnamed Lake	10.9	1a	Coastal Lowlands
Unnamed Lake	4.2	1a	Coastal Lowlands
Unnamed Lake	6.7	1a	Coastal Lowlands
Unnamed Lake	7.1	1b	Coastal Uplands
Unnamed Lake	6.1	1b	Coastal Uplands
Unnamed Lake	8.1	1b	Coastal Uplands
Unnamed Lake	4.2	1b	Coastal Uplands
Unnamed Lake	14.0	1g	Mid-Coastal Sediment
Unnamed Lake	4.4	1g	Mid-Coastal Sediment
Unnamed Lake	6.8	1g	Mid-Coastal Sediment

LAKENAME	HECTARES (ha)	Ecoregion No	ECOREGION NAME
Unnamed Lake	5.3	1g	Mid-Coastal Sediment
Unnamed Lake	4.2	1e	Outwash
Unnamed Lake	5.1	1d	Volcanics
Unnamed Lake	4.4	1d	Volcanics
Unnamed Lake	8.3	1f	Willapa Hills
Unnamed Lake	2.1	1f	Willapa Hills
Unnamed Lake	0.6	1f	Willapa Hills
Unnamed Lake	2.0	1f	Willapa Hills
Unnamed Lake	0.8	1f	Willapa Hills
Unnamed Lake	1.0	1f	Willapa Hills
Unnamed Lake	0.4	1f	Willapa Hills
Unnamed Lake	0.1	1f	Willapa Hills
Unnamed Lake	116.5	1a	Coastal Lowlands
Unnamed Lake	10.6	1g	Mid-Coastal Sediment
Unnamed Lake	0.4	1d	Volcanics
Unnamed Lake (?)	5.2	1b	Coastal Uplands
Unnamed Lake (?)	7.0	1b	Coastal Uplands
Unnamed Lake (?)	7.6	1b	Coastal Uplands
Unnamed Lake (?)	21.9	1b	Coastal Uplands
Unnamed Lakes	0.2	1c	Low Olympics
Unnamed Lakes	0.2	1d	Volcanics
Unnamed Lakes	1.0	1f	Willapa Hills
Unnamed Lakes	0.7	1f	Willapa Hills
Unnamed Lakes	0.0	1f	Willapa Hills
Unnamed Lakes	0.2	1f	Willapa Hills
Unnamed Lakes	0.1	1c	Low Olympics
Unnamed Lakes	0.0	1d	Volcanics
Unnamed Lakes	1.3	1f	Willapa Hills
Unnamed Lakes	0.6	1f	Willapa Hills
Unnamed Lakes	0.1	1f	Willapa Hills
Unnamed Lakes	0.1	1f	Willapa Hills
Unnamed Lakes	0.4	1c	Low Olympics
Unnamed Lakes	0.4	1f	Willapa Hills
Unnamed Lakes	0.2	1f	Willapa Hills
Unnamed Lakes	0.3	1f	Willapa Hills
Unnamed Lakes	0.1	1c	Low Olympics
Unnamed Lakes	1.3	1f	Willapa Hills
Unnamed Lakes	0.2	1f	Willapa Hills
Unnamed Lakes	0.1	1f	Willapa Hills
Unnamed lake	7.0	1b	Coastal Uplands
Upper Pony Creek Reservoir	48.7	1b	Coastal Uplands
Wagonwheel Lake	1.1	1d	Volcanics
Wentworth Lake	19.4	1b	Coastal Uplands
West Lake	7.6	1a	Coastal Lowlands
Wickiup Lake	5.6	1f	Willapa Hills
Wild Ace Lake	4.4	1a	Coastal Lowlands
Wild Cat Lake	1.7	1d	Volcanics
Willoughby Lake	2.0	1b	Coastal Uplands
Woahink Lake	312.3	1a	Coastal Lowlands
Yahoo Lake	3.7	1c	Low Olympics

Table 2. There are 30 lakes greater than 50 hectares in sufrace area in the Coast Range Ecoregion. These lakes account for 89.2% of the total surface area of lakes greater than 4 hectares. Lake Ozette alone accounts for 19.3% of the total lake surface area in the ecoregion.

Lakename	Area (ha)	Long (dd)	Lat (dd)	% Area
Ozette Lake	3007	-124.6	48.1	19.3
Lake Cresent	2031	-123.8	48.1	13.0
Lake Cushman	1623	-123.3	47.5	10.4
Quinault Lake	1434	-123.9	47.5	9.2
Siltcoos Lake	1205	-124.1	43.9	7.7
Tahkenitch Lake	622	-124.1	43.8	4.0
Tenmile Lake	480	-124.1	43.6	3.1
Wynoochee Lake	406	-123.6	47.4	2.6
North Tenmile Lake	342	-124.1	43.6	2.2
Woahink Lake	312	-124.1	43.9	2.0
Devils Lake	234	-124.0	45.0	1.5
Dickey Lake	208	-124.5	48.1	1.3
Summit Lake	207	-123.1	47.1	1.3
Lake Pleasant	199	-124.3	48.1	1.3
Eel Lake	151	-124.2	43.6	1.0
Lake Sutherland	142	-123.7	48.1	0.9
Horsfall Lake	132	-124.2	43.5	0.9
Mercer Lake	125	-124.1	44.1	0.8
Lake Aldwell	122	-123.6	48.1	0.8
Floras Lake	114	-124.5	42.9	0.7
Clear Lake	113	-124.2	43.6	0.7
Triangle Lake	111	-123.6	44.2	0.7
Duck Lake	101	-124.1	47.0	0.6
Loon Lake	97	-123.8	43.6	0.6
Cullaby Lake	84	-123.9	46.1	0.5
Barney Reservoir	81	-123.4	45.4	0.5
Loomis Lake	61	-124.0	46.4	0.4
Clear Lake	61	-124.1	44.0	0.4
Garrison Lake	53	-124.5	42.8	0.3
McGwire Reservoir	51	-123.4	45.3	0.3
Total	13900			89.2

Table 3. Median values for selected water quality parameters for lakes in each of seven lake categories. MD - mean depth, Chl a - chlorophyll, Sec - Secchi, Oxygen profile (O_2) : clino = clinograde, ortho = orthograde, na = not applicable. Mixing status (MS): mono = monomictic, poly = polymictic.

Lake Name	Lat	Long	Area	MD	SRP	TP	TN	NO_3	NH_3	TKN	Chl a	Sec	O_2	MS
Category 1 - Dystrophic Lakes														
BLACK LAKE	46.3	-124.0	12	-	-		10	10	-	0	-	-	?	?
CLAM LAKE	46.4	-124.0	4	1.0	0.0	166.5	940	0	-	-	26.7	0.8	clino	mon
CREEP&CRAWL	46.2	-124.0	0	1.0	0.0	184.0	1230	0	-	-	54.2	0.6	clino	poly
CULLABY LAKE	46.1	-123.9	84	1.6		77.5	410	30	60	0	3.1	1.0	clino	poly
FRESHWATER LAKE	46.4	-124.0	3	1.0	0.0	82.0	1070	0	-	-	24.3	0.4	na	poly
ISLAND LAKE	46.4	-124.0	22	1.4	0.0	26.0	530	2	-	-	10.0	2.0	na	poly
LONG LAKE	46.2	-123.9	5	0.8	0.0	152.0	875	3	-	-	23.0	1.2	clino	poly
SMITH-CLATSOP	46.1	-123.9	18	3.3		66.0	650	50	90	600	5.4	-	clino	poly
SUNSET LAKE	46.1	-123.9	15	2.5	0.0	90.5	530	15	60	0	11.6	1.3	clino	po
FAILOR LAKE	47.1	-124.0	25	1.8	0.0	22.0	280	1	5	-	17.5	2.4	clino	poly
STUMP LAKE	47.1	-123.3	11	-	-	42.0	520	-	-	500	29.5	2.1	clino	poly
Category 2 - Shallow Coastal Lakes														
BEALE LAKE	43.5	-124.2	21	1.7	-	12.0	250	50	20	200	7.8	2.0	ortho	poly
COFFENBURY LAKE	46.2	-124.0	22	1.5	-	22.5	410	50	50	400	0.6	1.8	ortho	poly
CROFT	43.0	-124.5	29	2.3	-	23.0	320	20	20	300	0.8	-	?	?
DEVILS-LINCOLN	45.0	-124.0	234	3.0	-	23.5	-	-	-	0	6.8	1.4	ortho	poly
FLORAS	42.9	-124.5	114	5.5	-	8.0	220	20	20	0	0.7	2.7	?	?
HORSFALL SPIRIT	43.5	-124.2	132	0.4	-	41.0	1120	20	20	1100	12.9	-	?	?
LAKE LYTTLE	45.6	-123.9	19	1.9	0.0	25.5	250	3	-	0	3.2	1.6	ortho	poly
NORTH TENMILE	43.6	-124.1	342	3.4	0.0	30.0	720	10	30	400	17.0	2.5	ortho	poly
SILTCOOS	43.9	-124.1	120	3.3	0.0	18.0	320	10	-	0	6.1	2.2	ortho	poly
SMITH-MAGRUDER	45.6	-123.9	9	-	-	8.0	230	-	-	-	-	-	ortho	poly
SOUTH TEN MILE	43.6	-124.2	480	3.0	0.0	35.0	970	100	130	600	7.5	4.2	ortho	poly
TAHKENITCH	43.8	-124.2	622	3.3	0.0	20.0	320	50		160	6.2	2.4	ortho	poly
Category 3 - Deep Coastal Lakes														
CLEAR-DOUGLAS	43.7	124.2	113	16.5	0.0	10.0	395	215	9	220	2.3	7.9	?	?
CLEAR-LANE	44.0	-124.1	61	12.2	0.0	10.0	120	44	4	0	1.5	6.4	?	?
CLEAWOX	43.9	-124.1	40	5.2	-	10.0	220	20	20	0	2.3	4.9	clino	mon
COLLARD LAKE	44.2	-124.1	15	6.6	0.0	10.0	235	5	20	0	4.3	3.9	clino	mon
EEL	43.6	124.2	151	10.5	0.0	20.0	230	228	3	0	4.1	4.0	clino	mon
LAUREL LAKE	43.0	-124.4	16	4.6	0.0	20.5	180	1	-	-	15.6	3.2	clino	mon
MERCER	44.1	-124.1	125	7.1	-	20.0	-	-	-	0	9.2	4.2	?	?
MUNSEL	44.0	124.1	37	9.3	0.0	10.5	160	1	0	0	2.9	5.5	clino	mon
SUTTON LAKE	44.1	-124.1	22	5.8	-	18.0	230	-	-	-	-	4.0	clino	mon
WOAHINK LAKE	43.9	-124.1	312	10.9	0.0	5.0	135	112	2	0	2.0	5.2	clino	mon

Lake Name	Lat	Long	Area	MD	SRP	TP	TN	NO_3	NH_3	TKN	Chl a	Sec	O_2	MS
Category 4 - Forested Lakes														
BEAVER LAKE	48.1	-124.2	15	6.5	0.0	10.0	150	13	18	500	22.4	2.5	clino	poly
DICKEY LAKE	48.1	-124.5	208	7.5	0.0	10.0	200	77	40	-	7.8	2.1	clino	mon
HORSESHOE LAKE	47.9	-122.8	5	-	0.0	9.5	280	2	6	500	2.6	4.0	clino	poly
LAKE WYNOOCHEE	47.4	-123.6	406	-	0.0	6.5	50	74	33	0	0.4	6.4	clino	mon
LAKE MILLS	48.0	-123.6	180	-	-	20.0	-	-	-	500	-	4.3	clino	poly
LAKE PLEASANT	48.1	-124.3	199	3.0	0.0	8.5	150	77	33	500	4.6	5.1	clino	poly
LAKE TARBOO	47.9	-122.9	8	-	-	10.0	-	-		500	11.6	3.0	clino	poly
LAKE WENTWORTH	48.0	-124.5	19	3.5	0.0	13.0	250	69	26	-	10.3	2.5	clino	poly
LOON-DOUGLAS	43.6	-123.8	97	16.3	0.0	10.0	230	30	20	0	0.5	2.6	?	?
NAHWATZEL LAKE	47.2	-123.3	115	3.9	0.0	7.0	220	65	22	-	1.3	4.0	clino	mon
OLLALA RESERVOIR	44.7	-123.9	40	8.2	-	8.0	150	-	-	-	-	4.0	clino	poly
RINKCREEK	43.2	-124.1	5	5.8	0.0	15.0	300	894	-	-	20.5	4.0	clino	mon
SANDY SHORE LAKE	47.9	-122.8	14	-	-	10.0	-	-	-	500	2.0	4.5	clino	poly
TOWN LAKE	45.2	-124.0	4	1.6	0.0	21.5	270	76	-	-	4.2	3.5	ortho	poly
TRIANGLE LAKE	44.2	-123.6	111	15.8	-	12.0	190	20	20	0	2.1	4.0	clino	mon
Category 5 - Log Ponds														
JOHNSON LOG	43.1	-124.2	33	1.2	0.0	145.0	2110	4	-	-	7.6	1.0	na	poly
LAKE CREEK	44.2	-123.5	11	-	-	16.0	140	-	-	-	-	2.0	na	poly
MCCLEARY LAKE	47.0	-123.3	8	1.0	0.0	39.0	850	2	-	-	-	1.0	na	poly
VERNONIA	45.9	-123.2	10	0.5	-	39.0	900	-	-	-	-		na	poly
Category 6 - Sea Water Intrusion Lakes														
GARRISON LAKE	42.8	-124.5	53	2.5	0.0	30.0	310	3	35	0	8.1	2.8	clino	mero
Category 7 - Unique Lakes														
LAKE CUSHMAN	47.4	-123.2	162	-	0.0	5.0	100	50	10	75	-	-	clino	mon
LAKE CRESCENT	48.1	-123.8	203	92.8	0.0	11.0	40	1	3	0	0.4	18.0	clino	mon
LAKE OZETTE	48.2	-124.7	300	38.4	0.0	10.0	205	60	30	120	19.5	3.8	clino	poly
LAKE QUINAULT	47.5	-123.9	143	41.8	0.0	12.5	120	65	21	-	1.1	10.1	clino	mon