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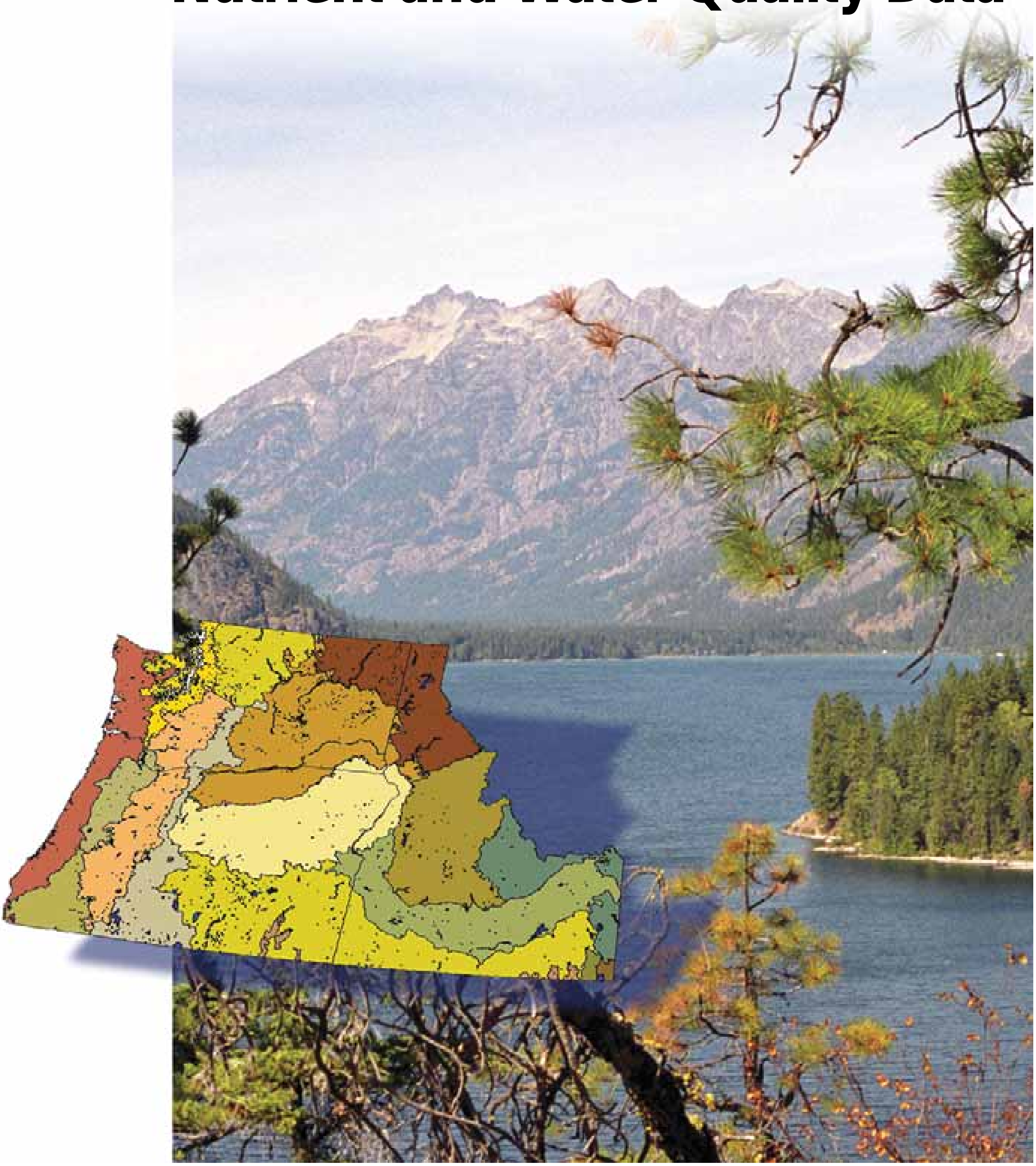
A GIS Inventory of Pacific Northwest Lakes/Reservoirs and an Analysis of Historical Nutrient and Water Quality Data



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A GIS INVENTORY OF PACIFIC NORTHWEST LAKES AND RESERVOIRS AND ANALYSIS OF HISTORICAL WATER QUALITY DATA

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ABSTRACT

Lakes and reservoirs were inventoried in the Pacific Northwest (Idaho, Oregon and Washington) to determine the number and location of these water bodies in the region. GIS data were obtained from various sources and combined into a single data layer. The lakes on the layer were verified against maps for water bodies $\geq$ 4 ha.

Results show that there are approximately 10,535 lakes/reservoirs in the PNW that have been assigned names. There are 3965 lakes/reservoirs $\geq$ 4 ha in surface area in this region. About 90% of these lakes are less than 200 ha and fully one-half (n=1985) are less than 10 ha.

The total surface area of lakes/reservoirs $\geq$ 4 ha (n=3965) was found to be 6391 km^2. Almost 50% of that area was accounted for by only 26 lakes. The balance of the total area was accounted for by the remaining 3939 lakes. Although lakes 4 - 10 ha (n=1985) accounted for one-half of the total number of lakes, these lakes accounted for 1.9% of total lake area.

A water quality database was compiled from various sources for lakes in the region. The data were screened and May - October medians (summer index values) calculated for total phosphorus, total nitrogen, Secchi depth and chlorophyll a. The behavior of these variables was analyzed across Level III Ecoregions. Significant differences among some Ecoregions were found for total P and total N. These differences were corroborated by comparisons to stream water quality across Ecoregions. Median summer lake total P and stream total P were highly correlated across Ecoregions, suggesting that these differences represent differences in landscape characteristics.

Values of summer index total phosphorus values were compared with total P assimilative capacity from Total Maximum Daily Loads (TMDLs) by Ecoregion. There was a significant correlation across Ecoregions between calculated assimilative capacity and median total P concentrations.

Methods are suggested as to the proper use of historical water quality data in developing numeric nutrient criteria for lakes. It appears that use of historical water quality data can be used to guide development of total P TMDLs for lakes and to address antidegradation. However, historical data are not sufficient to allow for 303(d) listing of water bodies.

CHAPTER 1. INTRODUCTION

1.1 Background

The National Water Quality Inventory: 200 Report to Congress cites nutrients (nitrogen and phosphorus) as one of the leading causes of water quality impairment in lakes (USEPA 2000). The national response to the nutrient problem has been limited primarily because of concerns over the scale of the problem, and because of the tremendous variability of nutrient conditions, both natural and cultural, throughout the nation.

Presently, the only national water quality criteria in existence for nutrients are for nitrate nitrogen and phosphorus. EPA presented ambient water quality criteria for nitrates, nitrites and phosphorus. The criterion for nitrate nitrogen was 10 mg/L for the protection of domestic water supplies (USEPA 1986). The nitrate criteria were intended to prevent over enrichment and to protect human and animal health. The phosphorus criterion was 0.10 ug/L elemental phosphorus to protect against the toxic effects of the bioconcentration of elemental phosphorus to estuarine and marine organisms, not on the potential to cause eutrophication.

In order to expand and update EPA guidance in the area of nutrient assessment and control, EPA held a National Nutrient Assessment Workshop in 1995 (USEPA 1996). Subsequently EPA developed a national strategy for the development of numeric nutrient criteria in surface waters.

The major elements of this strategy included:

1) Development of numeric criteria for both causal, e.g. phosphorus and nitrogen and response, e.g. water transparency, chlorophyl concentrations variables.

1) Use of a regional and waterbody-type approach for the development of nutrient water quality criteria.

2) Development of waterbody-type technical guidance documents, i.e. documents for streams and rivers; lakes and reservoirs; estuaries and coastal waters; and wetlands, that would serve as "user manuals" for assessing trophic state and developing region-specific nutrient criteria to control over enrichment.

3) Establishment of an EPA National Nutrient Team with Regional Nutrient Coordinators to develop regional databases and to promote State and Tribal involvement.

4) Development by EPA of nutrient water quality criteria guidance in the form of numerical regional target ranges, which EPA expects States and Tribes to use in implementing State management programs to reduce over enrichment in surface waters, i.e., through the development of water quality criteria, standards, NPDES permit limits, and total maximum daily loads (TMDLs).

5) Monitoring and evaluation of the effectiveness of nutrient management programs as they are implemented.

EPA has produced Technical Guidance Documents for development of numeric nutrient criteria for lakes and reservoirs (USEPA 2000). In addition a national database has been developed (USEPA 2001). Nationally ambient water quality criteria recommendations for lakes/reservoirs and streams/rivers have been published for nine Aggregate Nutrient Ecoregions (Fig. 1-1). In Region 10 national recommended criteria have been published for lakes in the Western Forested Mountains (Nutrient Ecoregion II) and the Xeric West (Nutrient Ecoregion III). These latter publications also include some recommendations for Level III Ecoregions (Omernik 1988).

This report summarizes results of efforts undertaken to develop numeric nutrient criteria for lakes and reservoirs in the EPA Region 10 states of Idaho, Oregon and Washington.

A GIS inventory of the lakes (used to mean both lakes and reservoirs) in these three states was compiled to define the population of water bodies that might be subject to criteria development. The inventory provides a characterization of the lakes with respect to their geography, e.g. number of lakes, geographic distribution, etc.

An analysis of historical water quality data was undertaken to determine how causal (nutrients) and response (water transparency, chlorophyll) parameters varied across Level III Ecoregions.

Finally, ways to use the results of analysis of historical data in developing numeric nutrient criteria are explored.

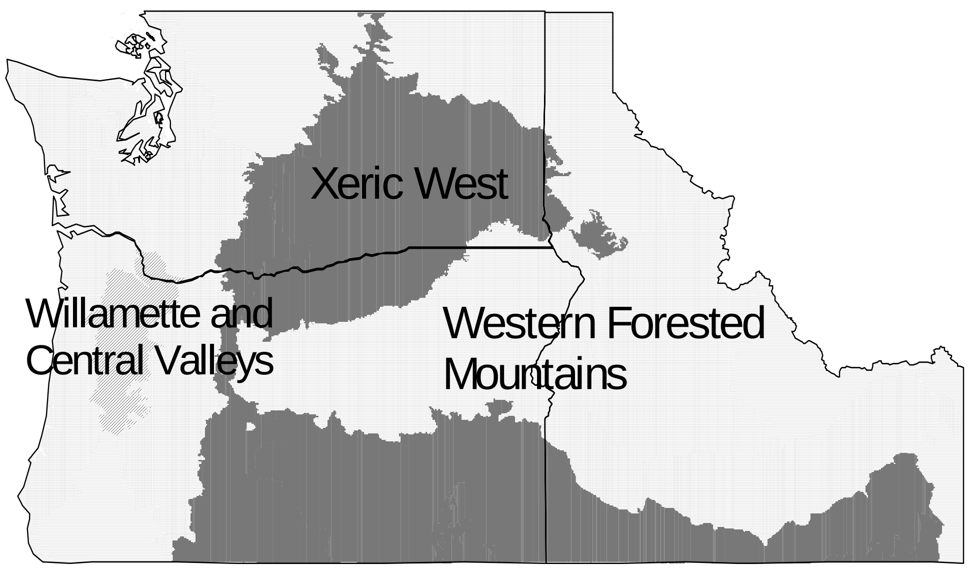

Figure 1-1. Map of Idaho, Oregon and Washington showing extent of the three Nutrient Ecoregions: Central and Willamette Valleys, Western Forested Mountains and Xeric West.

CHAPTER 2. LAKE INVENTORY

2.1 Methods

Two types of spatial data were used to develop an inventory of lakes and reservoirs in the Pacific Northwest (PNW). The first was Geographic Information System (GIS) data in electronic format obtained from various State agencies. These data consisted of features (polygons) representing water bodies and were at varying scales. The features were not all labeled, i.e. the names of a water body were not always provided. The second data layer was obtained from the Bureau of Land Management (BLM). This layer consisted of unique points with associated latitude and longitude. Each point had a name and was labeled as being either a lake or reservoir but had no data regarding the area of the water body.

The polygon data were compiled into one data layer. The features on the layer were then checked against topographic maps (1:100,000 for Oregon and Washington and 1:300000 for Idaho) (Delorme 1998, 2001a, 2001b). Lakes (including reservoirs) greater than 4 ha in surface area were included in this inventory because the scale of maps used permitted easy identification of such water bodies. Lakes in the polygon data layer that were not found on the maps were deleted. If a feature in the coverage did not have a name, it was assigned the name found on the corresponding map. If the feature did not have a name on the map then it was labeled ‘unnamed.’ Lakes that were intermittent were deleted from the coverage, as were features such as manmade ponds, quarries, fish ponds, etc. This data layer we termed the Verified Data Layer (VDL).

The VDL was then compared with the Bureau of Land Management data layer (points) naming lakes and reservoirs.

2.2 Results

The unedited data layers contained a total of 54,129 features (polygons) for the three states. Of that number 10,938 were named. However, these layers included features that were clearly not lakes, i.e. temporary water bodies, wetlands, etc. many of which where less than 0.1 ha in surface area. There were roughly 2,000 features $\geq$ 4 hectares removed from these data layers to generate the VDL; for the most part these were lakes in southern Oregon that were intermittent.

The VDL contains 3965 lakes/reservoirs greater than 4 hectares in surface (Fig. 2-1, Table 2-1, Appendix Table A-1).

The total area of lakes greater than 4 ha is 6391 km^2 (Table 2-1). The number lakes per Level III Ecoregion ranges from a low of 182 in the Coast Range to a high of 620 in the Columbia Plateau. The Willamette Valley has the lowest total area of lakes (107 km^2) and the Northern Rockies has the largest area of lakes (1087 km^2). The lowest density of lakes is found in the Blue Mountains (0.25 lakes/km^2 x 100) and highest density (2.84 lakes/km^2 x 100) is found in the Puget Lowlands (Fig. 2-1). It is not possible to discern any patterns in these figures among Ecoregions since these water bodies include both natural lakes and man-made reservoirs.

Within Ecoregions the distribution of lakes exhibits a clumped pattern (Fig. 2-1). Some areas have very high density whereas others have virtually no lakes, e.g. the southern portion of the Columbia Plateau.

The large total lake area in the Northern Rockies is accounted for the three of the largest lakes in the Region (Lake Pend Oreille, Franklin Roosevelt Lake and Lake

Couer d'Alene). Similarly the Northern Basin and Range contains Albert Lake, Summer Lake and Harney Lake. However, these lakes have large fluctuations in surface area.

There are no surface area data associated with this coverage. Features were verified against topographic maps and it appeared that most of the features were on the landscape and were less than 4 ha in surface area.

Comparison of the BLM and our VDL indicates that for features greater than about 2 hectares in surface area, the two coverages show a similar number of water bodies: the total number of lakes and reservoirs in the BLM layer is 10,535; the data layers used to generate the VDL contained 9,479 lakes greater than 2 hectares in surface area. Thus the 4 ha threshold leaves out as many as 5,000 water bodies (Table 2-2).

There is a wide range in number of lakes and reservoirs by state (Table 2-3). Oregon has 3,444 reservoirs whereas Idaho and Washington have 673 and 2,920, respectively. Washington has 2,920 lakes as compared with 1,737 and 1,253 for Oregon and Idaho, respectively.

The cumulative distribution of lakes ≥4 ha (n= 3965) in the VDL is presented in Figure 2-2. About half (n=1985) of the lakes are less than 10 ha in surface area. About 90% of the lakes are less than 200 ha.

In the population of lakes ≥ 4 ha a small number of lakes accounts for a large percentage of the total surface area of lakes. There are 23 lakes larger than 5300 ha and they account for the other 50% of the total lake surface area (Table 2-4). The remaining 3939 lakes account for the other 50% (Fig. 2-3). Although one-half of the lakes in the Pacific Northwest are less than 11 ha in surface area, they account for only 10% of the total lake surface area.

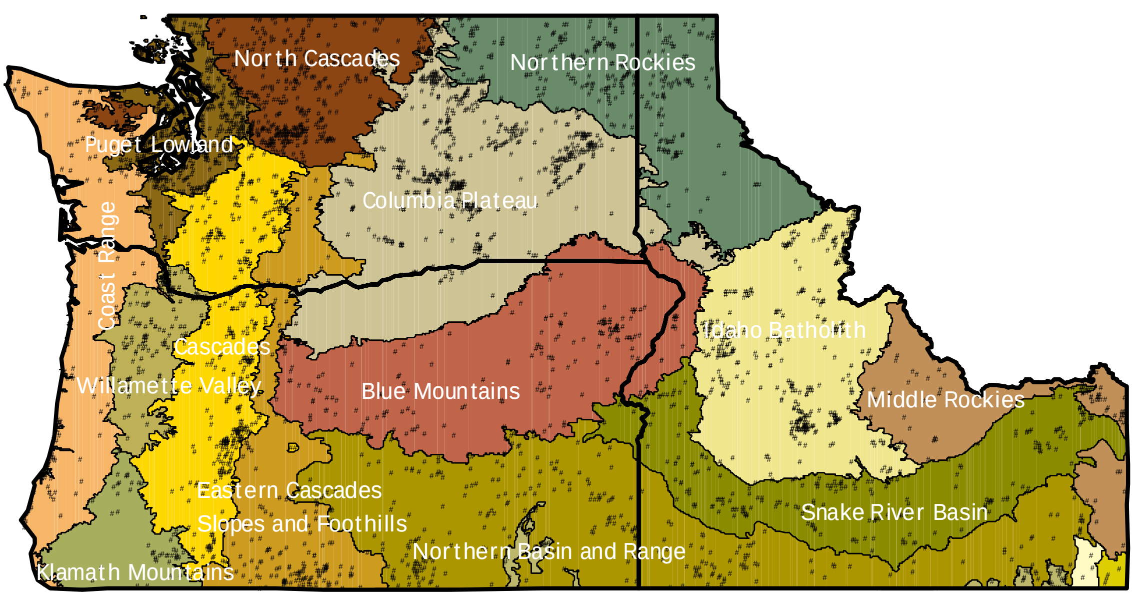

Figure 2-1. Location of the 3965 lakes ≥ 4 ha in the Pacific Northwest on the verified data layer. The fourteen Level III Ecoregions are also shown.

Table 2-1. Total number of lakes ≥ 4 ha in each Level III Ecoregion, associated total lake area and lake density (no/km^2 x 100). The highest number of lakes is found in the Columbia Plateau. The Norther Rockies has the highest total lake area whereas the Puget Lowlands has the highest lake density.

#	Ecoregion	Lakes No	Area (km^2)	Density (no/ 100 km ^{2})
1	Coast Range	171	156	0.40
2	Puget Lowlands	469	264	2.84
3	Willamette Valley	181	107	1.25
4	Cascades	395	447	0.88
9	Eastern Cascades	166	577	0.44
10	Columbia Plateau	620	994	0.73
11	Blue Mts	179	155	0.25
12	Snake River Basin	223	479	0.41
13	Cent Basin/Range	41	46	1.20
15	Northern Rockies	288	1087	0.52
16	Idaho Batholith	376	257	0.70
17	Middle Rockies	66	234	0.28
77	North Cascades	455	358	1.47
78	Klamath Mts	46	26	0.32
80	North Basin/Range	278	1045	0.29
	Total	3965	6391	

Table 2-2. Summary of the number of lakes/reservoirs in the BLM data layer as compared with lakes (≥4 ha) verified in this study. There are a total of 10,512 features on the BLM data layer. The population of lakes defined in this study (n = 3965) is an underestimate of the total number of water bodies in the PNW.

#	Ecoregion	BLM Lakes	BLM Res	This Study
1	Coast Range	280	160	171
2	Puget Lowlands	568	197	469
3	Willamette Valley	164	518	181
4	Cascades	1196	146	395
9	Eastern Cascades	160	249	166
10	Columbia Plateau	522	145	620
11	Blue Mts	253	656	179
12	Snake River Basin	177	296	223
13	Cent Basin/Range	10	20	41
15	Northern Rockies	459	90	288
16	Idaho Batholith	692	67	376
17	Middle Rockies	38	51	66
77	North Cascades	1021	39	455
78	Klamath Mts	46	256	46
80	North Basin/Range	309	1727	278
	Total	5895	4617	3965

Table 2-3. Number of lakes and reservoirs in the BLM data layer by state.

State	Lakes	Reservoirs
Idaho	253	673
Oregon	1737	3444
Washington	2920	508

Table 2-4. List of lakes in the Region greater than 5000 ha in surface area. These 23 lakes account for 3281 km^2 or nearly 50% of the total lake surface area in the Region.

	Lake Name	Lake Area (km^2)	% Total Area
1	Lake Pend Oreille	342	5.3
2	Franklin Roosevelt	315	4.9
3	Upper Klamath Lake	230	3.6
4	American Falls Res	227	3.6
5	Lake Umatilla	197	3.1
6	Lake Abert	164	2.6
7	Bear Lake	141	2.2
8	Lake Chelan	132	2.1
9	Summer Lake	122	1.9
10	Lake Coeur d'Alene	113	1.8
11	Goose Lake	112	1.8
12	Cascade Res	111	1.7
13	Banks Lake	109	1.7
14	Harney Lake	103	1.6
15	Grays Lake (wetland)	96	1.5
16	Priest Lake	95	1.5
17	Lake Washington	89	1.4
18	Blackfoot Res	70	1.1
19	Dworshak Res	67	1.0
20	Lake Wallula	60	0.9
21	Malheur Lake	60	0.9
22	Potholes Res	58	0.9
23	Crater Lake	53	0.8
	Total	3281	50.1

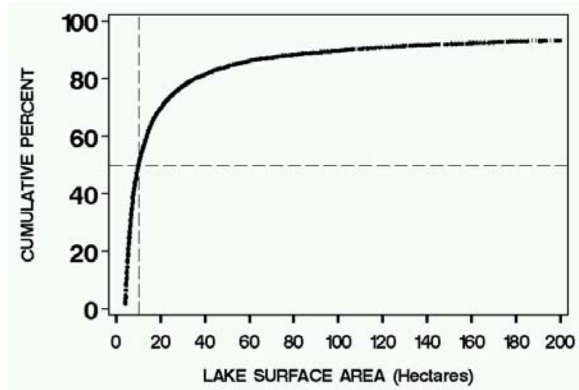

Figure 2-2. Cumulative distribution of lakes in the Region. About one-half the lakes are less than 10 ha in surface area.

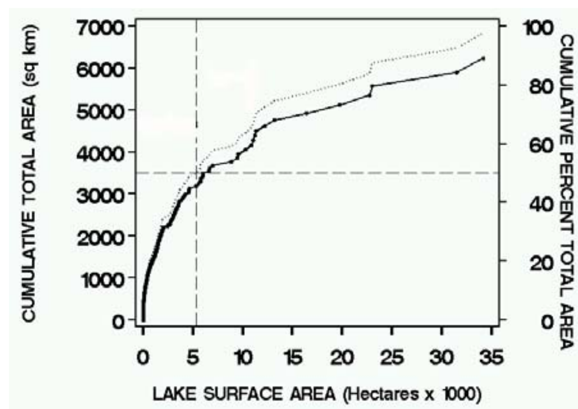

Figure 2-3. Cumulative total lake area (—) and percent total area (- - -) by individual lake surface area. Lakes greater than 5000 ha (n=23) account for one-half of the surface area in the Region. The remaining 3942 lakes account for the other half.

2.4 Discussion

This analysis shows that there are approximately 3965 lakes/reservoirs in the Pacific Northwest ≥ 4 ha in surface area. This same coverage indicates that there are about 9479 lakes ≥ 2 ha. The BLM data layer has a total of 10,535 water bodies labeled as either lakes or reservoirs without regard to surface area. As a first approximation there are 6570 lakes < 4 ha in area in the region. This corroborates the analysis of the size distribution of lakes ≥ 4 ha, i.e. a majority of lakes are relatively small.

There are 7,862 unique lake names in the BLM coverage. However, many unique features have the same name. For example, there are 58 “Lost Lakes” in the Region. There are ten lake names that have been used 28 or more times in the region (Table A-2). Lakes on state borders often have two designations for the same water body in a coverage, i.e. one lake is named twice. The extent of the naming of one lake twice was not investigated but appears to be rare relative to the use of one name to label many different lakes.

The verified coverage has at total of 10,938 named features. These named features are unique because they are associated with polygons. Electronic comparison of names in this coverage with the BLM names (n=10,535) resulted in 5,859 matches. The average area of the lakes for which names matched was 95 ha and for those not matching 20 ha. Visual inspection indicated that many of the names that did not match were actually the same and only differed by formatting or differences in naming convention, e.g. Lake Ozette versus Ozette Lake.

Thus there are roughly a total of 11,000 lakes and reservoirs in the region and about 7,000 lakes < 4 ha. Of those 7,000 roughly one third are between 3 and 4 hectares and two thirds less than 3 hectares. There are 4,000 lakes greater than 4 hectares, about 2,000 of which are less than 10 hectares.

It is evident that most lakes are relatively small (Fig. 2-2) and account for a small percentage of total lake surface area in the region (Fig. 2-3). The implications of this for development of numeric nutrient criteria are twofold. First, it is apparent that for smaller lakes, e.g. < 10 ha, because of their large number, it will be necessary to develop a lake classification or typology with respect to nutrient processing prior to developing nutrient criteria. Second, the development of lake categories for the largest lakes may not be necessary since there are relatively few of them in the region. These lakes may best be considered on an individual basis.

The relative importance of large lakes in the region in terms of their large contribution to total surface area may also be a consideration in developing a priority with respect to nutrient criteria development. Information on intensity of use, e.g. recreation, unique value of these large systems, as compared with smaller lakes, may be of help in determining which type of systems have the highest overall importance in the criteria development process.

The data layer developed here will also provide a better estimate of the population of lakes in the Pacific Northwest. Use of this population in probability samplig will reduce errors associated with including features on the landscape that are not lakes, e.g. wetlands, man made ponds.

Finally, this inventory provides an accurate description of the population of lakes greater than 4 hectares in surface area. This inventory can be used by investigators to design more accurate probability sampling schemes in the future.

CHAPTER 3. ANALYSIS OF HISTORICAL WATER QUALITY DATA

3.1 Database Development

Nutrient data were compiled from existing lake water quality databases in the Pacific Northwest (Idaho, Oregon, and Washington), and include;

- a post-1990 STORET database for EPA Region 10 obtained from EPA headquarters,
- the entire STORET database for Oregon, Washington, and Idaho from EPA Region 10
- a collection of non-STORET data for the region collected by Pacific States Marine Fisheries Commission,
- the EPA's Western Lakes Survey (WLS),
- and the Oregon Lake Atlas.

STORET Data

Many agencies routinely put their monitoring data into EPA's STORET system. As part of the national nutrient program, a national post-1990 (January 1, 1990 to September 1998) nutrient database was assembled by retrieving water quality data from STORET on the EPA's mainframe computer. Adhering to a post-1990 cut-off, however, eliminated hundreds of lakes that were sampled only in the 1970's and 80's so we also used the entire Pacific Northwest STORET data obtained from EPA Region 10. Data were retrieved from water bodies specified only as lake or reservoir for station types described as ambient (no pipe, hazard, sewer, or landfill type stations included). Data with a STORET remark code of B, E, F, G, H, J, N, O, P, Q, R, V, Y, or Z were deleted for data quality reasons. Data values with remark codes indicating value was below the detection limit were set to 0 (codes T, U, and W). Data values with remark codes indicating that the sample was detectable but off-scale or below practical quantification limit (codes I, K and M) were set to one-half the reported value. The data was also screened for duplicate values and duplicates were deleted. It should be noted that this STORET data is now considered to be "Legacy STORET".

Non-Storet data

The compilation of non-STORET data was undertaken to gather all the data that wasn't put into STORET by various groups and agencies involved in nutrient water quality monitoring throughout the states of OR, WA, and ID. This data was compiled by the Pacific States Marine Fisheries Commission. Federal, state and local agencies involved in water quality monitoring were asked for any nutrient and water quality data they had that wasn't in STORET. Data were obtained in many different formats, converted into common units and variable names and then compiled into one Excel spreadsheet for nutrient (water quality) data and one for site level (e.g., elevation, area, lat/long) data. All told there were 7,434 data records from 302 different sampling locations.

Western Lake Survey (WLS) data

The WLS was conducted in 1985 to quantify acidic deposition effects in lakes located in acid-sensitive regions of the western U.S. (Landers et al., 1987) Lakes were sampled after fall overturn in Fall, 1985. For nutrients, the database has measurements of total phosphorous, nitrate and ammonia as well as Secchi depth and lake morphometry. The data was collected following a rigorous QA program. There were 245 sample lakes in the Pacific Northwest.

Oregon Lake Atlas

As part of the Clean Lakes Program in Oregon, scientists from Portland State University conducted a survey and classification of lakes according to water quality status and published the results in an atlas of over 200 Oregon lakes (Johnson et al., 1985). Data included nutrient concentrations, depth profiles of dissolved oxygen and temperature, watershed information, and bathymetric information for the larger and/or most popular lakes in Oregon. Some of this data was in STORET but much of it was not.

Creating One Historical Database

Data from all sources were combined into one SAS database after converting variable names and units into a common format. There was a great deal of overlap in sample lakes among all these data sources and there is no consistent region-wide lake ID structure for knowing identical lakes between databases (there are many "Beaver" and "Long" lakes in the Northwest). One of the most time consuming tasks in the construction of one historical database was in matching lakes across data sources. The lake identifiers for the different databases all used a different coding and naming convention and it was impossible to electronically match lakes to see if the same lakes were sampled by multiple data sources with different ID codes. Also, many lakes were sampled in different places on the lake. These often had different station codes and there was no identifier in the database indicating that they were collected from the same lake (in the STORET data). All of the lake and site names and codes were gone through by hand and by using names, sizes, state/county location, latitude/longitude and topographic maps, a unique lake ID and site within-lake ID were created for each record in each database to indicate unique lakes and sampling sites within a lake. Nutrient variables that are in the database include total phosphorus, total nitrogen, total kjehldahl nitrogen, nitrate, ammonium, chlorophyll-a, and secchi depth. Other water quality variables include, temperature, dissolved oxygen, pH, turbidity, and conductivity. Virtually none of the data records has all of the water quality variables. The data was screened and obvious unit or analytical outliers deleted. Sample dates in the historic database ranged from March 16, 1965 to June 22, 1999. However, only data collected after 1970 were included in this analysis. Data from lakes 303(d) listed for nutrients were excluded from analysis.

The data pertaining to sampling depths varied among data sources. Actual sample depths were often not reported other than listed as "top" or "surface" or "bottom". Data records without depth information where only one sample was collected were considered to be surface or top data. In sample visits from a given day with multiple depth records, the shallowest one was considered "Top", the deepest as "Bottom" and the remainder as "Middle". In sampling visits with multiple observations on a given day without any depth data, top, middle, bottom classes were inferred by looking at the sample times, station name (sometimes labeled as epilimnion or hypolimnion), temperature, dissolved oxygen, and nutrient data. The earlier, warmer samples were assumed to be from the top. Just over half (54%) of the data records were classified as surface samples, 24% as mid-depths, and 22% as bottom samples.

3.2 Sample Lakes and Creating Index Values

In the combined data set, there were 25,536 data records from 1,107 unique lakes (Table 3-1). Among these lakes, 850 were represented by one sample site, 148 had two different sampling sites on the lake, 42 had three sample sites, 11 had four sites, and 59 had five or more sites.

The most extreme, Coeur d'Alene Lake, had

60 different sample locations. Lakes are not evenly disbursed throughout the Pacific Northwest and sample lakes in the historical database are even more clustered in small areas (Fig. 3-1). Four Ecoregions; Cascade Mountains, Northern Cascades, Northern Rockies, and Puget Lowlands contained most (76%) of the lakes in the historical database and each consisted of more than 100 sample lakes. Lakes with complete nutrient data (total P, chlorophyll-a, and secchi depth) were rare (Table 3-1). Lakes with complete data were mostly located in the mountainous ecoregions of Oregon. Almost half (42%) of the sample data were collected in summer but data was reported for all months of the year. Spring samples made up the next largest sampling time (27%), followed by Fall (17%), and winter (15%).

For regional analysis of the lake data, we created a single value, the summer index value, for each unique lake. We decided to restrict the analysis to only surface or top data collected between May and October (inclusive). The small amount of data collected before 1970 was deleted. The goal was to try to minimize seasonal influences without eliminating a large number of lakes from the database that didn't have samples in July and August. Of the 25,857 records in the database, 9,707 were from post-1970, May-October surface data. To calculate a single lake index value, we first calculated the median nutrient chemistry for each year within each unique lake sample location at each lake. Next we calculated a median value for each sample location by taking the median across all the yearly medians. The final lake chemistry index value was then taken as the median of all the median site location values for all sites on that 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. All told, the 9,707 surface observations were reduced to 2,909 lake by site yearly medians, then reduced to 1,857 different lake site medians, and finally reduced to 1,110 median lake index values.

Index values were calculated for streams from a separate database in a similar fashion. Each stream sampling station had a unique latitude and longitude. Annual median values for each parameter value were calculated for each station for the May-October index period. The median of those annual medians was the stream summer index value.

3.3 Chemical Characteristics of Summer Surface Index Data

Total phosphorus (TP) index data were present at almost all (1,052 of 1,107) lakes in the historical database (Table 3-2). Univariate population percentiles show that most of the lakes in the historical database are oligotrophic (Table 3-2). Median TP was 20.0 ug/L, TN 220 ug/L, chlorophyll-a 3.2 µg/L and Secchi 4.0 m.

Table 3-1. Distribution of the sample lakes in the historical database across states and level III ecoregions in Region 10. The percentage of lakes with data ranges from a low of 6% in the Snake River Basin to a high of 71% in the Cascades.

Eco No	Location State/Ecoregion	Total Records	No lakes with Data	No Lakes with complete data*	No Lakes > 4 ha	Percent lakes with data
	Idaho	3917	148	38	913	16
	Oregon	7707	350	211	1076	33
	Washington	12912	609	31	1942	31
1	Coast Range	2986	69	34	174	40
2	Puget Lowland	9056	231	15	469	49
3	Willamette Valley	684	14	6	181	8
4	Cascades	4679	280	68	395	71
9	Eastern Cascades Slopes/Foothills	401	17	11	166	10
10	Columbia Plateau	2473	61	2	620	10
11	Blue Mountains	266	31	4	179	17
12	Snake River Basin	477	13	9	223	6
13	Central Basin and Range	1	1	1	41	2
15	Northern Rockies	3881	69	7	288	24
16	Idaho Batholith	357	74	9	376	20
17	Middle Rockies	152	10	3	66	15
18	Wyoming Basin**	315	0	0	0	-
19	Wasatch and Uinta Mountains**	2	0	0	0	-
77	North Cascades	689	190	0	455	42
78	Klamath Mountains	0	0	0	46	0
80	Northern Basin and Range	142	18	13	278	
	Total	**26561**	**1080**	**183**	**3957**	**-**

* Complete nutrient data indicates simultaneous measurements of total phosphorus, Secchi depth and chlorophyll-a.

** Ecoregions with minimal area in Region 10.

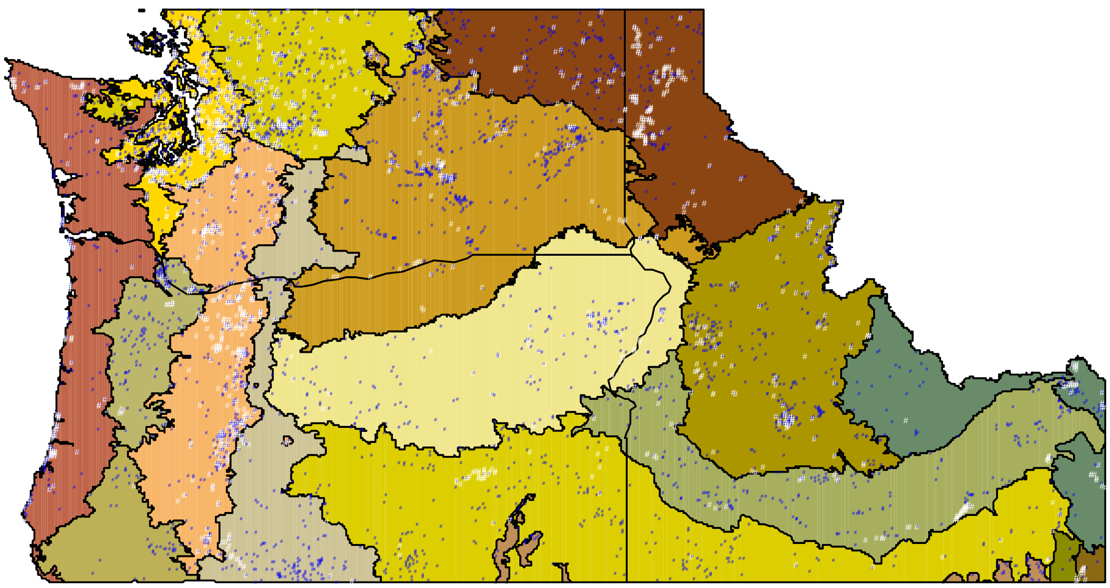

Figure 3-1. Locations of all inventoried lakes in the Pacific Northwest (black points) and those lakes with at least one sample for nutrient data (white points). Most of the samples in the Cascade Ecoregion are from the Western Lake Survey (EPA 1997). The other concentration of data is in the Puget Lowlands.

Table 3-2. Sample data percentiles for all data (ug/L) and summer index lake chemistry of the 992 lakes in the historical database. N is the total number of samples (all data) or number of lakes that had measured values for that nutrient variable.

Variable	n	p10	p25	media	p75	p90
All Data						
Total Phosphorus	12699	5.0	10.0	20.0	46.0	120.0
Total Nitrogen	9665	10.0	90.0	220.0	500.0	1040.0
Nitrate	10387	3.0	10.0	20.0	90.0	310.0
Ammonia	10384	1.0	8.0	20.0	58.5	160.0
TKN	13759	0.0	330.0	20.0	360.0	800.0
Secchi (m)	6149	1.2	2.1	3.5	5.2	7.9
Chlorophyll **a**	1703	0.5	1.3	3.2	9.2	20.0
Summer Index Values						
Total Phosphorus	992	2.1	20.0	10.7	29.0	62.0
Total Nitrogen	395	100.0	220.0	480.0	1000.0	1500.0
Nitrate	717	0.0	2.0	10.0	48.0	84.0
Ammonia	853	0.0	8.0	25.0	70.0	120.0
TKN	659	0.0	100.0	330.0	690.0	1200.0
Secchi (m)	526	1.5	4.0	4.4	7.5	11.8
Chlorophyll **a**	287	0.3	3.2	2.3	6.1	12.5

Seventy-five percent of the lakes had TP below 29.0 µg/L. Ammonium was observed in most lakes where it was measured; 75% of the lakes had ammonium ≥ 8 µg-N/L. Note that total nitrogen (TN) and chlorophyll-a were available from less than half the sampled lakes in the database. The typical lake in the historical database had a secchi depth of 4.4 m (Table 3-2).

The rest of this section will focus on four nutrient variables; TP and TN, chlorophyll-a, and secchi depth. The relationship between TP and secchi depth showed the expected pattern of clear lakes (high secchi depth) having lower TP while lakes with high TP tended to have low secchi depths (Figure 3-2).

Plots of all the other combinations of nutrient variables (seasonal index values) also show the expected relationship of higher chlorophyll-a and lower secchi depths with increasing nutrient concentrations. (Figures 3-2 to 3-7). All of the plots are very noisy with numerous outliers which is most likely due to the fact that the data were compiled from many different sources which all had different lab protocols, QA procedures, and field methods which probably changed over time. There does seem to be a large number of outliers at TN concentrations less than 20 µg-N/L (Figure 3-4). These low total N numbers are likely artifacts of high lab detection limits or QA problems. Values below 20 are very indicative of low total N concentrations but we have little confidence in nitrogen values <20 µg-N/L. A detection limit of 10 ug/L is also apparent in the total phosphorus plots (Fig. 3-3).

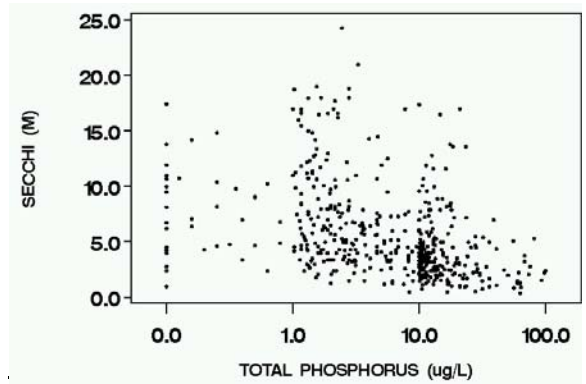

Figure 3-2. Relationship between total phosphorus and Secchi depth in all May-October surface data from historical data base

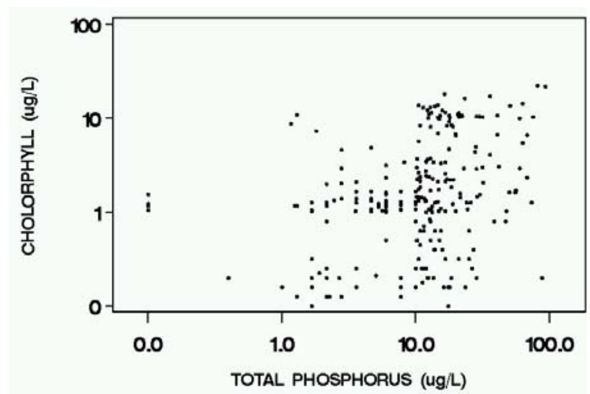

Figure 3-3. Relationship between total phosphorus and chlorophyll depth in all May-October surface data from historical data base.

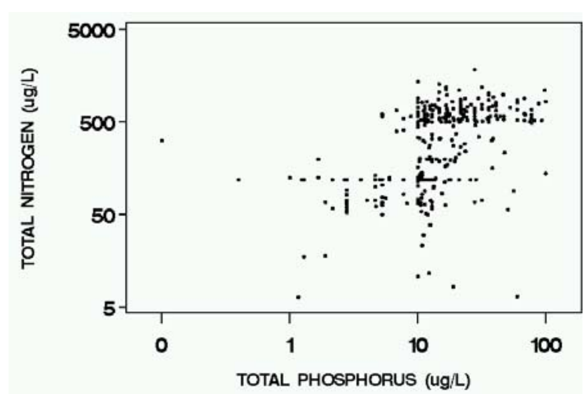

Figure 3-4. Relationship between total phosphorus and total nitrogen in all May-October surface data from historical data base.

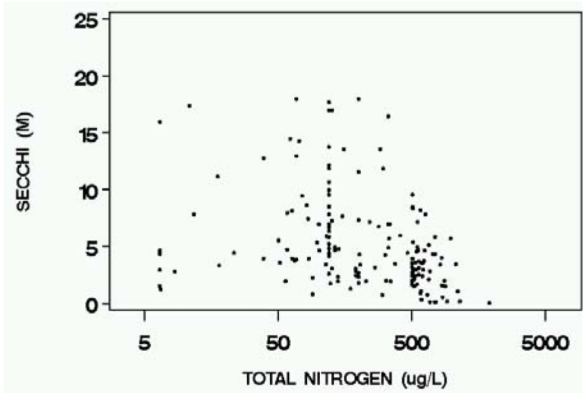

Figure 3-5. Relationship between total nitrogen and Secchi depth in all May-October surface data from historical data.

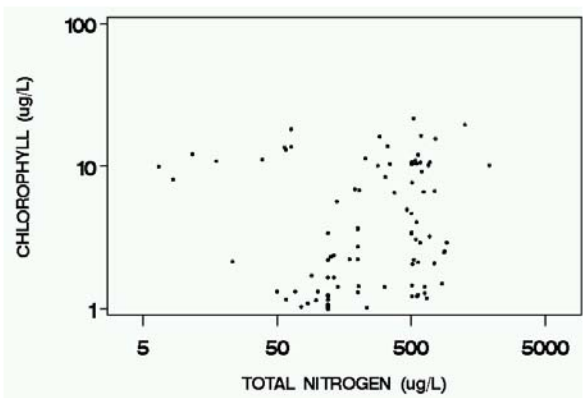

Figure 3-6. Relationship between total nitrogen and chlorophyll in all May-October surface data from historical data.

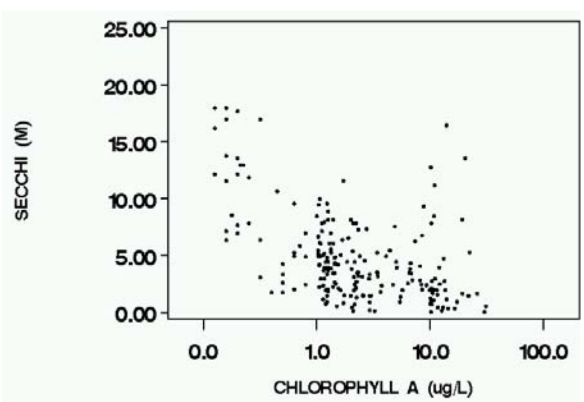

Figure 3-7. Relationship between Secchi depth and chlorophyll in all May-October surface data from historical data.

3.4 Level III Ecoregional Patterns

Patterns Across Ecoregions

Distributions of nutrient criteria variables were compared among Level III Ecoregions (Omernik, 1987) (Figures 3-8 to 3-12). Summer median total P values ranged from a low of 3.6 ug/L in the Idaho Batholith to 90 ug/L in the Norther Basin and Range (Table 3-3, Fig. 3-8). The median ecoregion TP concentration for five ecoregions was above the pooled TP median of 14.0 ug/L, six were below the median and two close to the median (Fig. 3-8).

Median regional TN was 478 ug/L. Median total nitrogen concentrations ranged from 100 ug/L in the North Cascades to 1,270 ug/L in the Northern Basin and Range (Table 3-4, Fig. 3-9). Variability in summer TN concentrations across ecoregions generally increased with increasing median concentrations.

Table 3-3. Summer index total phosphorus (µg/L) medians (med) and percentiles across level III ecoregions. N is the number of lakes with data.

#	Ecoregion	n	p10	p25	med	p75	p90
1	Coast Range	67	6.8	9.5	12.0	26.0	80.0
2	Puget Lowland	223	8.0	12.0	20.0	40.0	60.0
3	Willamette Valley	12	10.0	27.0	50.8	105.0	163.0
4	Cascades	240	2.0	4.9	10.0	25.8	56.6
9	Eastern Casc	16	6.0	16.2	22.0	110.2	202.5
10	Columbia Plateau	57	12.0	20.0	30.0	70.5	95.5
11	Blue Mountains	26	2.4	4.2	9.4	34.2	58.0
12	Snake River Basin	13	29.5	39.0	71.0	168.8	190.0
15	Northern Rockies	54	4.5	10.0	11.5	20.0	40.0
16	Idaho Batholith	74	0.0	0.8	3.6	7.0	17.0
17	Middle Rockies	6	3.2	7.0	23.9	50.0	60.0
77	North Cascades	189	1.4	2.6	5.0	9.0	11.3
80	Northern Basin	15	22.0	52.0	90.0	204.0	252.0

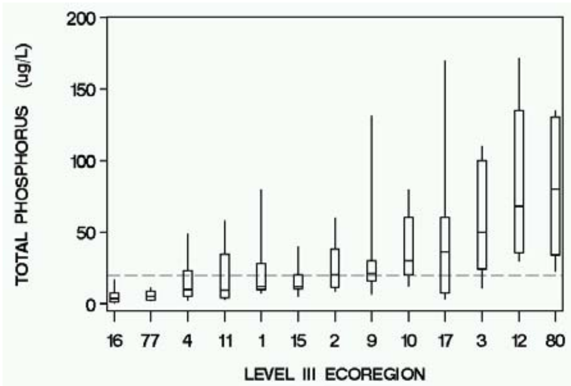

Figure 3-8. Box and whisker plots for seasonal index total phosphorus concentrations by level III Ecoregion in the historical database. The box represents the 25th to 75th percentile and the line in the box the median. Whiskers show the 10th and 90th percentiles. The horizontal line (10 ug/L) shows the median concentration for all the historical data. The data are plotted in order of increasing median values.

1 Coast Range
2 Puget Lowland
3 Willamette Valley
4 Cascades
9 Eastern Cascades Slopes
10 Columbia Plateau
11 Blue Mountains
12 Snake River Basin
15 Northern Rockies
16 Idaho Batholith
17 Middle Rockies
77 North Cascades
78 Klamath Mountains
80 Northern Basin and Range

An examination of N:P ratios shows that most lakes in most ecoregions are phosphorus limited (based on a molar N:P ratio < 35) (Figure 3-10). Three ecoregions had relatively high median N:P ratios; the Puget Lowlands, Northern Rockies and Idaho Batholith, suggesting that some of the lakes in these ecoregions may be nitrogen limited. Ecoregional patterns in Secchi depth and chlorophyll concentrations were consistent with those observed for TP and TN concentrations. The regional median Secchi depth was 3.5 meters. Median Secchi depth across ecoregions ranged from 0.6 m in the

Table 3-4. Summer index total nitrogen (µg/L) medians (med) and percentiles across level III ecoregions. N is the number of lakes with data.

#	Ecoregion	n	p10	p25	med	p75	p90
1	Coast Range	51	80	180	250	550	900
2	Puget Lowland	117	410	550	1000	1400	1700
3	Willamette Valley	6	520	570	770	1125	1200
4	Cascades	89	80	220	220	420	730
9	Eastern Casc	9	220	400	520	1620	3110
10	Columbia Plateau	21	340	710	980	1450	2300
11	Blue Mountains	9	45	220	230	655	735
12	Snake River	4	220	395	580	720	850
15	Northern Rockies	43	10	210	530	750	1200
16	Idaho Batholith	5	150	310	410	480	970
17	Middle Rockies		125	615	627	950	1450
77	North Cascades	27	50	60	100	110	120
80	Northern Basin	9	220	820	1270	2110	6060

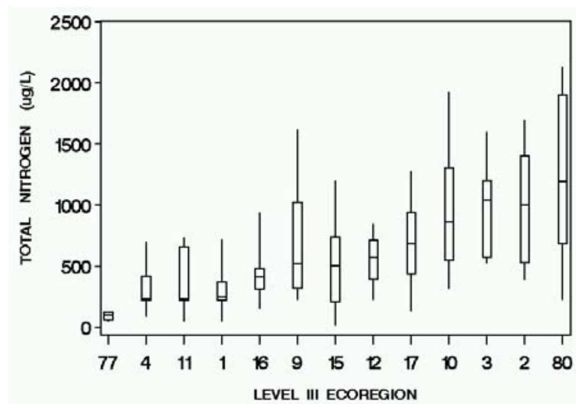

Figure 3-9. Box and whisker plots for seasonal index total nitrogen concentrations by level III ecoregion in the historical database. The horizontal line (478 ug/L) shows the median concentration for all the historical data. Legend same as for Fig. 3-8.

Northern Basin and Range to 7.0 in the North Cascades (Table 3-5, Fig. 3-11). The median pooled chlorophyll concentration was 4.0 ug/L. Median chlorophyll concentrations ranged from a low of 1.3 ug/L in the Cascades to a high of 12.8 ug/L in the Snake River Basin (Table 3-6, Fig. 3-12).

Total P was correlated with all other variables

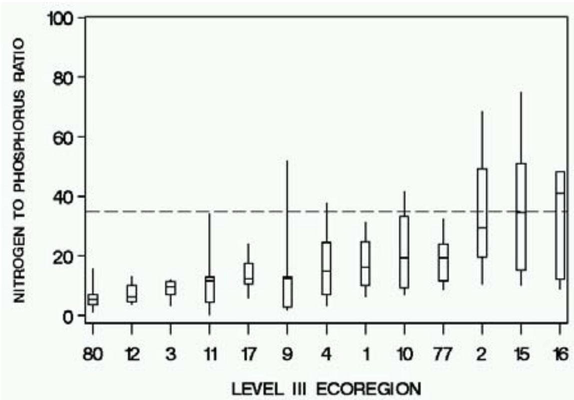

Figure 3-10. Box and whisker plots for seasonal index total nitrogen to total phosphorus ratio by level III ecoregion in the historical database. The horizontal line represents a N:P ratio of 35, above which lakes would be phosphorus limited. Legend same as for Fig. 3-8.

except TKN. TP was correlated with all variables except Secchi depth and chlorophyll were not correlated. Total N increased with TP across ecoregions (Fig. 3-13). Median Secchi depth exhibited a declining pattern with increasing total P (Fig. 3-14). Median chlorophyll concentrations increased with increasing total P across ecoregions (Fig. 3-15). Secchi depth generally decreased with increasing chlorophyll concentrations (Fig. 3-16).

The regression statistics for selected log transformed parameters are given in Table 3-7. All regressions were significant.

A one-way analysis of variance (ANOVA) on log transformed total P by ecoregion was highly significant (F=5.5, p<0.0001) indicating that mean TP concentrations were different among ecoregions. Duncan's multiple range test indicated that there are five groups of level III Ecoregions (Table 3-8).

A one-way analysis of variance (ANOVA) on log transformed total N by ecoregion was highly significant (F=31.9, p<0.0001) indicating that mean TN concentrations were different among ecoregions (Table 3-9).

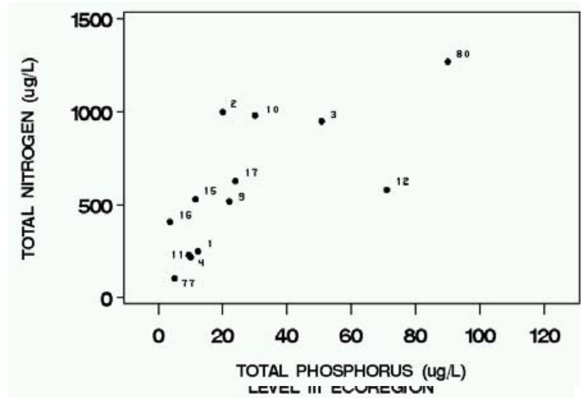

Figure 3-13. Relationship of median index total nitrogen to median total phosphorus across level III ecoregions. Legend same as for Fig. 3-8.

Figure 3-11. Box and whisker plots for seasonal index Secchi depth by level III ecoregion in the historical database. The horizontal line (4.8 m) shows the median Secchi depth for all the historical data. Legend same as for Fig. 3-8.

Although only eight ecoregions had sufficient data for analyses, the between ecoregion tests (Duncan's multiple range rest) revealed

Table 3-5. Secchi depth (m) sample data percentiles for index lakes by le vel III Ecoregions. N is the number of lakes that had data.

#	Ecoregion	n	p10	p25	median	p75	p90
1	Coast Range	56	1.0	2.0	3.4	4.2	6.1
2	Puget Lowland	31	1.2	2.0	2.5	3.5	4.8
3	Willamette V	9	0.2	0.5	0.8	2.6	5.0
4	Cascades	163	2.1	3.4	5.2	8.0	12.8
9	Eastern Cas	15	0.8	1.5	2.8	8.5	9.6
10	Columbia Plat	10	0.8	1.4	2.8	6.0	7.8
11	Blue Mountain	19	1.5	2.8	5.2	7.7	11.4
12	Snake River	11	1.0	1.0	1.4	1.6	1.7
15	Northern Rock	41	2.0	2.9	4.2	5.8	8.4
16	Idaho Batholi	71	2.4	3.8	5.8	9.5	12.0
17	Middle Rockie	5	3.0	3.2	4.4	5.5	6.6
77	North Cascade	79	2.4	4.2	7.0	11.3	16.5
80	Northern Basi	16	0.2	0.2	0.6	3.9	5.3

Table 3-6. Chlorophyll-a (µg/L) sample data percentiles for index lake chemistry by level III ecoregions. N is the number of lakes with data.

No	Ecoregion	n	p10	p25	median	p75	p90
1	Coast Range	36	0.8	2.0	5.0	9.4	17.5
2	Puget Sound	15	2.4	4.0	7.0	10.8	12.0
3	Willamette V	6	1.1	1.6	5.4	8.8	13.0
4	Cascades	163	0.2	0.5	1.3	3.0	9.3
9	EasternCas	13	1.0	1.7	2.0	4.7	11.5
10	ColumbiaPlat	2	0.9	0.9	2.5	4.2	4.2
11	Blue Mts	7	0.3	0.4	2.1	4.3	4.8
12	Snake River	9	1.8	5.2	12.8	31.3	40.5
15	Northern Rock	10	1.8	4.0	7.8	9.7	11.7
16	Idaho Bathlth	9	1.2	1.6	2.4	6.8	20.2
17	MiddleRockies	3	0.2	0.2	8.4	13.9	13.9
77	North Casc	0	-	-	-	-	-
80	N. Basin	14	2.1	80	4.2	5.6	25.0

Table 3-7. Regression statistics for the equation log(Dependent Variable)= (slope) x log(total P) + intercept, for ecoregional median for total N, nitrate and chlorophyll concentrations. Secchi depth was not log transformed.

Dependent Variable	N	Intercept	Slope	R^2
TN	**12**	**2.14**	**0.46**	**0.48**
NO_3	**15**	**-2.75**	**0.83**	**0.49**
Secchi	**13**	**0.98**	**-0.43**	**0.76**
Chlorophyll	**11**	**0.12**	**0.37**	**0.24**

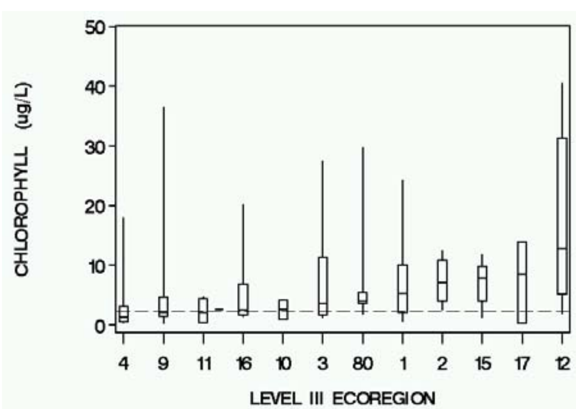

Figure 3-12. Box and whisker plots for seasonal index chlorophyll a concentrations by level III ecoregion in the historical database. The horizontal line (2.8 ug/L) shows the median concentration for all the historical data. Legend same as for Fig. 3-8.

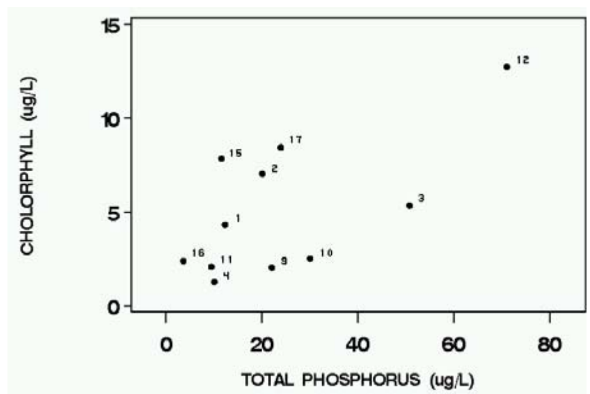

Figure 3-15. Relationship of median index chlorophyll to median total phosphorus across level III ecoregions. Legend same as for Fig. 3-8.

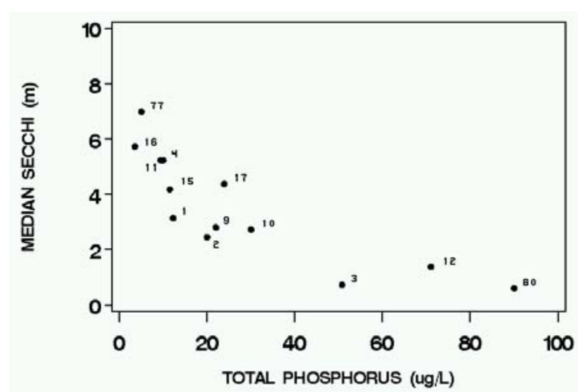

Figure 3-14. Relationship of median index Secchi depth to median total phosphorus across level III ecoregions. Legend same as for Fig. 3-8.

three significant groups of ecoregions in order of decreasing mean TN concentration (Table 3-10): Group 1 (North Cascades); group II (Blue Mountains, Coast Range, Cascades and Northern Rockies) and group III (Puget Lowlands, Columbia Plateau and Northern Basin and Range). order was different (Tables 3-9, 3-10). The total P group E (Idaho Batholith and North Cascades) corresponds to group I based upon total N (North Cascades) (Tables 3-9, 3-10). Total P group D (Cascades, Northern Rockies, Blue Mountains and Range) contains the same ecoregions as in TN group II. The Northern Basin and Range has the highest TP and TN concentrations. There are too few data to analyze ecoregions with intermediate TN concentrations. However, it is interesting to note that the Idaho Batholith is enriched in TN with respect to TP whereas the Snake River Basin shows the opposite trend.

Comparison of the groups based upon TP and TN revealed a definite grouping of ecoregions based upon these nutrients. The six ecoregions with the lowest TP and TN concentrations were the same, although the

These results indicate that there are roughly four groups of level III ecoregions based upon TP and to a degree on TN concentration:

1) Idaho Batholith, North Cascades
2) Cascades, Norther Rockies Blue Mountains, Coast Range
3) Puget Lowlands, Middle Rockies, Eastern Cascades and Foothills, Columbia Plateau,
   Willamette Valley
4) Snake River Basin, Northern Basin and Range

Table 3-8. Results of Duncan's multiple range test comparing mean total P concentrations (ug/L) across level III ecoregions. Ecoregions with the same letter are not significantly different. * Not included in ANOVA calculations because n < 10 for the ecoregion.

Group Duncan		Trophic	TP	Eco No	Ecoregion
	A	I	152	80	N. Basin/ Range
	A	I	83	12	Snake River
			44	3	Willamette Valley*
	B	II	42	10	Columbia Plateau
C	B	II	38	9	Eastern Cascades
		II	24	17	Middle Rockies*
C	B	II	22	2	Puget Lowland
C	D	III	18	1	Coast Range
	D	III	14	11	Blue Mts
	D	III	13	15	Norther Rockier
	D	III	11	4	Cascades
E		IV	5	77	N. Cascades
E		IV	4	16	Idaho Batholith

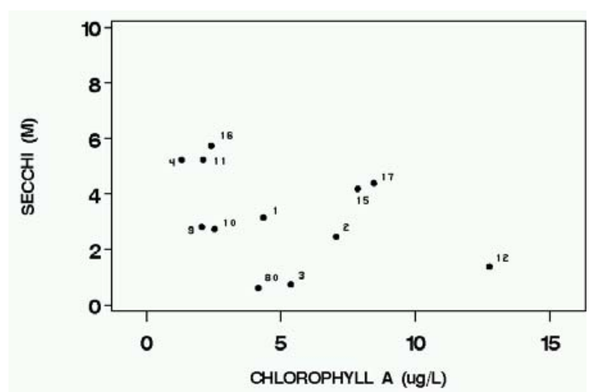

Figure 3-16. Relationship of median Secchi to median chlorophyll concentrations across level III ecoregions. Secchi decreases with increasing chlorophyll. Legend same as for Fig. 3-8.

Table 3-9. Results of Duncan's multiple range test comparing total nitrogen concentrations across level III ecoregions. Ecoregions with the same letter are not significantly different. Ecoregions without letters had n<9.

Grouping Duncan	Trophic	TN	Eco No	Ecoregion
A	I	1230	80	N. Basin/ Range
A	I	979	10	Columbia Plateau
	I	845	3	Willamette Valley
A	I	892	2	Puget Lowlands
		774	9	Eastern Cascades
		502	12	Snake River
		583	17	Middle Rockies
		390	16	Idaho Batholith
B	II	336	15	N. Rockies
B	II	226	4	Cascades
B	II	267	1	Coast Range
B	II	233	11	Blue Mts
C	III	155	77	N. Cascades

One-way analysis of variance indicated a highly significant difference among trophic groups on the basis of total P (F=530.0, p<0.001) and Secchi (F=299.8,p<0.001). Duncan's multiple range test indicated that each trophic group was significantly different from all other groups for these variables. Results for TN (F= 56.6,p<0.001), and chlorophyll (F=120.4,p<0.001) also showed differences among trophic groups. However, for TN only three significantly different groups (1, 2/3, 4) were identified, i.e. groups 2 and 3 were not significantly different. For chlorophyll only two groups were significantly different from one another (½, 3/4). Median values for selected water quality parameters for these four trophic groups are presented in Table 3-11.

Table 3-10. Median values for selected water quality parameters by trophic group.

TG	TP	Sol P	TN	TKN	NO_3	NH_3	Sec	Chl
I	4.3	2.2	257	177	8.5	5.0	6.4	2.4
II	11.1	9.1	240	200	12.2	17.7	4.7	3.2
II	23.9	6.0	950	560	35.0	40.0	2.8	5.4
IV	80.5	33.1	925	646	58.7	27.5	1.0	8.5

Patterns within Ecoregions and Trophic Groups

To investigate whether the TP-TN and nutrient-stressor relationships were different across ecoregions and trophic groups, TN, Secchi and chlorophyll were regressed against TP. Regressions across ecoregions appeared to be similar with no clear pattern between nutrient rich and nutrient poor ecoregions.

Regressions for log(TN)=log(TP) by trophic group had slopes ranging from 0.49 in group 2 to 0.66 in group 1 (Table 3-11). The slopes were not significantly different was no pattern between slope and increasing trophic level. The slopes of the log(Secchi)-log(TP) relationship were essentially identical, varying from -0.38 to -0.40. The slopes of the log(chl)-log(TP) were also similar but had relatively low R^2. These regression statistics were also similar to the ones calculated using all data across ecoregions (Table 3-8). Thus the relationship of TP-TN and nutrients and stressors did not appear to vary across either ecoregions or trophic groups.

Comparison of Lake and Stream Data

To further evaluate the observed patterns in nutrient concentrations across level III ecoregions, lake data were compared with existing data on rivers and streams. Data from the our Regional stream water quality database were analyzed as described for the lake data.

Median summer ecoregional TP, TN, NO_3, NH_3 and TKN values were computed for each level III ecoregion for streams and compared with corresponding lake medians by ecoregion. Stream total P concentrations varied across ecoregions in a manner similar to that for lakes (Fig. 3-17). Regression statistics for stream versus lake data are presented in Table 3-13. There were significant relationship between river and lake median NO_3, NH_3 TKN concentrations. But not total nitrogen. Generally summer median

Table 3-11. Regression statistics for data pooled across trophic groups for TN, Secchi or chlorophyll and the dependent variable (DV). The equation used was Log(DV) = slope) x (Log(TP)) + intercept, where N is the total number of data pairs used to fit the model.

TG	N	Int	Slope	R^2
Total N				
1	370	1.58	0.66	0.51
2	3449	1.74	0.49	0.26
3	3420	1.71	0.59	0.37
4	218	1.61	0.62	0.46
Secchi				
1	235	1.00	-0.38	0.20
2	965	1.16	-0.40	0.23
3	2292	0.95	-0.40	0.27
4	131	0.72	-0.38	0.25
	Chlorophyll			
1	12	0.52	0.31	0.41
2	687	0.18	0.28	0.07
3	767	0.48	0.28	0.09
4	37	0.58	0.25	0.22

Table 3-12. Regression statistics for relationship p for median summer index total P (ug/L) and various nitrogen species (mg/L) between lakes and streams. The equation parameterized was Stream (var) = slope*lake(var) + intercept.

Nutrient	N	Int	Slope	R^2
Total P	11	10.41*	1.50	0.79
Ammonia	10	0.01*	0.84	0.69
Nitrate	9	0.05	1.29	0.57
TKN	9	0.15	0.41	0.70

* Intercept not significantly different from zero (p<.05).

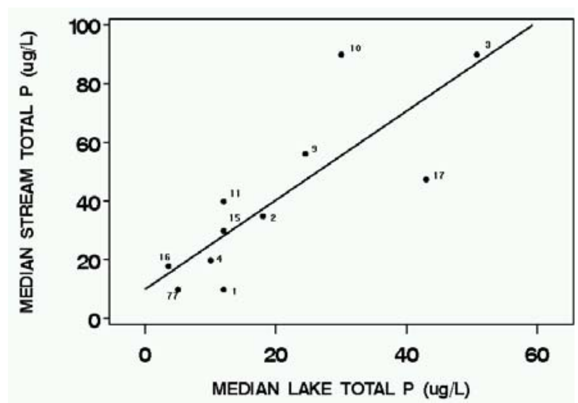

Figure 3-17. Relationship of median index total phosphorus values between streams and lakes across level III ecoregions. Numbers refer to ecoregions. TP concentrations were 50% higher in streams than in lakes in any given ecoregion.

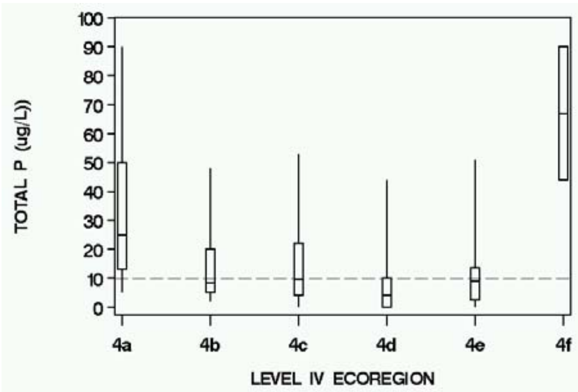

Figure 3-18. Box and whisker plots for seasonal index total phosphorus concentrations by level IV ecoregion in the historical database. The horizontal line (10 ug/L) shows the median concentration for the Level III Ecoregion, Cascades.

No	Level IV Ecoregion
4a	Western Cascades Lowlands and Valleys
4b	Western Cascades Montane Highlands
4c	Cascade Crest Montane Forest
4d	Cascade Subalpine/Alpine
4e	High Southern Cascades Montane Forest
4f	Southern Cascades

3.5 Level IV Ecoregional Patterns

There are 150 Level IV Ecoregions in Idaho, Oregon and Washington ranging from 127 to 26,000 sq km^2 in surface area (Fig. 3-20). About 45 of these Ecoregions are less than 10,000 sq km^2. Thus for purposes of stratifying the landscape for lakes these ecoregions may be too small. Four Level III Ecoregions (Puget Lowlands, Cascades, Columbia Plateau and Northern Cascades) had sufficient data (N> 10 lakes) for analysis. For example, the Cascades Ecoregion has six Level IV Ecoregions, five of which have sufficient data (Fig. 3-19). Four of those ecoregions (4b, 4c, 4d, 4e) are very similar to one another. Ecoregion 4a includes lakes in the Mt. St. Helens blast area and therefore would be expected to exhibit high total phosphorus levels. It appears that stratification to level IV in this Level III Ecoregion can provide additional information regarding patterns in index total phosphorus concentrations.

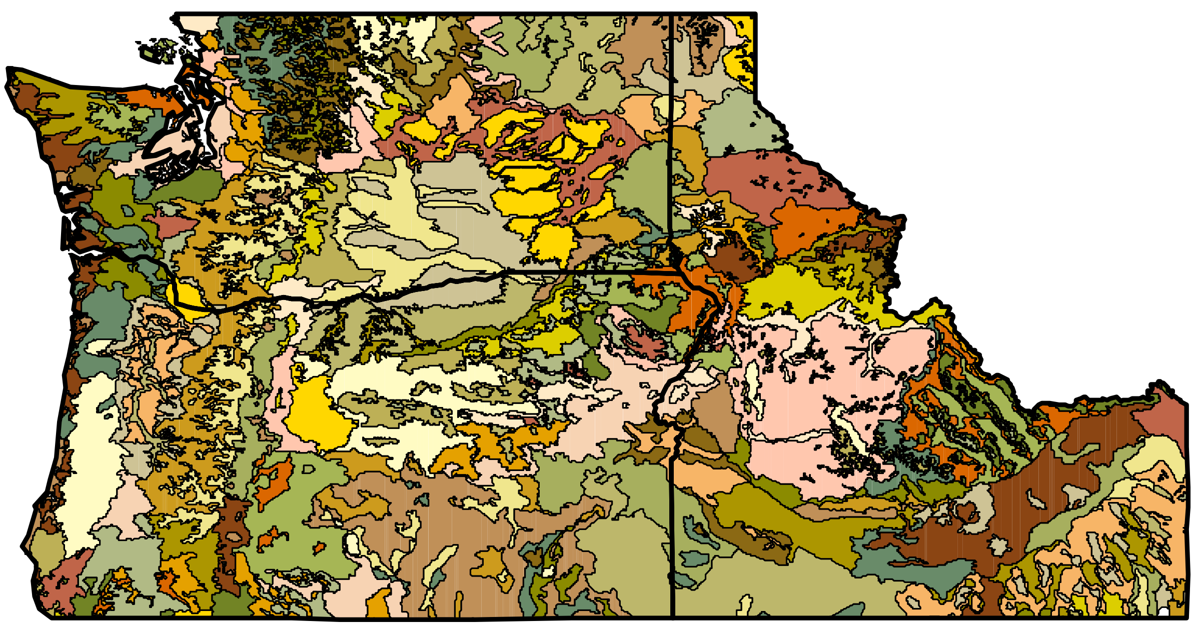

Figure 3-19. There are a total of 150 Level IV ecoregions in Idaho, Oregon and Washington

3.5 Discussion

Of the roughly 4,000 lakes in the Pacific Northwest, approximately 1,000 or 25% lakes are represented in the database (Table 3-1). However, only three Ecoregions (Coast Range, Puget Lowlands and Cascades) had a significant percentage of lakes with complete data. Nevertheless there were many Ecoregions with significant percentages of lakes with total P and Secchi data (Table 3-2). By far the least amount of data was available for chlorophyll a.

It is difficult to assess how well the water quality data in the database represents the lakes in a given ecoregion. For Ecoregions with significant amounts of data for a given parameter the data may be representative for lakes in that Ecoregion. This is particularly true for Ecoregions with little human disturbance. For example, of the 689 lakes in the North Cascades Ecoregion, 189 have data on total P. Since this ecoregion has relatively little disturbance the distribution of total P in the database may be taken, as a first approximation, to that of all the lakes in the Ecoregion. In addition, since there are 79 lakes with Secchi data, the relationship derived for Secchi and total P in this Ecoregion may be robust. However, there are no chlorophyll data so a total P-chlorophyll relationship cannot be derived. As similar situation exists in the Cascade Ecoregion. For these Ecoregions it may be possible to use the historical data as an accurate description of nutrient dynamics in these lakes.

In contrast, the Puget Lowland lakes are also well represented in the database but this Ecoregion has substantial agricultural and urban activity. Whether the higher median total P value, as compared with the above two Ecoregions, and the higher variability in TP is due to actual differences in lakes or a result of landscape disturbance is unknown. It most likely is a combination of these two factors. This is also true for other Ecoregions, e.g. Willamette Valley (median total P = 51 ug/L), Columbia Plateau (TP = 30 ug/L), Snake River Basin (TP = 71 ug/L), etc. that have experienced significant anthropogenic influence. This is evident in Fig. 3-8, where the Ecoregions on the right side of the graph tend to have relatively high human disturbance. For such Ecoregions, it will necessary to use additional methods in addition to historical data to describe nutrient dynamics in these lakes.

It is also apparent that values of total P, total N and Secchi are much better behaved across Ecoregions that chlorophyll a. This suggests that the latter is not as good a descriptor of lake condition as the former. This is consistent with the fact that chlorophyll concentration vary far more rapidly and widely than nutrients concentrations or Secchi, the inherent variability of chlorophyll concentrations is much higher than that of the other parameters. In addition, we feel that the historical chlorophyll values are also more likely to be subject to methodological errors and thus of less value than the other parameters.

Although the data were not evenly distributed among Ecoregions, there were still clear patterns among Ecoregions for all variables except chlorophyll (Figs. 8 - 11). These differences were a reflection of two gradients: differences in natural conditions and increases in human disturbance. The increase in medai total P by Ecoregion seen in Figure 3-8 represents a combination of these factors, i.e. Ecoregions on the left are very close to natural conditions with low disturbance and lakes on the right represent ecoregional differences and human disturbance. For lakes in Ecoregions with low disturbance median total P is low, e.g. Idaho Batholith, Northern Rockies, Cascades and Blue Mountains (left side of Fig. 3-8). The highest median total P values (right side of Fig. 3-8) were found in Ecoregions with high agricultural influence. However, these Ecoregions also may have high natural levels of total P in lakes, e.g. Snake River Basin. Thus the differences observed in total P, total N and Secchi among Ecoregions represents real differences among these Ecoregions. However, for only the Ecoregions with little disturbance can these differences be taken to be relatively little influences by landscape disturbance. For the other Ecoregions, additions measures must be taken to factor out the influence of landscape disturbance.

For most lakes in the database the N:P ratio was above 35 (Fig. 3-10). However, there were too few data for most Ecoregions to make a generalization. Nevertheless, available data appear to suggest that for lakes in the Pacific Northwest, total P is the nutrient of concern in lake eutrophication.

The aggregation of Ecoregions into Trophic Classes suggests that Level III Ecoregions may be combined for purposes of describing total P dynamics in those lakes. This may be most appropriate for Ecoregions with the least disturbance (Table 3-9). For example, there appears to be little significant difference between lakes in the Idaho Batholith and Northern Rockies with respect to total P (Fig. 3-8).

Aggregation of Level III Ecoregions can also be done by Trophic Group. With the exception of the Puget Lowlands and Middle Rockies, the four Trophic Groups described here correspond roughly to the Nutrient Ecoregions (Figs. 1-1, 3-21). The Willamette Valley appeared to fall within the Xeric West rather than the Western Forested Mountains.

In addition to the distribution of individual parameters among Ecoregions, there were significant relationships between parameter medians across Ecoregions (Figs. 3-13 - Fig. 3-16). These results are particularly striking in light of the fact that the database was compiled from different sources over a period of three decades. Thus the inter-Ecoregional differences observed are due to real differences in the behavior of these parameters among Ecoregions. However, it must be reiterated that differences among

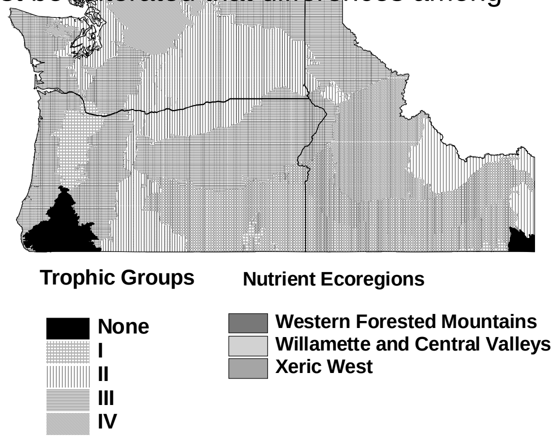

Figure 3-20. Comparison of Nutrient Ecoregions with Trophic Groups as defined in this study. Trophic Group I is in the Willamette and Xeric West Nutrient Ecoregions. Trophic Group II is primarily in the Xeric West and Groups IV and V are in the Western Forested Mountains.

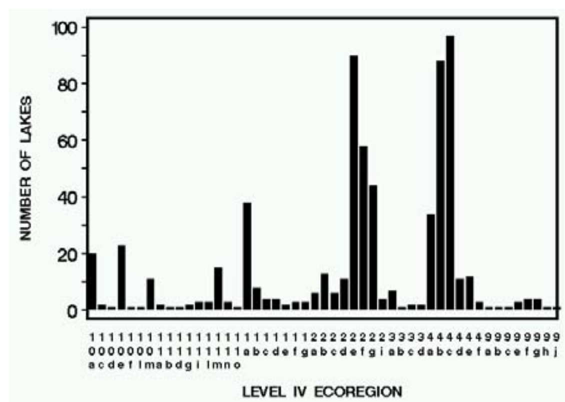

Figure 3-21. Number of lakes ≥ 4 ha in level IV Ecoregions. Th distribution of lakes is highly skewed, with few Ecoregions having a large number of lakes.

Ecoregions are due to both natural differences and degree of landscape disturbance. As mentioned, inter-Ecoregion differences on nutrient parameters reflect actual differences among Ecoregions.

This is corroborated by comparison of lake index and stream index total P values (Fig. 3-

17, Table 3-13). Median summer values were highly correlated across Ecoregions. This correlation shows that index total P values are a useful metric to characterize lakes by Ecoregion. It is interesting to note that summer total P values in streams is about 50% greater than found in lakes. This is not surprising considering the differences in total P processes between lakes and streams.

Stratification of lakes by Level III Ecoregions shows significant differences among Ecoregions with respect to nutrient parameters. However, these differences cannot be shown to be solely due to differences in location on the landscape, i.e. they are due to differences in location on the landscape and amount of landscape disturbance. Furthermore, for Ecoregions with low landscape disturbance there may be within Ecoregion differences in lakes regarding processing of nutrients.

For example, stratification of lakes in the Cascades Ecoregion into level IV Ecoregions showed differences in total P dynamics among Level IV Ecoregions (Fig. 3-20).

However, there appears to be no method with which to stratify lakes on the landscape in a single fashion. Figure 3-21 shows the number of lakes by Level IV Ecoregion. The number of lakes ranges from zero to over 200.

Moreover, the distribution of lakes is highly skewed; there are a several Level IV Ecoregions with over 80 lakes but most have very few. Therefore the use of Level IV Ecoregions in lake and landscape stratification must be used selectively.

CHAPTER 4. USE OF HISTORICAL DATA TO DERIVE NUTRIENT CRITERIA

4.1 Defining Criteria Using the Reference Condition Approach

One of the approaches for setting nutrient criteria is to define reference conditions using the population percentiles, e.g. 25th percentile of all lakes or 75th percentile of reference lakes by level III ecoregion (Fig. 4-1) (EPA 2000). The mean, 25th and 75th percentile values for all four log-transformed nutrient variables by ecoregion and by Trophic Group are presented in Table 4-1. Distributions of nutrient parameters by Trophic Group provide a good description of their component ecoregions. For total P (ug/L) the Groups have 25th and 75th percentiles of I (4.1 - 9.8), II (7.3 - 24.0), III (15.0 - 48.0, IV (40.9 - 161.7). With the exception of Group IV, samples sizes are large (Table 4-1). It is worth noting that the total P 75th percentile is roughly twice the corresponding mean. For total N (ug/L) the Groups have 25th and 75th percentiles of I (76 - 121), II (201- 521), III (571 - 1401), IV (558 - 1687). Sample sizes are not as large as for total P. The Trophic Groups for total P and total N form four roughly distinct groups based on 25th and 75th percentiles. Secchi depth for these groups was much more overlapping, I (5.0 - 11.7), II (4.0 - 8.1), III (2.8 - 5.3), IV (1.4 - 3.5). It is interesting to note that the mean Secchi in these Groups corresponds to the 75th percentile of the next highest Group, e.g. the mean of Group II (5.5 m) is close to the 75th percentile of Group III (5.3 m), etc. There are too few data to make any inferences regarding chlorophyll in these Groups.

Although the lakes included in the historical database did not include lakes 303d listed for

nutrients, the status of sampled lakes with respect to anthropogenic impact was not determined. Therefore these lakes cannot be considered a random sample of reference lakes nor a random sample of all lakes: they

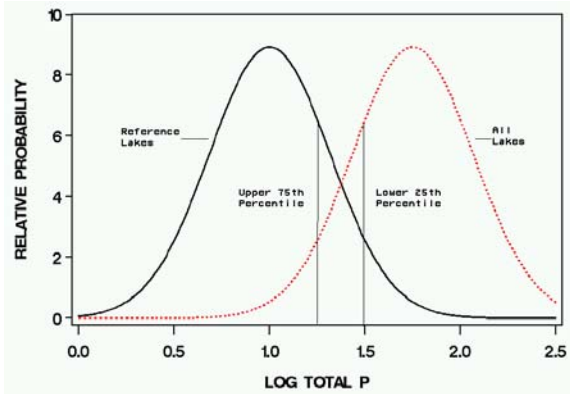

Figure 4-1. One approach for establishing reference conditions in lakes for total P. Reference lakes are those that are minimally impacted. All lakes are considered a random sample of all lakes in a given ecoregion, including those impacted. The upper 75th percentile of reference lakes or the lower 25th percentile of all lakes can be used as one method to establish criteria for total P.

are a sample of a some combination of impacted and unimpacted lakes, as described in EPA Lakes Guidance (EPA 2000).

Assuming the distributions in the historical database are a random sample of all lakes, the use of the 25th percentile would be the appropriate estimate of a reference conditions. This appears to be too restrictive as a standard for these four variables based upon basic limnological knowledge of these systems and also when compared to the distributions as a whole. For example, the 25th percentiles for total P ranges from 2.8 ug/L in the Idaho Batholith to 54.0ug/L in the Northern Basin and Range (Table 4-1, Fig. 3-8). The range by Trophic Group is 4.1 ug/L to 40.9 ug/L. Even the latter 25th percentile values appear too restrictive as reference conditions for seasonal median total P values.

The corresponding targets for total N and Secchi are also too restrictive. Conversely, assuming the distributions are mostly from

Table 4-1. Means, 25th and 75th percentiles by level III ecoregion and Trophic Group for the four nutrient parameters. Values are calculated from log-transformed summer index data. N - number of lakes in each category.

Trop Grp	#	Ecoregion	n	p25	mean	p75
Total P						
I	16	Idaho Batholith	74	2.8	5.2	8.5
	77	North Cascades	189	4.5	6.8	10.1
		Group I	263	4.1	6.3	9.8
II	1	Coast Range	59	10.0	19.0	28.0
	4	Cascades	235	6.3	13.1	25.0
	11	Blue Mountain	26	6.2	13.5	33.0
	15	Northern Rock	48	10.2	13.1	20.9
		Group II	368	7.3	13.9	24.1
III	2	Puget Lowland	204	13.9	24.3	42.0
	3	Willamette	8	19.1	48.4	142.7
	9	Eastern Cascade	14	18.0	25.7	32.0
	10	Columbia Plat	55	21.5	39.0	68.0
	17	Middle Rock	6	5.9	14.8	49.8
		Group III	287	15.0	26.9	48.0
IV	12	Snake River	13	38.3	59.8	137.0
	80	Northern Basin	15	54.0	84.2	206.0
		Group IV	28	40.9	71.8	161.7
Total N						
I	16	Idaho Batholith	5	313	408	481
	77	North Cascades	27	61	88	120
		Group I	32	76	112	121
II	1	Coast Range	48	168	261	462
	4	Cascades	85	221	259	397
	11	Blue Mountain	9	221	239	630
	15	Northern Rock	39	151	278	741
		Group II	181	201	262	521
III	2	Puget Lowland	103	612	883	1401
	3	Willamette	5	954	989	1201
	9	Eastern Cascade	7	321	753	2257
	10	Columbia Plat	20	603	931	1337
	17	Middle Rock	5	492	565	951
		Group III	140	571	872	1401
IV	12	Snake River	4	417	555	739
	80	Northern Basin	9	821	1269	2111
		Group IV	13	558	984	1687

Trop Grp	#	Ecoregion	n	p25	mean	p75
Secchi						
I	16	Idaho Batholith	71	4.8	6.6	10.5
	77	North Cascades	79	5.0	7.4	12.3
		Group 1	150	5.0	7.0	11.7
II	1	Coast Range	49	3.0	3.9	5.3
	4	Cascades	158	4.4	6.1	9.1
	11	Blue Mountain	19	3.8	5.6	8.7
	15	Northern Rock	35	4.0	5.4	7.1
		Group II	261	4.0	5.5	8.1
III	2	Puget Lowland	26	2.8	3.3	4.0
	3	Willamette	4	1.9	2.9	4.9
	9	EasternCascade	13	2.7	4.0	9.9
	10	Columbia Plat	10	2.3	3.6	7.0
	17	Middle Roc	5	4.3	5.2	6.5
		Group III	58	2.8	3.6	5.3
IV	12	Snake River	11	2.0	2.2	2.5
	80	Northern Basin	16	1.2	1.8	4.8
		Group IV	27	1.4	2.0	3.5
Chl a						
I	16	Idaho Batholith	9	2.6	4.1	7.8
	77	North Cascades	0	-	-	-
		Group I	9	2.6	4.1	7.8
II	1	Coast Range	28	2.7	5.3	11.0
	4	Cascades	157	1.5	2.4	4.1
	11	Blue Mountain	7	1.4	2.4	5.3
	15	Northern Rock	5	3.4	4.5	5.4
		Group II	197	1.7	2.7	5.0
III	2	Puget Lowland	12	5.7	8.0	11.2
	3	Willamette	4	2.3	4.1	8.8
	9	EasternCascade	12	2.4	3.5	8.1
	10	Columbia Plat	2	1.9	2.9	4.8
	17	Middle Rock	3	1.2	3.6	18.5
		Group III	33	2.8	4.7	11.2
IV	12	Snake River	9	5.6	11.4	26.7
	80	Northern Basin	14	4.5	6.3	6.6
		Group IV	23	4.7	7.9	17.1

unimpacted lakes, use of the 75th percentiles appear to be too lax as a reference condition for mean seasonal total P: 8.5 - 206.0 ug/L by ecoregion and 9.8 ug/L - 161.7 by Trophic Group (Table 4-1).

4.2 Determining Interim Criteria using Historical Data and Mean Total P Assimilative Capacity for Lakes

Comparison of Historical Lake Index Data to TMDLs

Distributions of lake TP were compared to assimilative capacity calculated in phosphorus TMDLs in by ecoregion. There are a total of 17 total P TMDLs that have been completed in seven different ecoregions. The median assimilative capacity for lakes was calculated for regions with more than one TP TMDL and plotted against ecoregional TP medians. The assimilative capacities were highly correlated with the ecoregional medians (Fig. 4-2). Regression of assimilative capacity against ecoregion mean total P (both log transformed) yielded in the following equation: (log[assimilative capacity] = 0.71*log[total P] - 10.6, r^2=.92) Virtually all of the calculated assimilative capacities fall within the 25th and 75th percentiles of the TP distributions in the historical database (Fig. 4-3).

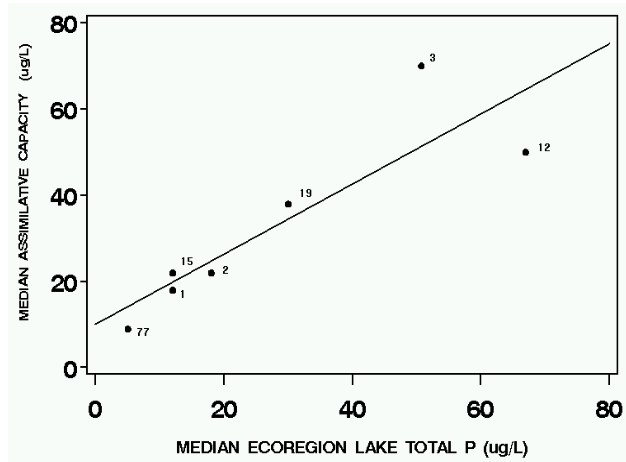

Figure 4-2. Relationship of median index median total phosphorus values in lakes and median assimilative capacities calculated in TMDLs across ecoregions. Numbers refer to Level III Ecoregions.

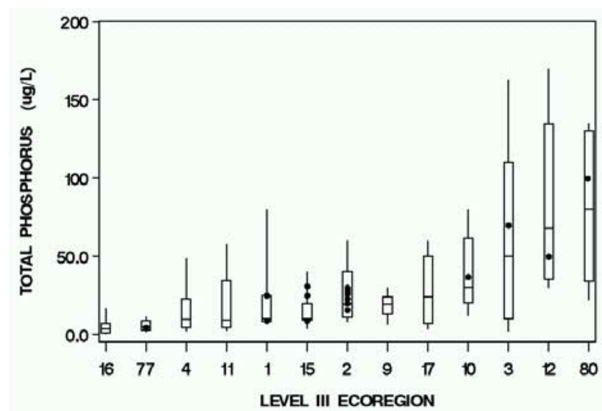

Figure 4-3. Median index total phosphorus values in lakes (box and whisker) and assimilative capacities calculated in TMDLs (points) across ecoregions. Calculated assimilative capacities tend to fall within the 25th and 75th percentiles of median lake values.

It is worth noting that a similar relationship was found between stream median TP concentrations and stream assimilative capacity published in stream TMDLs, i.e. assimilative capacities tended to fall withing the 25th to 75th percentiles of ecoregional TP concentrations(Figs 4-4, 4-5). However, the relationship between stream assimilative capacities and median total P concentrations in streams was not as strong as for lakes.

The assimilative capacities were calculated for each ecoregion and Trophic Group using the above regression equation and compared with the corresponding medians and 75th percentiles. The calculated assimilative capacity generally falls between the mean and 75th percentile, tending to be closer to the mean than the 75th percentile (Table 4-2).

Examination of the distributions of Index, 303(d) listed and TMDL total P values appears to corroborate this conclusion. Log-normal distributions of mean index total P, 303(d) listed lakes and assimilative capacity from TMDLs were constructed from the corresponding sample statistics for all lakes in Trophic Groups

II and III.

The mean total P concentrations for index lakes in Trophic Group II is 13.8 ug/L and the mean assimilative capacity form published TMDLs for lakes is 14.3 ug/L (Fig. 4-6). The mean total P concentrations of listed lakes in this Group is 34.2 ug/L. Thus the mean assimilative capacity of 14.3 ug/L is the 70th percentile of index lake total P values (Table 4-2, Fig. 4-6).

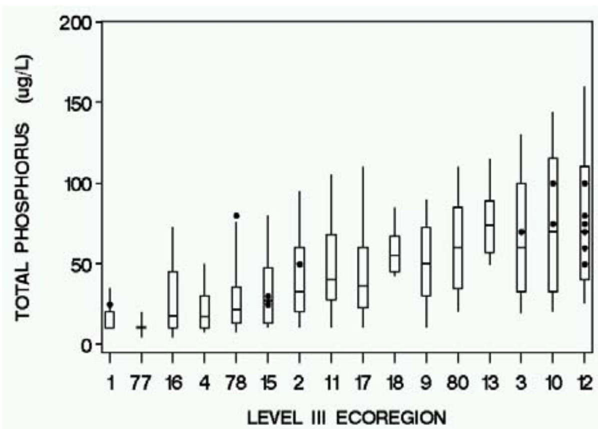

Figure 4-4. Relationship of median index median total phosphorus values in streams and median assimilative capacities calculated in TMDLs across ecoregions. Numbers refer to ecoregions.

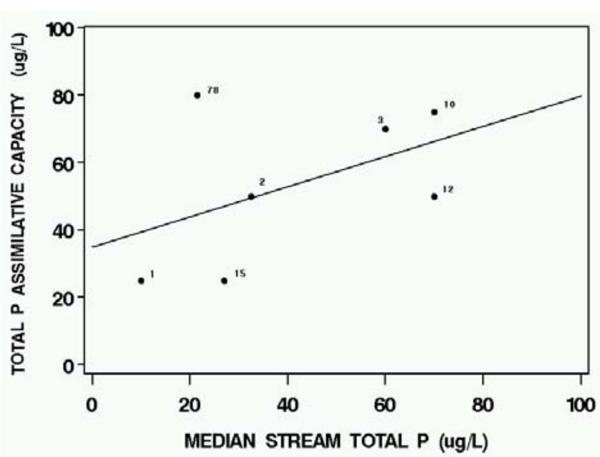

Figure 4-5. Median index total phosphorus values in streams (box and whisker) and assimilative capacities calculated in TMDLs (points) across ecoregions. Calculated assimilative capacities tend to fall within the 25th and 75th percentiles of median lake values

The mean assimilative capacity for Group III lakes is 24.7 ug/L and is 303d listed lakes and assimilative capacity from TMDLs were constructed from the corresponding sample statistics for all lakes in Trophic Groups II and III. The mean total P distribution is identical to the mean of the distribution of index lake total P values (Table 4-2, Fig. 4-7). This is equivalent to a growing season loading that produces a mean epilimnetic concentration of 24.7 ug/L. The mean concentration of listed lakes is 31.6 ug/L. The corresponding mean index Secchi depth is 2.9 meters and chlorophyll concentration is 4.2 ug/L (Table 4-1).

A one way ANOVA revealed that index, TMDL and listed total P concentrations were significantly different in Trophic Group II ($F = 10.41$, $p < 0.001$) but not in Group III ($F = 4.33$, $p < 0.014$). In Group II, index total P was different than P in listed lakes but assimilative capacity was not significantly different from

Table 4-2. Comparison of calculated assimilative capacity for total P (Assm Cap) from published TMDLs with log transformed summer index means and 75th percentiles of total P by level III ecoregion and Trophic Group. Calculated values generally fall close to the ecoregional mean total P value.

Trph Grp	#	Ecoregion	Mean Total P	Ass Cap	p75
I	16	Idaho Batholith	5.2	5.2	8.5
	77	North Cascades *	6.8	6.9	10.1
		Group I	*6.3*	*6.3*	*9.8*
II	4	Cascades	13.1	13.5	25.0
	15	Northern Rockies*	13.1	13.5	20.9
	11	Blue Mountains	13.5	14.0	33.0
	17	Middle Rockies	14.8	15.3	49.8
	1	Coast Range*	18.0	18.8	25.0
		Group II	*13.8*	*14.3*	*24.0*
III	2	Puget Lowland*	24.3	25.8	42.0
	9	Eastern Cascades	25.7	27.3	32.0
	10	Columbia Plateau*	39.0	42.2	68.0
		Group III	*26.8*	*28.6*	*47.0*
IV	3	Willamette Valley*	48.4	52.8	14.0
	12	Snake River Basin*	59.8	65.7	137.0
	80	Northern Basin	84.2	93.8	206.0
		Group IV	*71.8*	*79.5*	*161.7*

* Ecoregions with published nutrient TMDLs

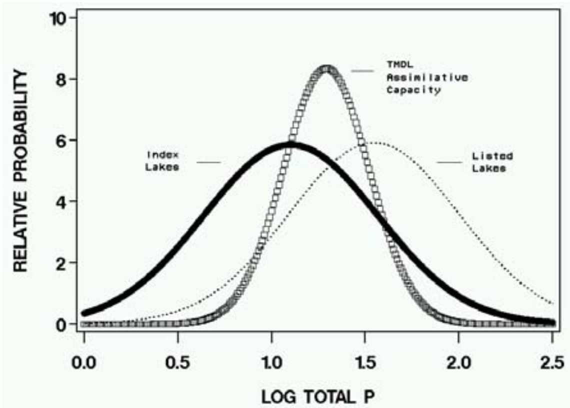

Figure 4-6. Distribution of index total P values in Trophic Group II lakes, 303d listed lakes and assimilative capacity from TMDLs. The mean assimilative capacity (11.7 ug/L) is equal to the 70th percentile of the distribution of index lake total P values.

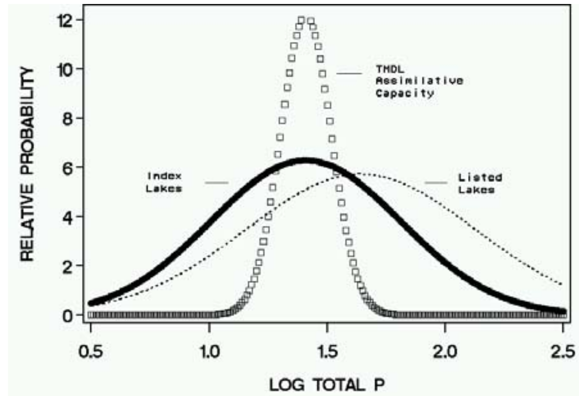

Figure 4-7. Distribution of index total P values in Trophic Group III lakes, 303d listed lakes and assimilative capacity from TMDLs. The mean assimilative capacity (24.7 ug/L) is equal to the median of the distribution of index lake total P values.

either.

A similar analysis for total N is not possible, since there have been no TMDLs developed for that nutrient in lakes. Nonetheless, the statistics in Table 4-1 can be used as a rough guide to total nitrogen concentrations in lakes by ecoregion and/or Trophic Group.

Use of Historical Data to Define Criteria

Based on historical data, an appropriate value for describing a reference mean summer total P in lakes appears to lie between the mean and 75th percentile values by Level III Ecoregion. A similar result obtains when ecoregions are aggregated into Trophic Groups.

However, the use of historical data to set criteria for summer P concentrations are not adequate if the criteria are intended for 303(d) listing purposes. Two factors preclude the use of these data. First, the data have been pooled within each ecoregion. Within ecoregions, there are an unknown number of lake types with respect to nutrient processing, i.e. lakes that have reference index total P distributions that differ from one another. For example, there appear to be at least five different such lake types in the Coast Range Ecoregion and four types of reservoirs in the Xeric West and Western Forested Mountains (Vaga et al. 2004a,b in prep).

The other factor precluding use of these data is the absence of information on the extent of anthropogenic impact on the sampled lakes, i.e. whether the lakes can be considered as reference lakes.

These results suggest that development of reliable nutrient criteria in this Regions requires:

1) development of lake categorization by Level III Ecoregion, where appropriate.

2) collection of water quality data by lake category.

3) development of a methodology to define reference lakes for each lake type.

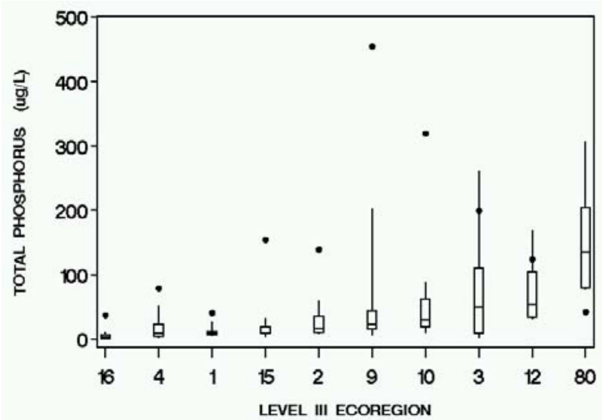

Figure 4-8. Comparison of the 95th percentile total P values in 303(d) listed lakes with distributions of summer mean index values. Most listed lakes have total P values much higher than the corresponding mean value for the Level III Ecoregion.

4.3 Use of Provisional Estimates of Total P Reference Ranges in TMDL Development and NPDES Permits

Although establishing numeric nutrient criteria for listing purposes based solely upon historical data may not be possible at this time, use of the third interquartile for total P in Table 4-1 may provide guidance in developing nutrient TMDLs for 303(d) listed lakes. For those ecoregions with few data, e.g. Willamette Valley, Middle Rockies, the appropriate Trophic Group interquartile can be used. The corresponding interquartiles for Secchi depth and chlorophyll can also be used to provide estimates of the behavior of those variables in response to reductions in nutrient loading.

Comparison of summer index total P and total P TMDLs distributions show that assimilative capacities from TMDLs generally are log-normal (Fig. 4-3, Fig. 4-2). The correspondence between calculated assimilative capacity and the third interquartile range of index distributions cannot be coincidental. Therefore the distributions of total P by Ecoregion represent, to a first approximation, a reasonable estimate of summer P values in lakes. Moreover, comparison of the 95th percentile of summer total P in nutrient-listed lakes with the distribution of historical summer total P by Ecoregion shows that historical data are clearly of use in developing total P TMDLs (Fig. 4-8). For most listed lakes, use of the median-75th percentile range is a reasonable first approximation to establishing a Total Maximum Daily Load for phosphorus in these systems. Obviously, the error associated with reducing total P concentration of listed lakes to the historical median in a given Ecoregion (for which adequate data exist) is insignificant relative to a concentration (loading) that wold be developed individually for a given lake.

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