WASHINGTON STATE
DEPARTMENT OF
ECOLOGY

NUTRIENT CRITERIA DEVELOPMENT IN WASHINGTON STATE

Phosphorus

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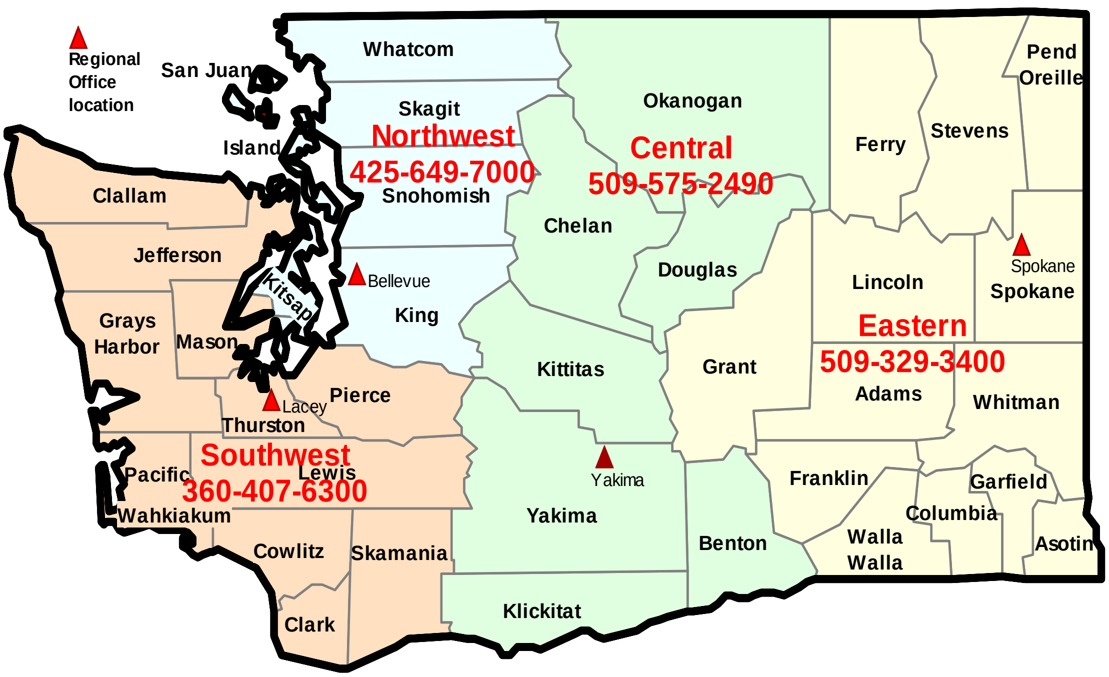

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Purpose of this Document:

The Environmental Protection Agency (EPA) has identified nutrient criteria development as one of its national priorities. As such, states in EPA Region 10, including Washington State have been asked to develop nutrient criteria plans for incorporation into their water quality standards development efforts.

In 1997, the state of Washington specifically addressed nutrient criteria development in its water quality standards revisions. After discussion with EPA on how to move forward with a nutrient criteria development plan that gives credit to the previous work that has been done, both agencies agreed in the joint state fiscal year 2004-2005 Performance Partnership Agreement (PPA) to address the issue during strategy development for the standards. Section 9 of the PPA, part 3Q requires that as part of long term strategy development, Ecology will submit to EPA a description of nutrient criteria development that has occurred in the state and a strategy for further nutrient criteria development by September 30, 2003.

This document is intended to fulfill the PPA requirement and describes both nutrient criteria development that has occurred in the state and future expectations for criteria development in the state of Washington.

Overview of Washington's Nutrient Control Plan

Washington has established an adaptive, multi-pronged strategy for protecting the state's waters from excess nutrient concentrations.

Statewide controls targeting nutrients:

- Concerned with the impacts from point and nonpoint sources, the state enacted restrictions on the concentration of phosphorous in laundry and dishwashing soaps.
- Nutrient management plans have been in effect and are being enforced across the state for dairies. The plans prohibit direct drainage to surface waters and provide high protection of subsurface flows.
- Combined Animal Feeding Operations (CAFO) permits are being revised to protect surface and ground waters under the successful model used for the state's dairy program.

Total phosphorous criteria for lakes:

- With the aid of statewide information on lake nutrient concentrations and well-accepted relationships between total phosphorous concentrations and eutrophic changes, the state adopted numeric action values in the state water quality standards to protect lakes. This lake program uses ecoregion-specific criteria as the default unless or until a more comprehensive lake study has been successfully developed.

- Lake specific studies that make use of the Section 314 lake study procedures established by EPA to be are used to develop lake-specific nutrient criteria that are tailored to protect the beneficial uses of specific lakes.
- These action values in the standards are also used to determine impairment status under section 303(d) and serve as targets for TMDLs.

Triggers for Riverine Systems:

- In Washington, changes to water quality due to excess nutrients are expressed first through the impacts to other more sensitive water quality criteria.
- Before nuisance levels of algal growth occur and aesthetics are noticeably impaired, streams and rivers will have violations of the state's dissolved oxygen, pH, and turbidity criteria. These criteria, which are designed to provide full support to sensitive aquatic life communities, have been found to be more reliable indicators of trophic health.
- Violations of these other trigger criteria, result in 303(d) listings and comprehensive water body-specific studies that are used to establish clean up requirements. These system-wide remedies examine the role of nutrients as well as other key facilitating parameters such as flows, temperature, and BOD when setting requirements for returning full health to the water body.

Marine water models:

- Due to the highly complex nature of marine systems and their response to nutrient additions, the state is focused on developing sophisticated water quality models for entire marine embayments or integrated systems.
- Models that are used to set protective nutrient concentrations as well as to assess the effects and needed controls for individual sources and tributaries are being developed on an ongoing basis. The goal is to develop models for all of Puget Sound that can be used both to protect against excess nutrients and to effectively protect the system against other conventional and toxic pollutants.

Water Quality Antidegradation:

- Washington recently adopted strict requirements for implementing Tier II of the federal water quality antidegradation program.
- Any new or expanding discharger that would be expected to detectably lower water quality would be required to go through an enhanced technology feasibility review. This step requires the use of any feasible alternatives that would lessen or eliminate their impact on water quality.
- Antidegradation Tier II will result in widespread consideration of nutrient removal technology.

Biocriteria:

- With help from EPA funding, Washington is nearing completion of the data collection and evaluation steps necessary to develop a proposal for establishing biocriteria in the state.
- The use of biocriteria that focus on stream macroinvertebrates will provide one more important tool for assessing whether excess nutrients are occurring in streams and serves as one more trigger for targeting clean-up efforts across the state.

Washington's nutrient control program combines prevention, carefully chosen criteria and system-targeted triggers, and comprehensive clean-up strategies together to ensure the beneficial uses of the state's waters will remain protected from the effects of excess nutrients.

Section 1.0: The Need for Lake Nutrient Criteria

1.1: Problems with Excess Nutrients in Washington

In Washington, an over-abundance of algae and other plants often affect lakes. This impact is most frequently caused by over enrichment of nutrients, such as phosphorus and nitrogen, which act as fertilizers.

Excessive nutrients can cause blooms of green and blue-green algae (cyanobacteria), which may form scum, mats, and a loss of water transparency. Nutrients can also stimulate excessive periphyton and macrophyte growth in lakes. The resultant loss of beneficial water-uses include:

- Loss of swimming, fishing, and aesthetic enjoyment due to nuisance algal blooms, periphyton, and macrophyte growth.
- Loss of aquatic life from dissolved oxygen depletion caused by excess algal and aquatic macrophyte respiration and decay.
- Loss of drinking water due to foul odor, clogging of filters, algae toxins, and formation of trihalomethanes (THMs) from the combination of algae and chlorine and other halogens (Cooke and Carlson 1989).

A report on Washington State waters (Ecology 1992 305(b)) showed 34 percent (or 29 lakes) with beneficial use impairments at least partially attributable to nutrients. Beneficial uses may include aesthetics, primary contact recreation, fishing, etc. This impairment amounted to approximately 19,155 acres of lake area. That same 305(b) report identified 84 lakes with use impairment out of a total of 266 lakes listed. Impairment of aesthetic enjoyment is listed as the beneficial use affected by nutrients. Beneficial uses were shown to be limited by total phosphorus in 23 lakes on Washington's water body limited list (Ecology 1994 303[d]). This list of water bodies was used to set environmental priorities for action when these water bodies did not meet water quality standards.

Another way used to determine lakes impacted by nutrients was to examine the number of lakes treated for excessive algae blooms. There were 124 permitted herbicide treatments issued for lakes and ponds in 1992. Many of these treatments were for excessive algae blooms triggered by high concentrations of phosphorus. These treatments may also have been caused by public dissatisfaction with lake use impairment.

One result of this dissatisfaction was Senate Bill 5320 passed by the Washington State Legislature in 1993 (now codified in RCW 70.95L) limiting phosphorus in laundry and dishwashing detergents. This law limits the amount of phosphorus in laundry detergents to no more than 0.5 percent phosphorus by weight and dishwashing detergents to no more than 8.7 percent phosphorus by weight. Thus the legislature enacted a statewide program to help protect Washington's waters from excess nutrients, contributing to the overall nutrient management strategy for the state.

The nutrients occurring in a particular water body may come from a variety of sources, including:

- Point source discharges
- On-site wastewater
- Agricultural practices
- Stormwater runoff
- Natural sources such as soil, ground water, and lake sediments.

The relationship between nutrients and aquatic plant growth has been well documented by Golterman (1975), Gilliom (1984), Carlson (1984), Welch (1992), and others. The need for nutrient criteria has been documented in specific areas of the state. Long Lake in Spokane County, has been assigned a specific criterion of 25 µg/L for phosphorus in Washington's surface water quality standards (Chapter 173-201a-130 WAC). The Spokane River nutrient criterion has limited phosphorus levels to control algal blooms. In addition, Lake Washington is often used as an example of successful nutrient control and has made a dramatic recovery in the years since diversion of nutrient laden sewage effluent. Appendix A lists other lake restoration studies that have occurred or are in the planning stages.

While Washington's lakes overwhelmingly bear the impacts to their beneficial uses from excess nutrient concentrations, nutrients can also affect some of the state's riverine and marine water systems. The relationship, however, between nutrients and beneficial use protection is more complex in these types of water bodies, and impacts to other water quality parameters (such as dissolved oxygen) tend to be what is first recognized.

1.2: EPA Guidance on Nutrient Criteria Development

Beginning with the April 2000, First Edition of the *Nutrient Criteria Technical Guidance Manual – Lakes and Reservoirs*, EPA has developed guidelines and frameworks for each state to develop its own set of nutrient criteria on an ecoregional basis for the protection and improvement stream, lake, and reservoir water quality. The ecoregional divisions that EPA recommended are the same as those used by Ecology in developing lake-phosphorus criteria adopted in 1997.

On November 14, 2001, Geoffrey Grubbs, EPA Director of Office and Science and Technology, issued the memo titled "Development and Adoption of Nutrient Criteria into Water Quality Standards." In the memo, EPA requested, "each state and authorized tribe to develop a nutrient criteria plan to outline the specific strategy, milestones, and schedule for developing and adopting nutrient criteria, taking into consideration specific situations, needs, and processes." EPA notes that the nutrient plans are not required by EPA. However, by submitting plans to EPA for comment the states can obtain guidance and assistance for developing and adopting their own nutrient criteria.

Ecology believes that the nutrient criteria for lakes approved by EPA on February 9, 1998 satisfies the requirements of EPA's mandate for states to develop plans and then adopt criteria for nutrients in lakes. Because Ecology already has EPA approval of its ecoregional nutrient criteria for lakes, the primary focus of this document is to describe the process that Ecology used to develop and adopt its ecoregional nutrient criteria for the protection and enhancement of Washington lakes. This can be found under Section 2: Process for Establishing Lake Nutrient Criteria.

Section 2.0: Process for Establishing Lake Nutrient Criteria

2.1 Introduction

On December 19, 1997, as part of the required triennial review required by federal rule to review the surface water quality standards, Washington State Department of Ecology (Ecology) incorporated a process into its surface water quality standards for adopting lake phosphorus criteria on an ecoregional basis. This process was based on nutrient concentrations found in lakes having relatively low human influence in the watershed (25 percent or less watershed development) for each of the eight ecoregions (Omernik and Gallant, 1986) in Washington State. The revised water quality standards including establishing lake nutrient criteria, were subsequently approved by EPA Region 10 in a February 9, 1998 letter from Philip G. Millam, Director, Office of Water, to Tom Fitzsimmons, Director, Department of Ecology.

The process for establishing the ecoregional lake nutrient criteria was initiated in 1994 by Ecology's Environmental Investigations and Laboratory Services Program - EILS (now Environmental Assessment Program – EAP). In addition to an Ecology twelve-member internal technical committee chaired by Eric Schlorff, an external technical advisory committee of 44 members was formed to review and comment on the development of the criteria. Following five public workshops throughout the state in 1996, the recommended criteria were finalized by March 1997 and were ultimately incorporated into the Surface Water Quality Standards as adopted in December 1997.

2.2 Summary of Methodology for Lake Criteria

Washington State's Surface Water Quality Standards for lake ecoregional phosphorus criteria is found in WAC 173-201A-030(6) - Establishing Lake Nutrient Criteria. This includes a table of action values that triggers a prescribed response for the establishment of phosphorus criteria for individual lakes (see Section 5.2).

The following discussion on the establishment of Washington State ecoregional total phosphorus (TP) criteria is based on the third draft - August 1996 (unpublished), *Nutrient Criteria: Review and Analysis for Washington State Lakes*. It has been edited to reflect the total phosphorus (TP) lake ecoregional criteria that were subsequently adopted into the surface water quality standards. Two technical advisory committees (external and internal) were active during the three-year development of the draft document. Most of the concepts of this unpublished draft were incorporated into the 1997 revisions to the Washington State Surface Water Quality Standards. The new standard (WAC 173-201A-030(6)) was based on protecting lake uses via the control of nuisance and toxic algae. The objectives of that document were to:

1) Review existing nutrient water quality literature
2) Review criteria developed by other states and provinces
3) Review data on Washington lakes
4) Recommend total phosphorus criteria and other approaches, as necessary, to control nutrient impacts.

In the development of the Washington State Lake Total Phosphorus Ecoregional Criteria, data from a combination of background conditions and trophic states were used to determine the proposed action value in each ecoregion. This method recommended a range of total phosphorus (TP) values. A land-use development level of 0% to 25% was used to determine near background conditions. The TP values within the 50th to 75th percentiles were used to bracket the range of TP. This range provided protection and allowed some level of development to occur while protecting beneficial uses at near-natural conditions.

The final ecoregional action values were developed by choosing a value that occurred where the recommended ranges of the background conditions and trophic boundaries overlapped.

Lakes in the Eastern Cascades Foothills ecoregion and the Willamette Valley ecoregion were quite different from lakes in neighboring ecoregions. This combined with high variability between lakes in these regions gave rise to the recommendation that they should be studied individually.

The trophic values for the criteria were chosen from existing literature. The trophic boundary values came from the Organization for Economic Co-Operation and Development (OECD, 1982).

In addition to numeric criteria, the state’s nutrient criteria recognize that studies to develop lake-specific criteria should be allowed where citizens or affected parties feel criteria are not protective enough or are too protective. These studies would involve the public and affected entities, require public hearings, and require plans to be approved by the Department of Ecology. Past studies may be accepted if they have gathered the necessary information as outlined in the discussion of the lake-specific approach. Whenever possible, these actions are to be coordinated with Ecology's watershed-basin approach.

2.3 Literature Review

2.3(a) Nutrient Criteria Used by Other States and Provinces

A literature review revealed that lake nutrient criteria vary greatly across the U.S. and Canada (Table 2-1). Table 2-1 is arranged in order of increasing phosphorus concentration.

Limits on total phosphorus (TP) are used most often to control nuisance algal blooms. Only the state of Oregon used chlorophyll-*a* as an action level. North Carolina was in the process of changing from a chlorophyll-*a* to a phosphorus criterion. Fifteen out of sixteen state and provincial governments regulated TP to control algal growth. The TP water quality criteria ranged from 10 to 100 µg/L. Utah used TP values higher than the other criteria listed as indicators of problems. Arizona, North Carolina, and Virginia had requirements for monitoring total nitrogen (TN). No action is required in addition to the TN monitoring. A detailed discussion of some state approaches to nutrient control follows Table 2-1.

The following illustrates the varied approaches that states use to regulate nutrients:

a) Some states differentiated nutrient criteria by type of water body, such as lakes, rivers, and estuaries.

b) Some states had adopted criteria for:
   - total phosphorus
   - total nitrogen
   - chlorophyll-*a*

c) Some states had proposed/adopted different criteria to protect different water-uses such as recreation, aquatic life, or drinking water.

d) Some states had proposed ecoregional criteria. Each ecoregion specified different levels of phosphorus to prevent nuisance levels of algae. The criteria depended on several factors relating to land-use and vegetation within an ecoregion and water-uses (were proposed in Minnesota and North Carolina).

e) Some states have standards that were expressed as effluent limits rather than ambient water quality criteria.

Table 2-1: Lake Nutrient Criteria for U.S. and B.C., Canada

From EPA 1988 criteria summary for phosphorus, nitrogen, and recent reports from individual state and provincial programs. (In order of increasing phosphorus concentration for lakes.) Proposed standards.

STATE OR PROVINCE	**PARAMETER OR WATER TYPE**	**SAMPLE FREQ & NOTES**	**TP (µg/L)**	**TN (µg/L)**	**NITRATES (µg/L)**	**CHL-*a* (µg/L)**
B.C.	Lakes drink & rec. aquatic life	Seasonal mean	 <10 5-15			
Washington	Coastal Range, Puget Lowlands, and Northern Rockies Cascades Ecoregion Columbia Basin Ecoregion	Ultra-oligotrophic Oligotrophic Lower mesotrophic Ultra-oligotrophic Oligotrophic Ultra-oligotrophic Oligotrophic Lower mesotrophic Upper mesotrophic	4 or less 10 or less 20 or less 4 or less 10 or less 4 or less 10 or less 20 or less 35 or less			
Minnesota	Lake ecoregions northern forests central hardwoods western plains northern plains	 See discussion of different beneficial uses for Minn. Lakes	 <15, <30 <30, <40 <40, <90 <90			
Maine	Class GP-*a*, GP-B	Single sample	15, 50			
Indiana	Lake Michigan	Monthly ave	30			
Arizona	Lake	Yearly ave	30	300-1000		
Illinois	Reservoir/lake Lake Michigan	Single value	50 7			
Arkansas	Lakes	Single value	30			
N.J.	Lakes/ponds/res	Single value	50			
N.C.	Lakes ecoregions mountain lakes piedmont & coastal lakes	Monthly ave	 20 50	550-750		
Nevada	Class A lakes Class B lakes Lake Tahoe	Single value Single value Soluble P	75 300 7 (sp)			
California	All fresh	Single value	100		10000	
Virginia	Lakes	Monthly ave	250			
Utah	Lakes	Indicator only	250			
Oregon	Stratified lakes Other waters	Seasonal mean				10 15
U.S. E.P.A. 1986 Goldbook	Lakes and reservoirs	Spring, volume-Weighted	25			

The North American Lake Management Society published *Developing Eutrophication Standards for Lakes and Reservoirs* in May of 1992 to help narrow the choice for nutrient criteria. That publication reviewed the standards and criteria of seven states and B.C., Canada.

The approaches discussed in detail below were either similar to Washington's water quality standards, or came from states with similar conditions to those in Washington. Vermont's approach was not discussed because it applied mainly to a few large lakes and depended on the results of lake user surveys, which had not been conducted here in Washington.

The state of Maine's approach was not discussed because of its dependence on predominantly forested areas and low trophic status. This was very different from Washington, which has large areas of agriculturally influenced lake watersheds as well as lakes located in non-urbanized forested areas.

Minnesota's Use of Ecoregions and TP

Minnesota proposed nutrient criteria for lakes based on ecoregional variations in phosphorus and lake productivity (Heiskary and Wilson, 1989, 1990). Minnesota used the ecoregions developed by the US EPA. The EPA ecoregion delineations are based on regional patterns of similar land uses, soils, land surface forms, and potential natural vegetation (Omernik and Gallant, 1986).

Minnesota has seven ecoregions, four of which contain 98 percent of the state's lakes. Minnesota therefore developed criteria only in those four regions. The first region is predominantly forested, the second region is partially forested, and the third and fourth regions are predominately agricultural.

Ecoregion		TP criteria
Northern forests:	drinking water and	
	cold water fishery	<15 µg/L
	swimming and aesthetics	<30 µg/L
Central hardwoods:	drinking water	<30 µg/L
	swimming and aesthetics	<40 µg/L
Western plains:	drinking water,	<40 µg/L
	swimming and aesthetics	
	(full support)	<40 µg/L
	(partial support)	<90 µg/L
Northern plains	Swimming and aesthetics	
	(partial support)	<90 µg/L

Minnesota lake managers could predict average summer nuisance conditions and a range of probable water transparency depths based on TP sampling within each ecoregion (Heiskary, 1993). These criteria would probably continue to be used as *benchmarks* tools rather than be adopted into standards.

North Carolina's Use of Ecoregions

In the late 1970's, North Carolina adopted chlorophyll-*a* criteria of:

- 40 µg/L for warm water and
- 10 µg/L for cold water.

Chlorophyll-*a* provides a measure of algal biomass. North Carolina was moving away from using chlorophyll-*a* because it is not a predictive indicator in lakes. Total phosphorus is more stable and is an indicator of potential algal blooms (Reed, 1992).

North Carolina was proposing new total phosphorus criteria based on ecoregions:

Ecoregion	TP criteria
Mountain	20 µg/L
Lowland	50 µg/L

The proposed phosphorus criteria were based on the nuisance levels of algae that equated to the older chlorophyll-*a* criteria.

Oregon's Use of Chlorophyll-*a*

Oregon established nuisance levels of phytoplankton growth based on chlorophyll-*a* concentrations. The initial level of concern was a slight lake impairment. When chlorophyll-*a* indicated an impairment, the Oregon State Department of Environmental Quality was to initiate a study and develop a control strategy. The criteria were:

a) Natural lakes which thermally stratify: 10 µg/L chlorophyll-*a*.

b) Natural lakes which do not thermally stratify, reservoirs, rivers and estuaries: 15 µg/L chlorophyll-*a*.

Samples were to be collected over any three consecutive months at a minimum of one representative location (Chapter 340-41-150 Oregon DEQ)

British Columbia's Total Phosphorus Criteria

British Columbia (B.C.) established criteria in the late 1980's that applied water-use impacts to lakes (Nordin, 1985). The B.C. criteria used total phosphorus as an indicator of potential phytoplankton blooms. The criteria and the uses protected by the B.C. criteria were:

Lakes:	Drinking water	<10 µg/L TP
	Recreation	<10 µg/L TP
	Aquatic life	>5 and <15 µg/L TP
	(lakes with salmonids as predominant fish species)	

The B.C. criteria served as the basis for site-specific water quality objectives that required a detailed evaluation of individual lakes. The criteria could be modified up or down into an *objective criterion*. Studies of individual lakes would influence the *objective criteria*, which served as policy guidelines for resource managers to protect water-uses in lakes.

2.3(b) Applicability of Other State's Criteria

Chlorophyll-*a* vs. Phosphorus

Most states use phosphorus to determine phytoplankton growth potential in lakes because the relationship between TP and algal growth is strong and predictable.

The cost of sampling is another important factor in determining appropriate criteria. The Washington State Manchester Environmental Laboratory costs for analyzing a chlorophyll-*a* sample is roughly twice the cost of analyzing a TP sample. Field preparation of chlorophyll-*a* samples is also more time consuming than phosphorus.

However, a single statewide phosphorus criterion will not work for Washington due to the wide range in phosphorous concentrations among ecoregions in the state. This wide range can be explained in part by the different soils, elevations, climate and vegetation among the ecoregions. There may still be some variability within an ecoregion, but the range of variability is narrowed.

Ecoregions

Omernik and Gallant (1986), who have undertaken the predominant ecoregional work around the US, divided Washington State into eight ecoregions (see Figure 2-1).

The ecoregion approach for lakes proposed by Minnesota and North Carolina, offers good correlation of phosphorus to actual algae blooms. Groups of lakes in Washington also respond to nutrients differently because of diverse terrain, climate, and vegetation.

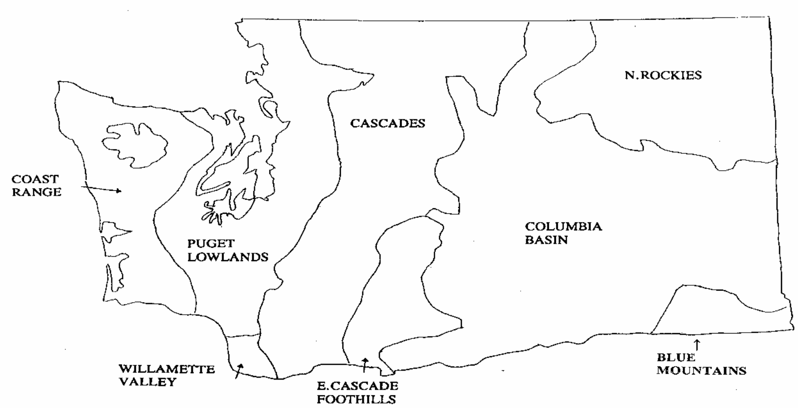


Figure 2-1: Washington State Ecoregions

Water-Use Approach

Lake water-use classifications have been used by Minnesota and B.C. and include classes for drinking water, swimming, and aesthetics. The intent of Washington's phosphorus criteria is to establish a level of nutrients that supports aesthetics as related to recreation. Use of these criteria would support substantially all other uses.

Washington State surface water quality standards are currently structured with different classifications to protect levels of uses in streams. In addition to the lake phosphorus criteria, Washington's lake class protects substantially all of the following uses (Chapter 173-201A-030(5) WAC:

> Water supply (domestic, industrial, agricultural); stock watering; fish and shellfish; salmon migration, rearing, spawning, and harvesting; other fish migration, rearing, spawning, and harvesting; clam and mussel rearing, spawning, and harvesting; crayfish rearing, spawning, and harvesting; wildlife habitat; recreation (primary contact recreation, sport fishing, boating, and aesthetic enjoyment); commerce and navigation.

The impact to aesthetics and recreational swimming were determined to be more predictable with respect to phosphorus concentrations (Ecology, 1992, 305(b)) and were uses not directly protected by other water quality criteria. While higher nutrient inputs may cause a loss of dissolved oxygen and result in a loss of the macroinvertebrates that fish eat, the dissolved oxygen criteria are implemented independently. Additionally, it was determined to be infeasible to develop TP criteria that were defensibly linked to oxygen concentrations due to the wide range of confounding factors that occur between lakes.

Two technical advisory committees (internal and external) were formed to review lake nutrient issues and provide input to developing ecoregional TP criteria for lakes in Washington State. The committees were asked if they wanted nutrient levels established for different lake uses similar to that of Minnesota or B.C. The response was that most committee members supported aesthetics overall. They also did not support establishing general-multiple use criteria unless there was good data to support the criteria. However, there was support for determining uses supported on a lake-by-lake approach through lake-specific studies.

Until a lake-specific study could be done to determine the existing uses, it was assumed that a lake that had not been studied in detail would by default support all uses. This process is similar to how the surface water quality standards were written for Washington State rivers and marine water bodies.

Now, using the ecoregion approach, criteria can be established to support aesthetics at expected, achievable levels for each ecoregion. Citizens who want to establish criteria for their lake can propose those criteria based on a minimum of four samples during the summer growing season or a more comprehensive lake-specific study. Then a criterion

proposal can be submitted to Ecology for adoption into the Water Quality Standards during the next triennial revision process.
Additionally, if TP values are higher than the ecoregional action value, then the lake would be placed on the 303(d) list of water bodies with water quality limitations. Lakes placed on the 303(d) list receive priority status for lake-specific studies. The goal of the lake-specific studies is to identify and implement in-lake and watershed practices to reduce the phosphorus concentrations to levels that support aesthetic and recreation, along with their other beneficial uses.

2.3(c) Criteria Suggested by Literature

Studies that focused on lakes in Washington were used as much as possible, however, a few important studies of North American lakes were included (e.g., Carlson [1977], and OECD [1982]) because of their wide use by lake managers. Table 2-2 displays lake management recommendations by universities and government agencies. Only reports that recommend specific criteria levels are shown. Table 2-2 also summarizes important conclusions about lake nutrient impacts by comparing use impacts, trophic levels, and nutrient criteria.

Approximately 50 Washington lake restoration studies have been conducted (Appendix A lists). These restoration studies document conditions of lakes before, and sometimes after restoration. Earlier studies did not necessarily recommend specific criteria, although the goals of the studies were to always improve the lakes' water quality. In addition, lake nutrient concentrations were reported for a number of lakes in King and Thurston Counties (Brenner and McGuire, 1990; Brenner, et al., 1990; Davis, 1993). Some of the data from these reports were used in developing a database for this report. Ecology's advisory committee recommended that lakes be approved for a criterion, only after developing a lake-specific study that included a watershed improvement process and public participation.

Trophic States, TP, and Secchi in Literature

Water-uses are strongly tied to different trophic states observed in lakes. The literature basis for the following discussions on trophic states are cited in Table 2-2 where values are given as ranges based on several lake regions. These are not recommendations, but represent actual conditions at which certain uses were perceived to be supported or not supported.

Both the Organization for Economic Cooperation and Development (OECD) (1982), and Simpson and Reckhow (1979) set the highest TP levels, probably because the large number of lakes they examined covering North America and Europe had a wide range of TP concentrations. Gilliom (1984) used lakes in the Puget Sound region and Carlson (1977) used Midwestern U.S. lakes.

Ultra-Oligotrophic Conditions

The OECD ultra-oligotrophic category for lakes suggests these waters would have very high clarity and low productivity with TP less than 4 µg/L. The ultra-oligotrophic Secchi transparency values range from 6 to 12 meters and chlorophyll-*a* values range from 1 to 2.5 µg/L. This ultra-oligotrophic TP value was used by Patmont (1989) to recommend a

TP value of 4.5 μg/L for Lake Chelan. Water-uses are supported for recreation, drinking water, and aquatic life.

Oligotrophic Conditions

Low algal productivity will generally exist with TP in the range of 0 to 10 μg/L (Nordin, 1985; Funk and Moore, 1985; Gilliom 1984; OECD, 1982; Simpson and Reckhow, 1979). Carlson, (1977) states that at TP ranges from 0 to 12 μg/L, mean chlorophyll-*a* will be less than 3 μg/L and Secchi transparency depths will be greater than 5 meters. Water-uses are supported for recreation, drinking water, and aquatic life. The water is generally of high clarity and is aesthetically pleasing. According to Nordin (1985), and Ney, et al (1990), fisheries productivity will be quite low at TP concentrations less than 5 μg/L.

Mesotrophic Conditions

Moderate algal productivity will generally exist with TP in the range of 10 to 20 μg/L (OECD 1982; and others) or 12 to 24 μg/L (Carlson,1977), chlorophyll-*a* in the range of 2 to 6 μg/L, and Secchi transparency depths between 3 and 5 meters (Gilliom, 1984). Cold-water fisheries may be adversely affected by some degree of hypolimnetic oxygen depletion. There may be additional benefits to salmonids in lakes from having TP less than 15 μg/L (Nordin, 1985).

Eutrophic Conditions

Moderately high algal productivity will generally exist with TP in the range of 20 to 30 μg/L (Gilliom, 1984) or 35 to 100 μg/L (OECD, 1982) or >24 μg/L (Carlson, 1977), chlorophyll-*a* ranging from 4 to 12 μg/L, and Secchi transparency depths between 2 to 4 meters in Puget Sound lakes (Gilliom, 1884). Algal blooms are intense and frequent. Primary contact recreation (i.e., swimming) is affected, although secondary contact recreation (i.e., wading) may be fully supported. Warmer water, lower dissolved oxygen (DO), and altered pH may affect fisheries. Alternatively, a range of 20 to 50 μg/L TP was recommended by Simpson and Reckhow (1979) who examined a wider range of North American lakes.

Hypereutrophic Conditions

High algal productivity will generally exist in Puget Sound lakes with TP greater than 30 μg/L. At TP greater than 30 μg/L, the following conditions would be expected: chlorophyll-*a* greater than 10 μg/L, Secchi transparency depth less than 3 meters; floating scum, high sedimentation rates, and/or excessive macrophyte growth (Gilliom, 1984). Intense algae growth will reduce macrophyte growth by shading out light. Impacts to uses include the loss of recreation and fish kills. The OECD report does not consider a lake to be hypereutrophic until TP levels are greater than 100 μg/L, chlorophyll-*a* is greater than 25 μg/L, and Secchi transparency depth is less than 1.5 meters. Simpson and Reckhow (1979) found North American lakes to be hypereutrophic when TP is greater than 50 μg/L. Heiskary and Wilson (1989), found Minnesota lakes to have overlapping trophic status with eutrophic/hypereutrophic conditions occurring between TP levels of 65 to 150 μg/L and definite hypereutrophic conditions above TP levels of 130 μg/L. A hypereutrophic threshold using an annual mean TP >150 μg/L was established for West Medical Lake in Washington. (Willms and Pelletier, 1992).

Table 2-2: Lake Nutrient Criteria Suggested in Literature

AUTHOR/REFERENCE	TP µg/L	TN µg/L	CHL-*a* µg/L	SECCHI meters	COMMENTS AND CONDITIONS
Patmont, et al 1989 (Lake Chelan)	4.5			12	Ultra-oligotrophic. Max. chl-*a* 0.6. Watershed uses limited to protect in-lake TP and pristine conditions.
Heiskary, Wilson, 1989 (Minnesota Lakes)	14-27 23-50 65-150 130-250		<15 7-37 60-140 30-55		Forested lakes. Mesotrophic to mildly eutrophic. North central mostly forested lakes. Generally eutrophic. Corn belt plains lakes. Eutrophic/hypereutrophic. Glaciated plains lakes. Hypereutrophic.
Patmont, 1987, (Long lk. Spokane, WA)	25				Mesotrophic
Nordin, 1985 (B.C., Canada Lakes) (spring overturn conc.)	<10 <10 5-15				Drinking water-use retained. Recreation use retained. Aquatic life (lakes with salmonids as predominant Species).
Funk & Moore, 1985 (Reflection Lks. WA)	<10	<10	<9.6		Pristine alpine, oligotrophic lakes. (Cascade Ecoregion)
Gilliom, 1984 (Puget Sound Lakes, summer concentrations)	0-10 10-20 20-30 >30		<3 2-6 4-12 >10	>5 3-5 2-4 <3	Low algal productivity. Supports all recreation uses. Moderate algal productivity. Some oxygen depletion. Cold-water fishery may be endangered. Mod-high algal productivity. Algal blooms intense and frequent. Increased fisheries problems. High algal productivity. Floating scum. Loss of recreation uses. Fish kills common.
Funk & Gibbons, 1982 (Long Lake, WA.)	30-70				Reductions of TP due to restoration.
OECD, 1982 (N. America & Europe Temperate and non-temperate)	<4.0 <10.0 10-35 35-100 >100		<1.0 <2.5 2.5-8 8-25 >25	>12 6-12 3-6 1.5-3 <1.5	Ultra-oligotrophic. Max. chl-*a* <2.5 Oligotrophic. Max. chl-*a* <8.0, Mesotrophic. Max. -chl-*a* 8-25, Eutrophic. Max. chl-*a* 25-75, Hypereutrophic. Max. chl-*a* >75,

AUTHOR/REFERENCE	TP µg/L	TN µg/L	CHL-*a* µg/L	SECCHI meters	COMMENTS AND CONDITIONS
Simpson & Reckhow 1979 (N. American temperate lakes. Including some southern lakes)	<10 10-20 20-50 >50				Oligotrophic. Uses for recreation, and cold water fishery retained, high clarity and aesthetically pleasing Mesotrophic. Uses for recreation retained. Less clarity. Eutrophic. Uses for secondary contact recreation retained, and productive warm water fishery. Hypereutrophic. Some fish uses retained but high levels of sedimentation. Algal and macrophytes may reduce open areas.
Carlson, 1977 (Northern US lakes)	<12 12-24 >24			>4 2-4 <2	Oligotrophic Mesotrophic Eutrophic
Walker, 1985 (Vermont, N. American Reservoirs, South African Reservoirs)			10		Critical Chlorophyll-*a* value determined from bloom frequency. Above this value, algae bloom are more frequent and therefore more of a concern.

Section 3.0: Data Review of Washington Waters

This section discusses the data from Washington's lakes and the methods used for recommending the total phosphorus (TP) ecoregional action values.

3.1 Data Sources

Data from the 1971-1975 USGS Water Resource Bulletins (Bortleson, 1972-1975, and Bortleson, 1981) were used for determining what would be pre-development, natural concentrations of TP.

The primary data sources were the USGS Water Resource Bulletins 42 and 43 (Bortleson et al., 1972-1979, 1981), which reported data from 1971 through 1975. Bulletin 43 includes a large sample of lakes, but in almost all cases represents only single samples from each lake. Bulletin 42 is a smaller subset of the lakes sampled in Bulletin 43, but each lake was sampled four or more times in a season and includes chlorophyll-*a*. The Bulletin 42 and 43 data was used for the box-plots, ANOVA analysis and development levels.

3.2 Method Used to Analyze Ambient Lake Data

The method used which was originally called the primary method, determines natural conditions or near-background levels of TP in the lakes. Several other methods used earlier in this process were not well supported by advisory committee members and were dropped. The method used to recommend ecoregional action values compares TP values in drainage basis designated as mostly undeveloped. An analysis of variance (ANOVA) was used to compare the full range of values from each ecoregion and look for similarities between ecoregions.

3.3 Data Considerations for Lakes

Chapter 173-201A-120 WAC defines lakes and reservoirs as having a mean hydraulic detention time of greater than 15 days. All lakes used for this report met this requirement. Some reservoirs were included in the database if the detention time was greater than 15 days.

Summer means were used where several months to a year of data were available. The summer growing season was defined as June through September. Where there were several years of sampling for any one lake, only the most recent year of data or the most complete data set for each lake was used.

For the historic lakes data (Bortleson et al. 1972-1979 Water Resource Bulletin 42) where there were several samples during a single season for each lake, the samples were calculated as means and were used instead of data from Bulletin 43.
Because much of the data was from different sources over different years, quality assurance and quality control (QA/QC) checks other than that originally used was not possible with much of this data.

3.4 Ecoregional Analysis

The ecoregions of Washington are described by Omernik and Gallant (1986) for the Pacific Northwest. Their work divided Washington into nine ecoregions, eight of which were examined in this analysis (Figure 3-1). No lake data was available for the Blue

Mountains ecoregion. In their analysis, the Olympic Mountains, which are mostly within the Olympic National Park, were given the same ecoregional distinctions as the Cascade Mountains. No phosphorus data was available for the Olympic Mountain area. Because of the remote and protected nature of this area, we concluded that these lakes were naturally very low in phosphorus concentrations. We made the same assumptions for the lakes in the Cascades. Note that there is no ecoregion number five shown. This is because ecoregion number five, as defined by Omernik and Gallant (1996), is located outside of Washington State.

Data from 763 lakes in Bulletins 42 and 43 (Bortelson, et al., 1972-1975) were used in the ecoregional analysis. Figure 3-1 shows that 98 percent of the lakes fall into following five ecoregions:

1) Coast Range, 17 lakes
2) Puget Lowlands, 270 lakes
4) Cascades, 135 lakes
7) Columbia Basin, 260 lakes
8) Northern Rockies, 60 lakes

The remaining three ecoregions had very few lakes with data and therefore were not included in the analyses. However, they are discussed at the end of this section. These three remaining ecoregions are:

3) Willamette Valley, 7 lakes
6) East Cascades and Foothills, 4 lakes
9) Blue Mountains, 0 lakes

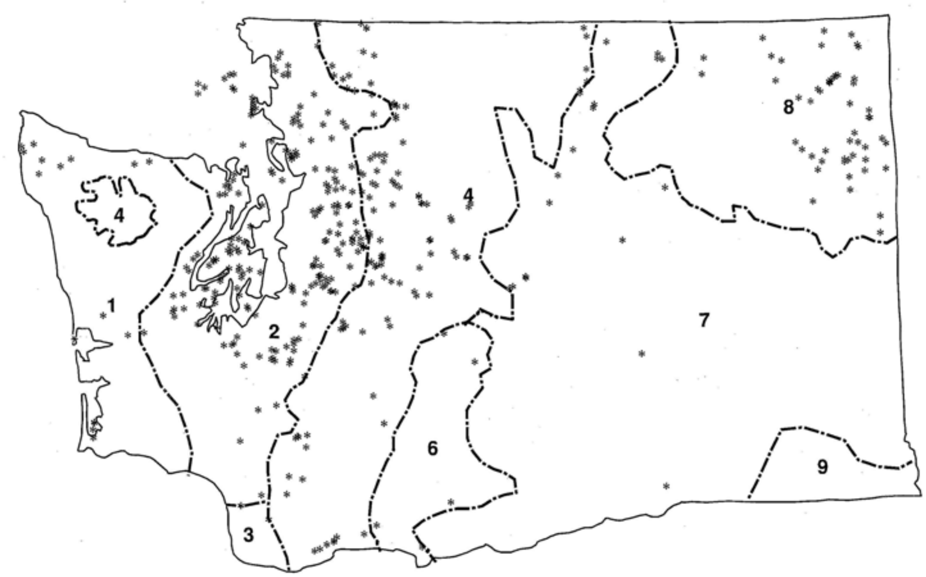


Figure 3-1: Washington State Ecoregions and Major Lakes
(Each dot represents a lake)

The ecoregional analyses used to map the ecoregions were conducted by Omernik and Gallant (1986). The northwest ecoregions were mapped to provide a geographic framework for more efficient management of aquatic ecosystems. The factors used to differentiate the ecoregions include land surface form, potential natural vegetation, land-use, and soils.

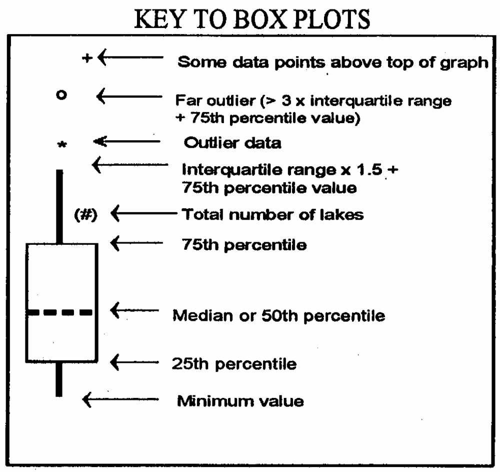
The ecoregional factors for the Coast Range analysis included:

- Land surface form: low to high mountains
- Potential natural vegetation: spruce/cedar/hemlock
- Land-use: forest and woodland, mostly un-grazed
- Soils: Udic soils of high rainfall areas

Complete descriptions of the ecoregions may be found in "Ecoregions of the Pacific Northwest" (Omernik and Gallant, 1986).

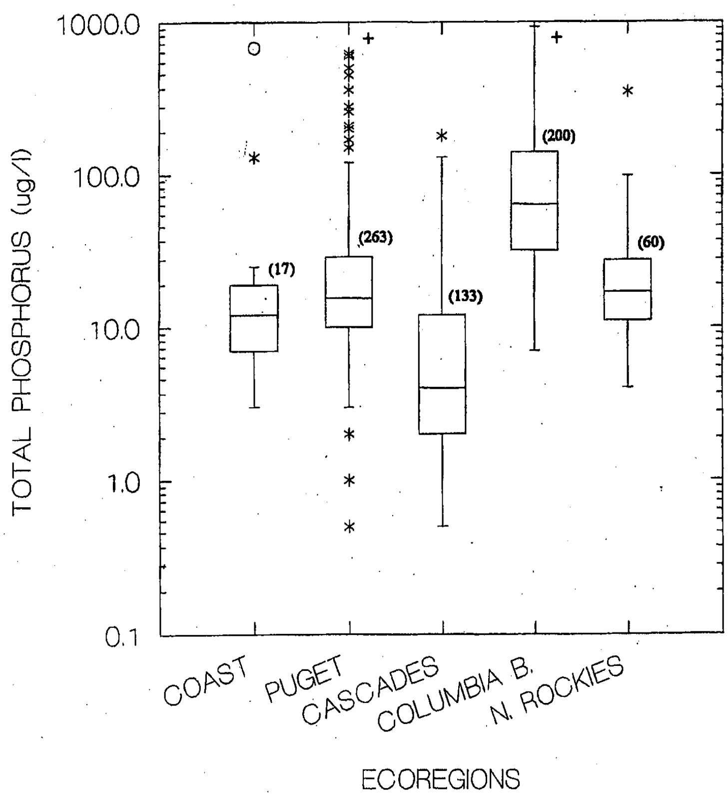
TP values were sorted into ecoregions (Figure 3-2) to determine if the ecoregional approach could be used for developing phosphorus criteria in Washington. Graphical representations of the 1971-1975 data show differences in total phosphorus between three sets of the ecoregions.

Most of the data in each ecoregion overlaps in the highest and lowest quartiles (Figure 3-2). However, in the interquartile range (the 25th to 75th percentiles) there is little overlap in TP concentration among the Cascades, the Columbia Basin, and the Puget lowland ecoregions.



Ranges for box-plots design from SYSTAT statistical software

FIGURE 3-2: BOX PLOT OF TP BY ECOREGION (1971-1975 LAKES DATA)



The most significant difference in median TP concentrations, an order of magnitude, (Table 3-1) was between the Cascades and the Columbia Basin. Very little difference was shown between the Coast Range, the Northern Rockies, and the Puget Lowlands.

Table 3-1: (From Figure 3.2. 1971-1975 Lakes Data for All Lakes

(All development levels)

ECOREGION	NO. OF LAKES	PERCENTILES					MEAN	COEF OF VAR
		MIN	25	MED	75	MAX		
COAST R.	17	3	7	**12**	20	680	58	2.8
PUGET L.	263	0	10	**16**	29	1200	39	2.7
CASCADES	133	0	2	**4**	12	180	12	1.9
COLUMBIA B.	200	7	33	**75**	305	14000	517	2.6
N. ROCKIES	60	4	11	**17**	28	350	28	1.7

3.5 Criteria Based on Near-Background Conditions

3.5(a) Phosphorus

This method used TP values in lakes with moderately low land-use development values. The ranges of TP from this method were then compared to the trophic states suggested in literature.

The source of land-use development levels used in this analysis came from cultural land-use data collected for the water resource Bulletins 42 and 43 (Bortleson, et al. 1975). Land uses included: residential urban, residential suburban, agricultural, and forest/unproductive. These land uses were listed as a percentage of the area of a drainage basin along with lake surface area. The percentages of undeveloped drainages were determined by summing the percent of forest/unproductive area with the percent of lake area within each drainage. Some of these lakes in non-developed drainages may have also had near shoreline development of homes or cabins. However, a cursory examination of TP levels in these undeveloped drainages indicated there was no direct correlation between the TP levels and near-shore development. All lakes probably received some level of impact from humans regardless of the lake's isolation. Sources may include wind blown sediments from agricultural areas and nutrients in precipitation, as well as nutrients applied to forests for tree growth enhancement and livestock grazing. These lake TP concentrations in undeveloped drainages could be used as achievable concentrations in developed lakes.

Natural conditions, or natural background levels, were supported and defined by the surface water quality standards (chapter 173-201A-020 WAC) as meaning surface water quality that was present before any human-caused pollution. Lakes that do not receive anthropogenic sources of TP therefore represent natural conditions.

The committees did not want to set criteria that were not achievable or that were below what naturally could be attained. Although, some lakes in each ecoregion would naturally have TP values above the criterion. The proposed way to address these naturally high nutrient lakes was through the lake-specific approach.
Because there were not enough undeveloped lakes in the Columbia Basin ecoregion, a pre-development TP concentration level could not be accurately determined. However, a value was adopted from lakes that had such low levels of development that the TP concentrations were considered to reflect near-natural conditions.

An analysis of variance (ANOVA) was conducted for the full range of values found in each ecoregion under three different scenarios of development (undeveloped, all lakes regardless of development, and 25 percent or less development). The TP data was first log transformed to normalize the data distribution. A single factor ANOVA was used to compare sets of two to five ecoregions. An additional test of the variance was conducted using a two-sample F-test. This test compared the variances of samples in one ecoregion to another and showed similar results to the ANOVA.

The developed scenario used all lakes in each ecoregion regardless of development levels (Figure 3-2, Table 3-2). The second scenario used drainage basins that were virtually undeveloped (Figure 3-3 and Tables 3-3 and 3-4). The third and last scenario shows drainage basins with 25 percent or less development within each lake's drainage (Figures 3-4 and 3-5 and Table 3-5).

Table 3-2: Analysis of Variance for TP in Each Ecoregion

(Bulletin 43 data, 1971-1975, Regardless of development)

ECOREGIONS COMPARED	NO. OF LAKES	F	F crit.	P value	RESULTS
COAST R., PUGET L., CASCADES, COLUMBIA B., N. ROCKIES	17 263 133 200 60	123.9	2.38	4.3E-79	Probably not the same population
CASCADES, COLUMBIA B.	133 200	334.8	3.8	3.53E-52	Probably not the same population
COAST R., PUGET L., N. ROCKIES	17 263 60	0.29	3.02	0.7	Probably the same population
COAST R. PUGET L.	17 263	0.22	3.88	0.64	Probably the same population

Table 3-2 shows the ANOVA of TP levels for all drainage basins regardless of development levels. The analysis shows that the Coast Range, the Puget Lowlands, and the Northern Rockies may be treated as one population. However, the Cascades and the Columbia Basin should be treated separately from one another and the rest of the ecoregions.

FIGURE 3-3: BOX-PLOT OF TP BY ECOREGION FOR UNDEVELOPED LAKE DRAINAGES (1971-1975 LAKES DATA)

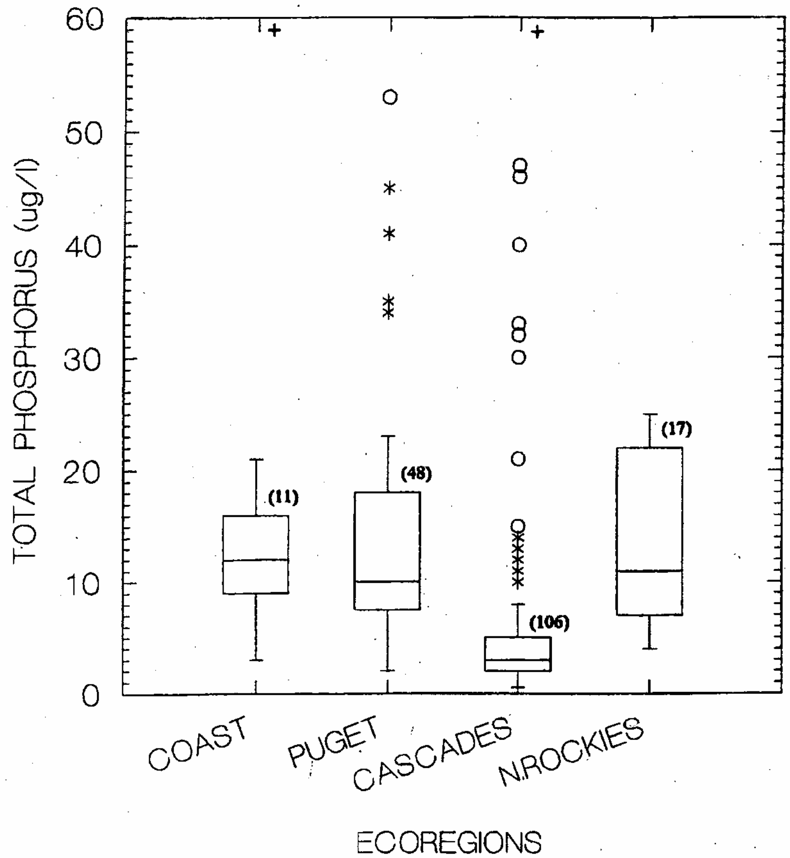


Table 3-3: TP Data Points (from Figure 3-3) for Undeveloped Lake Drainages (1971-1975 Lakes Data)

ECOREGION	NO. OF LAKES	PERCENTILES (µg/L TP)					MEAN µg/L TP	COEF OF VAR
		MIN	25	MED	75	MAX		
COAST R.	11	3	9	**12**	16	680	84	2.4
PUGET L.	48	2	7	**10**	18	53	14	0.8
CASCADES	106	0	203	**6**	180		8	2.5
N. ROCKIES	17	4	7	**11**	22	25	14	0.6

Table 3-4: Analysis of Variance for TP

(Bulletin 43 data, 1971-1975, undeveloped lake drainages)

ECOREGIONS COMPARED	NO. OF LAKES	F	F crit.	P Value	RESULTS
COAST R., PUGET L., CASCADES, N. ROCKIES	11 48 106 17	23.0	2.66	1.22E-12	Probably not the same population
COAST R., PUGET L., N. ROCKIES	11 48 17	2.29	3.12	0.11	Probably the same population

Table 3-4 summarizes the ANOVA for lakes in undeveloped drainages in each ecoregion. It showed that not all the ecoregions should be treated as the same population. However, when the Cascades were excluded, the remaining three ecoregions (the Coast Range, the Puget Lowlands, and the Northern Rockies) had similar enough attributes to be treated as one population. The ANOVA for both undeveloped and regardless of development showed similar results. There was then no reason to conduct ANOVA for drainages with 25 percent or less development since it would have compared data between the two extremes.

In the Columbia Basin, there were only three lakes with zero development. This posed a significant problem considering the Columbia Basin had approximately 260 lakes and represents a large area of the east side of the state. At 10 percent or less land-use development, the Columbia Basin had only 11 lakes. At a land-use development level of 25 percent or less, there were 16 lakes from the Columbia Basin. These lakes were sampled during June through September. The 16 lakes in the Columbia Basin comprised a more robust sample for comparison with other ecoregions. Therefore, the choice of 25 percent or less development was considered the best information available to determine near-natural background conditions in the Columbia Basin.

FIGURE 3-4: LAKES IN DRAINAGES WITH 25% OR LESS DEVELOPMENT

(Each dot represents a lake)

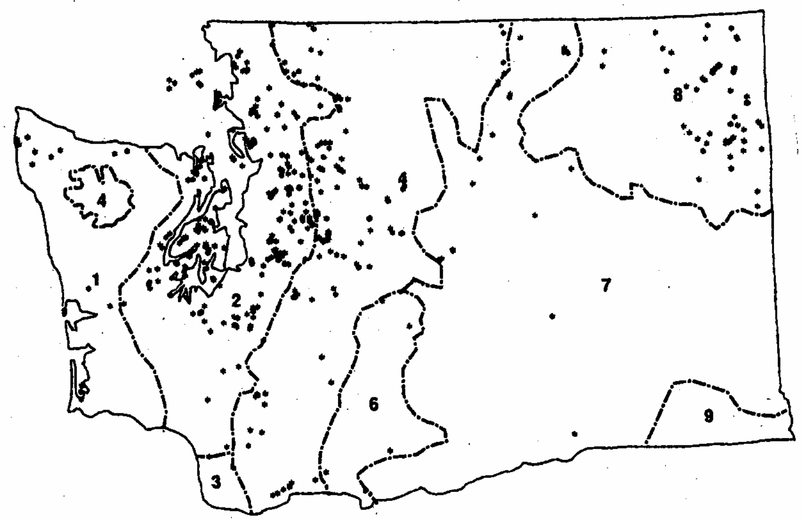


FIGURE 3-5: BOX PLOT OF TP BY ECOREGION FOR LAKES IN BASINS WITH 25% OR LESS LAND USE DEVELOPMENT

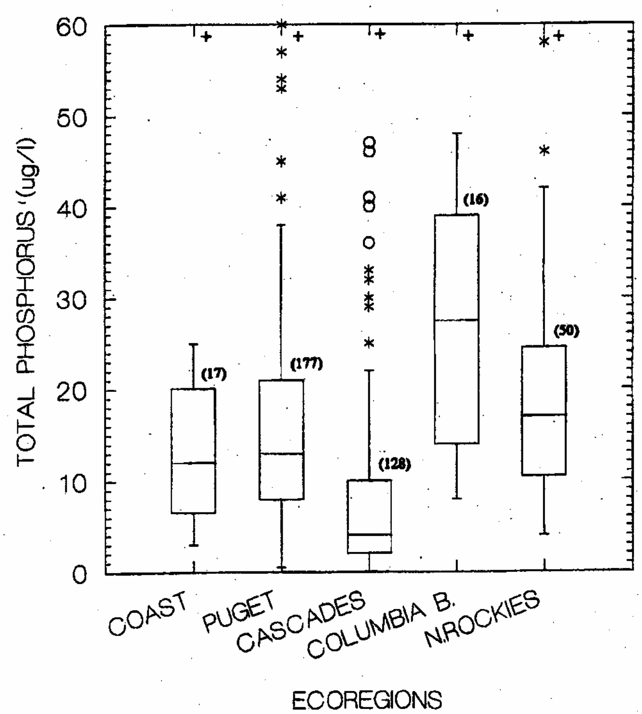


Table 3-5: 1971-1975 Lakes TP Data for Lake Drainages
With 25% or Less Development

ECOREGION	NO. OF LAKES	PERCENTILES (µg/L TP)					MEAN	COEF OF VAR
		MIN	25	MED	75	MAX		
COAST R.	17	3	7	**12**	20	680	58	2.8
PUGET L.	177	0	9	**13**	23	260	21	1.4
CASCADES	128	0	2	**4**	11	180	11	2.0
COLUMBIA B.	16	8	14	**32**	41	1500	128	2.9
N. ROCKIES	50	4	11	**17**	25	350	27	1.8

As shown in Table 3-5, the range of values between the 25th and the 75th percentiles illustrates that the median values were very representative of the central tendency of the TP data. However, the committee recommended that the range between the 50th and the 75th percentile would be more representative of an attainable TP level.

The committee therefore recommended adopting 'action values' derived from values between the 50th and 75th percentiles and using those drainages with 25 percent or less development (Figures 3-4 and 3-5). It was considered unreasonable to use an action value higher than the 75^{th} percentile. Many lakes would not be adequately protected using the 75^{th} percentile values. On the other hand, by setting action values below the 50^{th} percentile, many lakes with low development levels would exceed the action values. Adopting the 50^{th} to 75^{th} percentile range reduced outliers and provided a reasonable and protective approach.

In addition, the committee used the TP values shown in Table 3-6 as those values that could be achievable. These values were based on 25 percent development of the watershed.

Table 3-6: Total Phosphorus Percentiles for Lake Drainages with 25% or Less Land-Use Development (1971-1975).

Ecoregions	Coast Range	Puget Lowlands	Cascades	Columbia Basin	Northern Rockies
Percent of Development	0% $\leq$ 25%	0% $\leq$ 25%	0% $\leq$ 25%	0% $\leq$ 25%	0% $\leq$ 25%
25TH to 75TH PERCENTILE	**9 - 16 7 - 20** (µg/L TP)	**7 - 20 9 - 23** (µg/L TP)	**2 - 6 2 - 11** (µg/L TP)	NA **14 - 41** (µg/L TP)	**7 - 22 11 - 25** (µg/L TP)

The percentile values derived from the Bulletin 43 data (Bortelson et al. 1975) indicate the number of lakes affected by the choice of a particular action value. For example, about 50 percent of the lakes would have TP values above the action value if the value were set at the 50th percentile. However, the number of lakes above the action value would be greater than 50 percent if the 50th percentile from undeveloped lakes were used.

An examination of the following data sources was conducted to determine how many lakes would be above or below the ecoregional action value.

- Independent Lake restoration Phase I, and II studies (see list in Appendix A). Represents data sampling from 1975-1992, depending on study. This data was used in evaluating the present condition of lakes.

- Seattle Metro and King County Lake Studies (Brenner and McGuire, 1990, Brenner, et al. 1990). This data was used only in evaluating the present condition of lakes.

- Thurston County Lakes (Davis, 1993). Represents data sampling from 1991-1992. This data was used only in evaluating the present condition of lakes.

- Department of Ecology, Environmental Investigations and Laboratory Services Program, Volunteer Lakes Program (Hallock, 1995). Represents data sampling from 1989-1994. This data was used only in evaluating the present condition of lakes. Some of the late May data was used from this source because the lakes were believed to be stratified and the data would have been shifted heavily to late summer if left out.

By comparing recent TP data with that of the 1970s, it was shown that the percent of lakes below the 75th percentile value was:

Coast Range = 82 percent (improvement)
Puget Lowlands = 68 percent (degradation);
Cascades = 79 percent (improvement)
Columbia Basin = 38 percent (degradation)
Northern Rockies = 78 percent (improvement)

3.5(b) Chlorophyll

Rector and Hallock (1990) reported a strong correlation of both TP and chlorophyll-*a* with Secchi depth using 1989 and 1990 lake sampling data (Table 3-7). The chlorophyll-*a* explained approximately 70 percent of the variability in Secchi depth and TP explained between 49 to 69 percent of the variability in chlorophyll-*a*. The results from these studies showed the relationship of TP and Secchi depth with chlorophyll-*a* in recent data.

There were not enough lakes sampled by Rector and Hallock (1990) to conduct complete ecoregional analyses.

Table 3-7: Regression Coefficients

(Rector and Hallock, 1990)

Log(mean Secchi (m)) = a + b Log(mean chlorophyll-*a* (µg/L))

Study	a	b	r^2	n
1990	0.76	-0.39	0.69	10
1989	0.85	-0.53	0.75	24

Log(mean chlorophyll-*a* (µg/L)) = a + b Log(spring TP (mg/L))

Study	a	b	r^2	n
1990	3.25	1.58	0.69	9
1989	2.67	1.14	0.49	25

3.6 Comparing the near-background conditions to trophic states

The 25th to 75th percentile TP values for lakes of low development were compared to published trophic states. The intent of this method was to establish the existing TP values assuming that they represented near-natural conditions. In addition, a comparison to trophic state illustrated the type of uses that should be maintained for each recommended ecoregional criteria. Trophic state boundaries strongly influenced the recommended criteria. The trophic boundary located closest to the upper end of the interquartile range was used.

Coast/Puget Ecoregion

The background conditions for Coast Range undeveloped drainages had an interquartile range (25th to 75th percentiles) between 9 to 16 µg/L(figure 3.6). Drainages with 25 percent or less development had an interquartile range from 7 to 20 µg/L.

Undeveloped drainages in the Puget Lowlands had an interquartile range from 7 to 18 µg/L. Drainages with 25 percent or less development ranged from 9 to 23 µg/L.

Comparing published trophic states to the above ranges shows that a mesotrophic state was most reasonable for the Coast and Puget ecoregions. Gilliom (1984) and Simpson and Reckhow (1979) recommended 10-20 µg/L TP for mesotrophy using Puget Sound and North American lake data. Carlson recommended 12 to 24 µg/L TP for mesotrophy using Midwestern American lakes and OECD (1982) recommended 10 to 35 µg/L TP using North American and northern European lakes. The committee agreed that the trophic state provided by Gilliom (1984) and Simpson and Reckow (1979) provided the most relevant, regionally specific action value.

An action value of 20 µg/L TP was recommended. Much weight was given to preserving mesotrophic conditions suggested in the literature matched to the middle to upper interquartile range. The suggested action value corresponded to the 75th percentile for the Coast Range for undeveloped drainages and slightly above the 75th percentile for the undeveloped drainages in the Puget Lowlands. The action value was slightly less than the 75th percentile for the drainages with 25 percent or less development in the Puget lowlands.

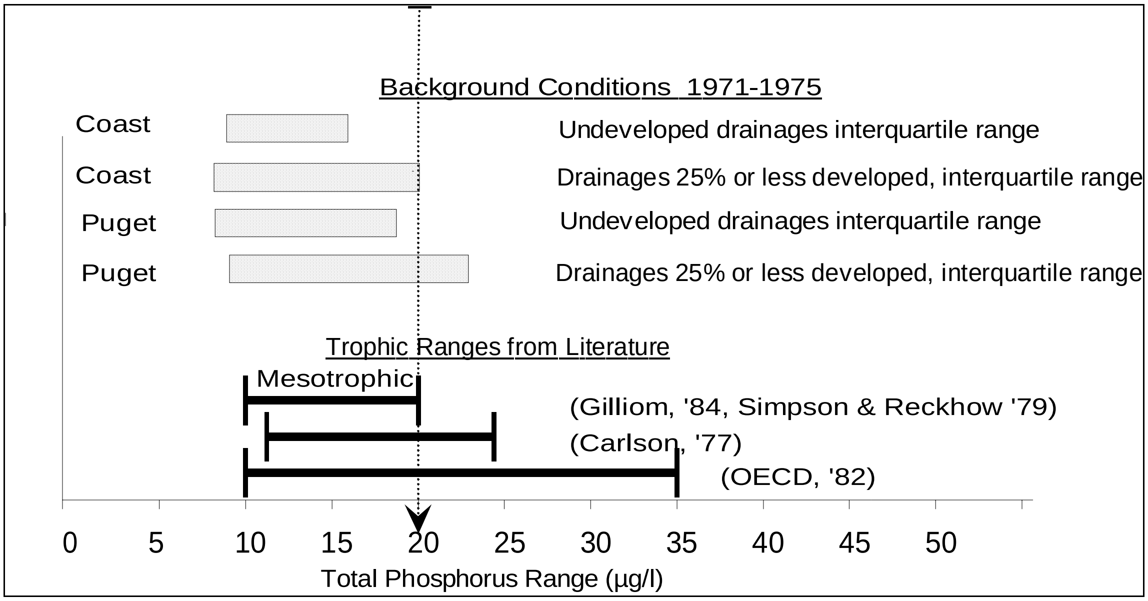


Figure 3-6: Decision Matrix for Coast Range and Puget Lowlands

Cascades Ecoregion

The interquartile range generated for undeveloped drainages in the Cascades Ecoregion was between 2 and 6 µg/L TP. The range for drainages with 25 percent or less development was 2 to 11 µg/L TP (figure 3-7). Much weight was given to trophic states as described in the literature that corresponded with the interquartile ranges generated with the data. The committee agreed that preserving an oligotrophic state was the most reasonable choice for this ecoregion. Gilliom (1984), and Simpson and Reckhow (1979) recommended a range between 0 to 10 µg/L TP for oligotrophy. According to Carlson's trophic state index (1977), a transition from an oligotrophic state to a mesotrophic state occurs at a TP level of 12 µg/L and a Secchi of 4 m. According to OECD (1982), this transition occurs at a TP of 10 µg/L and a Secchi of 6 to 12 m. Therefore, a criterion of 10 µg/L TP was recommended.

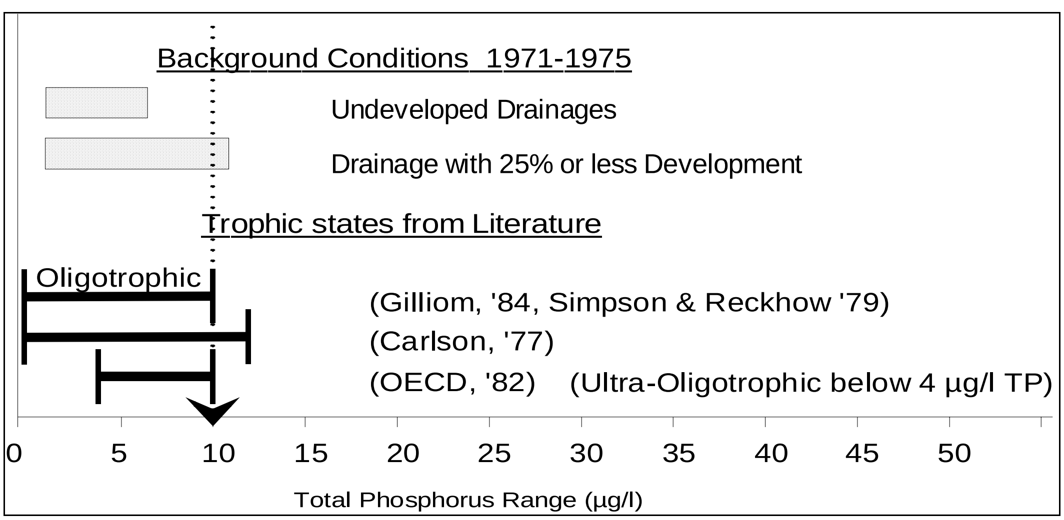


Figure 3-7: Decision Matrix for the Cascades

Columbia Basin Ecoregion

In the Columbia Basin Ecoregion, there were only three lakes in undeveloped drainages. The range of values for these three lakes is not shown here. However, they are incorporated into the 25 percent or less development range. The drainages with 25 percent or less development had an interquartile range of 14 to 41 µg/L TP (Figure 3-8). In the Columbia Basin, the number of lake basins with up to 25 percent development was small compared to most of the other ecoregions in the state.

The mesotrophic ranges for TP determined by Gilliom (1984) were based on Puget Sound lakes and may not apply well to Columbia Basin conditions when comparing chlorophyll-*a* and Secchi ranges. According to OECD (1982), a mesotrophic state would occur around a TP level of 10 to 35 µg/L, a chlorophyll-*a* of 2.5 to 8 µg/L, and a Secchi depth of 6 to 3 m. These OECD values match well with conditions in the Columbia Basin.

According to Carlson (1977), a transition to eutrophy occurs at 24 µg/L TP and at Secchi depths of less than 2 m.

For the Columbia Basin Ecoregion, the committee determined that the trophic state boundary should occur in the middle to upper interquartile range. An action value of 35 µg/L TP was subsequently recommended by the committee. This also coincided with the mesotrophic/eutrophic boundary recommended by the OECD.

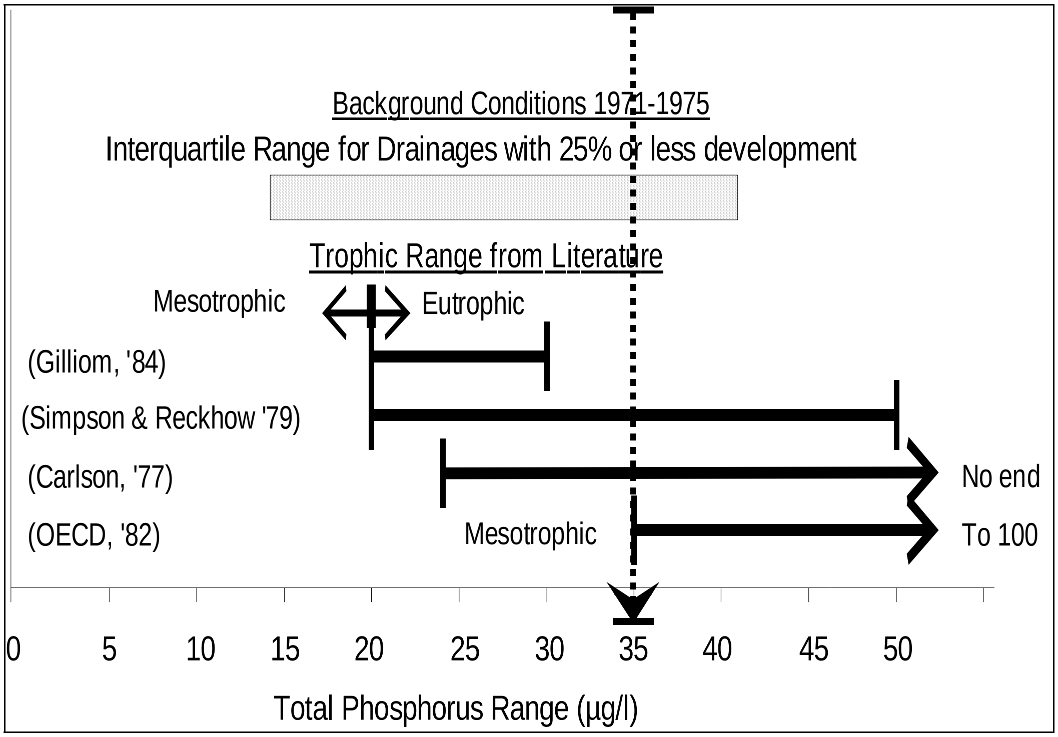


Figure 3-8: Decision Matrix for the Columbia Basin

Northern Rockies Ecoregion

Undeveloped drainages in the Northern Rockies Ecoregion had an interquartile range of 7 to 22 µg/L TP. The drainages with 25 percent or less development had an interquartile range of 11 to 25 µg/L TP (Figure 3-9). An action value of 20 µg/L TP was recommended for the Northern Rockies. The mesotrophic limit given by Gilliom (1984), which was based on Puget Sound lakes, may also apply to the Northern Rockies. This was due to similarities among the Puget Lowlands, the Coast Range and the Northern Rockies in the ANOVA analysis discussed in Section 3.2. The recommended action value was at the mesotrophic/eutrophic boundary for TP recommended by Gilliom (1984) and well within the mesotrophic limits recommended by Carlson (1977) and OECD (1982).

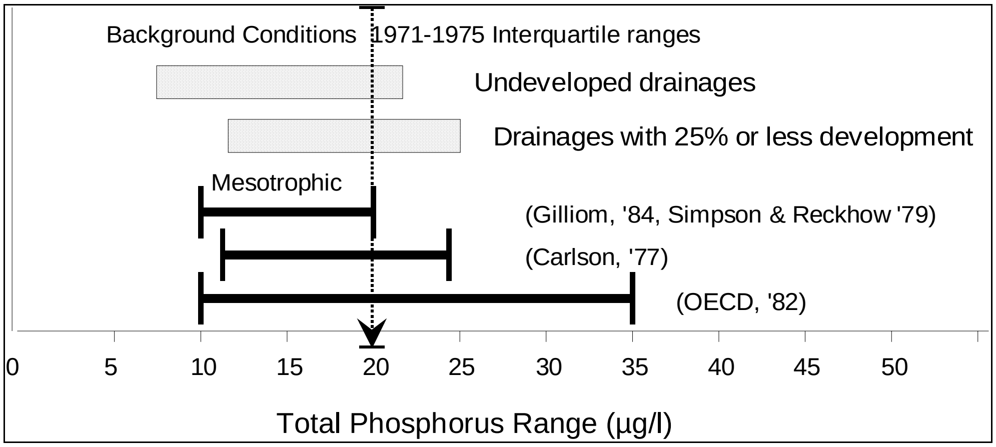


Figure 3-9: Decision Matrix for The Northern Rockies.

East Cascades and Willamette Valley

The East Cascades and the Willamette Valley ecoregions have a small number of lakes and were therefore not included in the analysis for establishing Washington lake TP ecoregional criteria. The TP and Secchi values are shown in Table 3-8 for each lake along with median values.

Table 3-8: TP Measures from the East Cascades and Willamette Valley Ecoregions (1971-1975 Lakes Data, 1992 Ecology EILS)

EAST CASCADES FOOTHILLS		WILLAMETTE VALLEY	
TP (µg/L)	SECCHI (m)	TP (µg/L)	SECCHI (m)
27	5.0	29	5.6
30	3.6	41	1.6
12	1.7	560	0.2
290	0.3	29	1.1
		190	0.3
		73	0.5
		66*	---
MEDIANS		MEDIANS	
28.5	2.7	66.4	0.8

The Willamette Valley ecoregion TP and Secchi depth values were not comparable to the values of either the Puget Lowlands or the Cascades. The median TP values for the Willamette Valley were high when compared to the median TP values for the Puget lowlands.

The committees recommended not establishing lake TP action-values for the Willamette Valley and Eastern Cascade ecoregions. They recommended that each lake in those two ecoregions should be studied on an individual basis and not use pre-established action values. Lake-specific studies have already taken place for three of the lakes: Lacamas, Vancouver, and Horseshoe. These three lakes have been intensively studied as Phase I and II lake restoration projects funded by lake management grants.

Nitrogen limitation

Nitrogen-limited lakes were discussed by the committee to consider the feasibility of establishing criteria and action values. They determined that the data have been too variable to allow development of an absolute standard. However, they acknowledged that TN to TP ratios should be maintained above 10:1 to prevent blue green algae dominance. Therefore, when setting TP limits, consideration should be given to TN to TP ratios. For instance, for a TP concentration of 20 µg/L to be protective, TN would generally need to be above 200 µg/L.

Section 4.0: Discussion of Lake-Specific Approach

This section outlines the process for conducting lake-specific analyses for establishing lake-specific criteria. This process is compatible with EPA's Clean Lakes Guidance and Ecology's Lake Restoration Program.

- Any action to set a lake-specific criterion shall require public involvement.
- A plan to study the lake must be developed in consultation with local officials and affected parties and approved by Ecology. However, Ecology does not need to fund or conduct the study.
- The study must include at a minimum:
  a) A comprehensive limnological study of the lake, significant tributaries and the watershed including loadings from point and non-point sources of nutrients (total phosphorus and total nitrogen), existing and potential changes in nutrients, chlorophyll-*a*, Secchi disk depths, dissolved oxygen in the hypolimnion and epilimnion if thermally stratified, and in-lake nutrient recycling.
  b) The study must determine existing and potential lake uses, how to protect lake uses, and whether any of those uses are lost or impaired due to excessive nutrients and/or other pollutants, algae or aquatic plants.
  c) Consideration must also be given to TP/ TN ratios.
  d) A matrix must be developed for all water quality improvement methods, their costs and potential for achieving improvements in water quality.
  e) A matrix must be developed showing the public's priorities of implementing water quality improvements and the expected water quality improvements for each or combinations of the improvement methods.
  f) Public participation, including a study of the local public's perceptions of lake aesthetic uses, involvement in recommending draft recommendations for numerical criteria, and a public hearing in which a vote is taken to accept the proposed water quality improvements as goals (i.e., setting criteria for phosphorus and other parameters such as Secchi disc, chlorophyll *a* and hypolimnetic oxygen concentrations).
  g) Final reports available to the public.

Section 5.0: Recommendations for Lake Nutrient Criteria

5.1 Advisory Committee Conclusions

The advisory committee recommended adopting TP criteria based on ecoregional action levels. A combination of background conditions and trophic states was used to arrive at the proposed action value for each ecoregion. The method recommended a range of TP values. A land-use development level of 0 percent to 25 percent was used to develop the near background condition. The TP values within the 50th to 75th percentiles were used to bracket the range. This range provided protection and allowed some level of development to occur while protecting beneficial uses at near-natural conditions.

The final ecoregional action values were developed by choosing values that occurred where the recommended ranges of the background conditions and trophic boundaries overlapped.

Lakes in ecoregions that do not have action values (Eastern Cascades Foothills and Willamette Valley ecoregions) were quite different from lakes in neighboring ecoregions and should be studied individually to establish criteria.

The criteria are determined by a minimum level of sampling or a more comprehensive lake-specific study. The minimum level of sampling consists of a mean of four or more samples taken from the epilimnion (near lake surface) during the months of June through September in one or more years. Samples must be spread throughout the season. If existing TP levels are at or below ecoregional action levels, the criterion can be set at or below the trophic states into which they fit.

If the TP concentrations were higher than the ecoregional action value, then attainment of the ecoregional action value would be recommended. These lakes would receive priority for comprehensive lake-specific studies according to the five-year rotation of Ecology’s statewide watershed approach. They would also be listed on the latest revision to the impaired water body (303[d]) list. Existing and potential characteristic uses would be determined and if they were attainable (as determined following EPA’s Section 314 Clean Lakes Guidance), the TP criteria for achieving those uses would be the recommended goals. If characteristic uses were not achievable, then higher TP criteria could be recommended that would be protective of the remaining uses. The criteria should not be intended for lakes or ponds with surface areas less than five acres or ponds entirely contained on private property that do not drain to other lakes and streams.

Studies to develop lake-specific criteria should be allowed where citizens or affected parties feel criteria are not protective enough or are too protective. These studies would involve the public and affected entities, require public hearings, and require plans to be approved by the Department of Ecology. Past studies may be accepted if they have gathered the necessary information as outlined in the discussion of the lake-specific approach. Whenever possible, these actions will be coordinated with Ecology's watershed-basin approach.

Ecology used the process described previously and the resulting committee recommendations to develop lake nutrient criteria. Section 5.2, which follows, contains the resulting regulatory language adopted into the states water quality standards.

5.2 Washington's Lake Nutrient Criteria Rule Language

The lake nutrient criteria adopted by the state of Washington are found at Section 30 paragraph (6) of Chapter 173-201A of the Washington Administrative Code:

(6) **Establishing lake nutrient criteria.**

(a) The following table shall be used to aid in establishing nutrient criteria:

Table 1: The ecoregional and trophic-state action values for establishing nutrient criteria:

Trophic State	If Ambient TP (µg/L) Range of Lake is:	Then criteria should be set at:
Coast Range, Puget Lowlands, and Northern Rockies Ecoregions:		
Ultra-oligotrophic	0-4	4 or less
Oligotrophic	>4-10	10 or less
Lower mesotrophic	>10-20	20 or less
	Action Value	
	>20	lake-specific study may be initiated
Cascades Ecoregion:		
Ultra-oligotrophic	0-4	4 or less
Oligotrophic	>4-10	10 or less
	Action Value	
	>10	lake-specific study may be initiated
Columbia Basin Ecoregion:		
Ultra-oligotrophic	0-4	4 or less
Oligotrophic	>4-10	10 or less
Lower mesotrophic	>10-20	20 or less
Upper mesotrophic	>20-35	35 or less
	Action Value	
	>35	lake-specific study may be initiated.

Lakes in the Willamette, East Cascade Foothills, or Blue Mountain ecoregions do not have recommended values and need to have lake-specific studies in order to receive criteria as described in (c)(i) of this subsection.

(b) The following actions are recommended if ambient monitoring of a lake shows the epilimnetic total phosphorus concentration, as shown in Table 1 of this section, is below the action value for an ecoregion:

(i) Determine trophic status from existing or newly gathered data. The recommended minimum sampling to determine trophic status is calculated as the mean of four or more samples collected from the epilimnion between June through September in one or more consecutive years. Sampling must be spread throughout the season.

(ii) Propose criteria at or below the upper limit of the trophic state; or

(iii) Conduct lake-specific study to determine and propose to adopt appropriate criteria as described in (c) of this subsection.

(c) The following actions are recommended if ambient monitoring of a lake shows total phosphorus to exceed the action value for an ecoregion shown in Table 1 of this section, or where recommended ecoregional action values do not exist:

(i) Conduct a lake-specific study to evaluate the characteristic uses of the lake. A lake-specific study may vary depending on the source or threat of impairment. Phytoplankton blooms, toxic phytoplankton, or excessive aquatic plants are examples of various sources of impairment. The following are examples of quantitative measures that a study may describe: total phosphorus, total nitrogen, chlorophyll-*a*, dissolved oxygen in the hypolimnion if thermally stratified, pH, hardness, or other measures of existing conditions, and potential changes in any one of these parameters.

(ii) Determine appropriate total phosphorus concentrations or other nutrient criteria to protect characteristic lake uses. If the existing total phosphorus concentration is protective of characteristic lake uses, then set criteria at existing total phosphorus concentration. If the existing total phosphorus concentration is not protective of the existing characteristic lake uses, then set criteria at a protective concentration. Proposals to adopt appropriate total phosphorus criteria to protect characteristic uses must be developed by considering technical information and stakeholder input as part of a public involvement process equivalent to the Administrative Procedure Act (chapter 34.05 RCW).

(iii) Determine if the proposed total phosphorus criteria necessary to protect characteristic uses is achievable. If the recommended criterion is not achievable and if the characteristic use the criterion is intended to protect is not an existing use, then a higher criterion may be proposed in conformance with 40 CFR part 131.10.

(d) The department will consider proposed lake-specific nutrient criteria during any water quality standards rule-making that follows development of a proposal. Adoption by rule formally establishes the criteria for that lake.

(e) Prioritization and investigation of lakes by the department will be initiated by listing problem lakes in a watershed needs assessment, and scheduled as part of the Water Quality Program's watershed approach to pollution control. This prioritization will apply to lakes identified as warranting a criteria based on the results of a lake-specific study, to lakes warranting a lake-specific study for establishing criteria, and to lakes requiring restoration and pollution control measures due to exceedence of an established criterion. The adoption of nutrient criteria is generally not intended to apply to lakes or ponds with a surface area smaller than five acres; nor to ponds wholly contained on private property owned and surrounded by a single landowner; and nutrients do not drain or leach from these lakes or private ponds to the detriment of other property owners or other water bodies; and do not impact designated uses in the lake. However, if the landowner proposes criteria the department may consider adoption.

Section 6.0: Protecting Riverine Systems from Excess Nutrients

During the same review timeframe that Ecology used to develop the lake nutrient criteria, Ecology evaluated the feasibility and benefits of establishing nutrient criteria for flowing water systems. Ecology examined periphyton growth, chlorophyll *a*, nitrogen, and total phosphorous levels in ecoregions on the west and east sides of the state. Ecology's researchers were unable to find a predictive relationship between excess production and eutrophication and measured nutrient concentrations. Flow rates, shading, and available light are also confounding factors in eutrophication processes in streams and rivers. Thus, efforts to develop statewide nutrient criteria for river and stream systems were curtailed. Ecology has chosen an alternative pathway for the control of nutrient concentrations in riverine systems that rely on other indicators and triggers for trophic health, and more water body specific modeling to select nutrient threshold values.

Washington State has established aquatic life criteria for pH and dissolved oxygen, which serve as sensitive indicators of riverine eutrophication. The most utilitarian of these measures is dissolved oxygen. Throughout most of the state, a single daily minimum below 9.5 mg/L in the upper watershed or below 8.0 mg/L in the lower watershed causes waters to be examined for potential impairment. In a few select slow moving streams heavily impacted by human alteration, and typically in the arid region of the state, a single daily minimum 6.5 mg/L serves as the trigger. While these dissolved oxygen values were set to provide a high level of protection and support for metabolic function, they also set a standard that cannot be attained in rivers with nuisance algal growth.

In establishing permit limits or in establishing load and wasteload allocations through TMDLs or water clean up plans, the role of nutrients in affecting oxygen levels is evaluated and protective limits established where nutrients are interfering with attainment of the daily minimum oxygen levels. Thus compliance plans for the dissolved oxygen criteria examine the influence of BOD, nutrients, and temperature to ensure the trophic health of the water body is maintained or restored.

The second key indirect indicator of river eutrophication is the state's pH criteria. The criteria set ranges of acceptable pH, which eutrophic streams typically violate, that if exceeded cause the water body to be evaluated for potential impairment. The carbon dioxide used for photosynthesis by aquatic plants and algae results in increases in the pH of waters where such plant production is high. While the pH criteria are less sensitive indicators of trophic health than the dissolved oxygen criteria in use by the state, they do provide an important supplementary trigger for initiating necessary water body investigations. Excess nutrients in the state are identified by increasing trends in pH concentrations and by exceedences of the upper pH levels established for the water bodies. After such problems are identified, the criteria serve as targets for restoration and clean up that directly incorporate the causal effect of nutrients.

Section 7.0: Protecting Marine Systems from Excess Nutrients

Due to a lack of data in estuaries and the known highly complex relationship between nutrients and trophic health in marine systems, statewide criteria were not recommended for marine waters. Ecology has chosen an alternative pathway for the control of nutrient concentrations in marine systems that relies on other indicators and triggers for trophic health, and more water body specific modeling to select nutrient threshold values. These alternative triggers function as described above in Section 6.0 for riverine systems. The interrelationship between nutrient concentrations in marine systems, however, is even more complex than in fresh water systems. Tidally reversing and complex currents, stratified and unstratified sections of the receiving water, changing in the limiting nutrient form (phosphorous versus nitrogen) with depth and location, and the non-linear contributions from freshwater streams and rivers make setting statewide nutrient criteria in marine waters too problematic.

Ecology has begun the process of developing sophisticated models for its marine waters that can be used to account for the complex variables that affect compliance with water quality standards. A primary driver in marine waters for setting the agency's priorities is the failure to comply with dissolved oxygen criteria. Paramount to this issue is the role that is played by excessive nutrient contributions from tributaries and point sources in these waters. Several large sectors of Puget Sound have been modeled to date with the focus on where problems with dissolved oxygen and excess algal production have been found to exist. Ecology is making use of internal as well as external funding to expand the modeled areas of the Sound. These models are priority as they not only help the state protect and restore the trophic health to its waters, but because they are the best tool to use to ensure that all water quality standards will be met in this complex marine environment.

Section 8.0: Rehabilitating of Nutrient-Limited Streams and Lakes.

Anadromous fish serve as a conduit for transporting valuable nutrients from the ocean upstream to headwater streams and lakes. The decay of adult fish after spawning releases these marine derived nutrients that feed both aquatic and terrestrial systems. In recent years, research has demonstrated that the loss of nutrients associated with the depletion of anadromous fish runs in Pacific Northwest streams and lakes is limiting the productivity of these systems. This reduction in productivity in turn is creating a barrier to returning natural fish production in these nutrient limited streams and lakes.

Experimental enhancements of rivers that are nutrient limited using hatchery fish carcasses, processed fish carcasses and artificial fertilizers are underway in Washington and elsewhere in the Pacific Northwest. These efforts are being used to develop a policy for adding nutrients to oligotrophic systems to boost recovery of natural levels of anadromous fish. The ongoing work will be used to identify the best forms of nutrients and the levels of nutrient additions that result in increased juvenile fish health and survival without causing problems of excess nutrients, such as excessive aquatic plant growth or oxygen depression. Work to date suggests that small increases in nutrients are fully utilized by the aquatic system and result in meaningful increases in juvenile fish production and smolt survival without measurable impacts on dissolved oxygen and without causing nuisance algal or vascular plant growth.

References

Bothwell, Max. L. 1989. Phosphorus-Limited growth dynamics of lotic periphytic diatom communities: Areal biomass and cellular growth rate responses. Can. J. Fish. Aquat. Sci., Vol 46.

Bothwell, Max. L. 1992. Eutrophication of rivers by nutrients in treated Kraft pulp mill effluent. Water Poll. Res. J. Canada. Vol. 27, No. 3 447-472.

Bortleson, G.C., J.B. McConnell, N.F. Dion, and L.M. Nelson. 1972-1979. Reconnaissance data on lakes in Washington. Water supply bulletin 42, Volumes 1-7. USGS.

Bortleson, G.G., 1981. Reconnaissance data on lakes in Washington. Water supply bulletin 43. Volumes 2-4. USGS.

Brenner, R., B. McGuire, 1990. Status of water quality in small lakes Seattle-King county region: 1989 survey. Water Pollution Control Department, Municipality of Metropolitan Seattle.

Brenner, R. et al. 1990. Quality of local lakes and streams 1989-1990 update. Water Pollution Control Department, Municipality of Metropolitan Seattle.

Carlson, Robert E. 1977. A trophic state index for lakes. Limnol. Oceanogr. 22:361-369.

Carlson, Robert E. 1984. The trophic state concept: A lake management perspective. Third annual conference proceedings on lake and reservoir management; 1983 October 18-20; Knoxville, Tennessee. U.S. Environmental Protection Agency: Washington, D.C. 427-430.

Clark, B.J. 1989. The assessment of the recreational fishery potential of the Cheakamus River upstream of the anadromous barrier: progress in 1988. Lower Mainland Fisheries report No. 156, B.C. Ministry of Environment. In: Kistrits 1990.

Cooke, Dennis G., and Robert E. Carlson. December 1989. Reservoir management for water quality and THM precursor control. Kent State University, prepared for the American Water Works Association.

Davis, Susan, 1993. Personal communication regarding lakes data. Environmental Health, Thurston Co.

Derksen, G. 1981. Water quality and periphytic algal standing crop of the Capilano and Seymour Rivers, North Vancouver, British Columbia. In: Water quality criteria for nutrients and algae. Richard Nordin. Victoria, British Columbia: Water Management Branch, Ministry of Environment. 1985.

Ecology, Department of, 1992. Statewide water quality assessment: 305(b) report. Water Quality Program. Publication #92-04.

Ecology, Department of, 1994. Water quality limited list: 303(d) list. Water Quality Program.

Eilers, J.M. et al. 1987. Western lake survey phase I, characteristics of lakes in the Western United States, Volume II: Data compendium for selected physical and chemical variables. U.S.E.P.A. Office of research and Development, Washington, DC.

Funk, W. H., and H. Gibbons, et al. 1982. Preliminary assessment of multiphase restoration efforts at Liberty Lake, Washington. Corvallis Environmental Research Laboratory. U.S. Environmental Protection Agency.

Funk, William H., and Barry C. Moore et. al. 1985. Baseline study of Reflection Lakes Mount Rainier National Park. State of Washington Water Research Center.

Gilliom, Robert J. 1984. Tools for assessing lake eutrophication in the Puget Sound Region, Washington. Third annual conference proceedings on Lake and Reservoir Management; 1983 October 18-20; Knoxville, Tennessee. U.S. Environmental Protection Agency: Washington, D.C. 32-39.

Gilliom, R. J., G.C. Bortleson. 1983. Relationships between water quality and phosphorus concentrations for lakes of the Puget Sound region, Washington. U.S. Geological Survey open file report 83-255.

Golterman, H.L. 1975. Physiological limnology: An approach to the physiology of lake ecosystems. New York: Elsevier Sci. Pub. Co.

Hallock, David. 1995. Unpublished lakes data spanning 1989-1994 (1989-1992 previously published) from lake water quality assessment project. Washington State Department of Ecology.

Hecky, R. E., P. Kilham. 1988. Nutrient limitation of phytoplankton in freshwater and marine environments: a review of recent evidence on the effects of enrichment. Limnol. Oceanogr. 33(4, part 2) 796-822.

Heiskary, Steven A. 1993. Personal communication regarding Minnesota criteria. Minnesota Pollution Control Agency.

Heiskary, Steven A., and Bruce C. Wilson. May 1990. Minnesota lake water quality assessment report, second edition. Minnesota Pollution Control Agency.

Heiskary, Steven A., and Bruce C. Wilson. 1989. The regional nature of lake water quality across Minnesota: An analysis for improving resource management. J. Minn. Academy Sci. 55(1): 71-77.

Holmes, D.W. per 1984 personal comm. Unpublished data for sites 060004 (Savona) and 0600163 (Walhachin) collected 1976-1977. Waste Management Branch, B.C. Ministry of Environment. In: Nordin, 1985.

Horner, R. R., E.B. Welch, M. Seeley, and J. Jacoby. 1986. Velocity- related critical phosphorus concentrations in flowing water, phase II. Final report to National Science Foundation. Award No. CEE-83-04731.

Horner, R. R., E.B. Welch, M. Seeley, and J. Jacoby. 1990. Responses of periphyton to changes in current velocity, suspended sediment and phosphorus concentration. Freshwater Biology 24, 215-232.

Jacoby, Jean M. 1987. Alterations in periphyton characteristics due to grazing in a cascade foothill stream. Freshwater Biology 18, 495-508.

Joy, Joe. 1993. Draft assessment of nutrient/eutrophication criteria for lotic water scope of work. Environmental Investigation and Laboratory Services Program. Washington State Department of Ecology. Olympia.

Kistritz, R.U., and D.D. MacDonald. 1990. Draft procedure for deriving water quality guidelines for nutrients, algae and aquatic vascular plants in Canadian stream ecosystems. Inland Waters Directorate, Environment Canada.

Landers, D.H. et al. 1987. Western lake survey phase I, characteristics of lakes in the Western United States, Volume 1: population descriptions and physico-chemical relationships. U.S.E.P.A. Office of Research and Development, Washington, DC.

Langer, O.E., and M.D. Nassichuck. 1976. Toxicity of chlorinated sewage effluent to fish, salmon eggs and periphyton on the Nicola and Coldwater Rivers. In: Water quality criteria for nutrients and algae. Richard Nordin. Victoria, British Columbia: Water Management Branch, Ministry of Environment. 1985.

Munro, K.A., S.C. Samis and M.D. Nassichuk. 1985. The effects of hatchery effluents on water chemistry, periphyton and benthic invertebrates of selected British Columbia streams. Vancouver, B.C.: Habitat Management Division, Department of Fisheries and Oceans. Report No. 1830.

Ney, John J., C. Moore, M. Tisa, J. York, R. Neves. Factors affecting the sport fishing in a multiple use Virginia reservoir. Lake and Reservoir Management. 1990 6(1): 21-32.

Nordin, Richard. 1985. Water quality criteria for nutrients and algae. Victoria, British Columbia: Water Management Branch, Ministry of Environment.

(OECD) Organization for Economic Co-Operation and Development. 1982. Eutrophication of Waters: Monitoring, Assessment and Control. Vollenweider, Richard, Chairman, of the Technical Bureau. Paris, France.

Omernik, James M., and Alisa L. Gallant. 1986. Ecoregions of the Pacific Northwest. U.S. Environmental Protection Agency. EPA/600/3-86/033.

Patmount, C.R. 1987. The Spokane River Basin: allowable phosphorus loading. Seattle, WA: Harper-Owes.

Patmount, C.R., G. Pelletier, Welch, Botton, and Ebbesmeyer. 1989. Lake Chelan water quality assessment. Seattle, Washington. Harper Owes.

Perrin, Chris J., Max. L. Bothwell, and Pat A. Slaney. 1987. Experimental enrichment of a coastal stream in British Columbia: Effects of organic and inorganic additions on autotrophic periphyton production. Can. J. Fish. Aquat. Sci. 44: 1247-1256.

Rector, Julie, and David Hallock. 1989. Lake water quality assessment project. Washington State Department of Ecology. Pub No. 91-60.

Rector, Julie, and David Hallock. 1990. Lake water quality assessment project. Washington State Department of Ecology. Pub No. 92-124.

Reed, Dianna. 1992. North Carolina Department of Environment, Health and Natural Resources. Personal communication.

Sheehan, S.W., G.L. Ennis and R.L. Hallam. 1980. A water quality study of the Flathead River in British Columbia prior to proposed coal mining. In: Water quality criteria for nutrients and algae. Richard Nordin. Victoria, British Columbia: Water Management Branch, Ministry of Environment. 1985.

Smith, V. H. 1992. The nitrogen and phosphorus dependence of algal biomass in lakes: An empirical and theoretical analysis. Limnol. Oceanogr., 1101-1112.

Simpson, Jonathan T., and K. H. Reckhow. 1979. A method for the prediction of phosphorus loading and lake trophic quality from land-use projections. East Lansing, Mi.: Department of Resource Development, Michigan State University.

Sumioka, S.S., and D.P. Dion. 1985. Trophic Classification of Washington lakes using reconnaissance data. Water supply bulletin 57. Department of Ecology. USGS.

Walker, W. Jr. 1985. Statistical bases for mean chlorophyll-*a* criteria. Lake and reservoir management. North American Lake Management Society. 1:57-67.

Welch, E. B. 1992 revised, Ecological effects of wastewater, second edition. New York. Chapman and Hall.

Welch, E. B., Richard Horner, and Clayton Patmont. 1989. Prediction of nuisance periphytic biomass: a management approach. Wat. Res. 23(4), 401-405.

Welch, E. B., J.M. Jacoby, R.R. Horner, and M.R. Seeley. 1988. Nuisance biomass levels of periphytic algae in streams. Hydrobiologia 157: 161-168.

Welch, E. B., D.E. Spyridakis, J.I. Shuster, and R.R. Horner. 1986. Declining lake sediment phosphorus release and oxygen deficit following wastewater diversion. Journal WPCF, 58(1): 92-96.

Welch E.B., R.J. Totorica, and R.R. Horner. 1992. Approach to develop nutrient loading criteria for Franklin D. Roosevelt Lake. Dept. of Civil Eng. Univ. of Washington.

Willms, Roger, and Greg Pelletier. 1992. Impacts of Eastern State Hospital and Lakeland Village wastewater discharges on the quality of West Medical Lake. Washington State Department of Ecology. Olympia.

Wilson, K.H., C.D. Harrison, and C.N.H. Lam. 1984. The growth and control of nuisance blooms of alga Didymosphenia geminata in Fulton River spawning channel No. 2. Unpubl. Can. Tech. Rept. of Fish. Aquat. Sci., Dept. Fish. Oceans., Vancouver, B.C. In: Kistritz, 1990.

Appendix A: Lake Restoration Studies

TP SUMMER MEANS APRIL-OCTOBER

LAKE NAME	COUNTY	MEAN TP µg/L	REFERENCE
Ballinger	Snohomish	43	Restoration of phase III, Kramer, Chin & Mayo Inc. Oct 1986, Seattle.
Big	Skagit	3.0	Restoration Study Final, URS Co. Nov, 1977.
Campbell	Skagit	49(pre alum) 28(post alum)	Entranco Eng. Inc. Final report restoration evaluation. 1987.
Capitol	Thurston	63.7	CH2M Hill. June 1978.
Capitol	Thurston	52.5	Davis, S., S. Berg., J. Michaud. Bud Inlet/Deschutes River Part II Water Quality Study. Final Report. Thurston Co. Public Health and Social Services Dept. March 1993.
Carlisle	Lewis	72	Moore, Barry, W. Funk. WSU Water Research Center. Oct. 1990.
Chelan	Chelan	3.2	Water Quality Plan, RW Beck, Seattle, Wash. Dec 1991.
Chelan	Chelan	3.0	Harper, Owes/Patmont, Pelletier, Welch, Benton, and Ebbesmyer, Ecology. 1989.
Crabapple	Snohomish	4.1	Entranco Eng. Inc. Seven Lakes; Water Quality Analysis and Management Plan. Kirkland, Wash., April 1986.
Curlew	Ferry	23.2	Juul, Steve, W. Funk. A study of water quality at Curlew Lake. Water Research Center Pullman. August 1988.
Deer	Stevens	10.1	Department of Biology, Eastern Washington University. Cheney Wash. Entranco Eng. Inc. Bellevue, March 1991.
Diamond	Stevens	10.1	Singleton, L., J. Thielan, D. Kruger. An assessment of the trophic status. Ecology Water and Wastewater Monitoring. 1980.
Eloika	Spokane	6	Soltero, R., L. Campbell, K. Merrill, R. Plotnikoff, L. Sexton. Dept. of Biology, E. Wash. Univ. Cheney, July 1988.
Erie	Skagit	115(pre alum) 26(post alum)	Entranco Eng. Inc. Final report restoration evaluation. 1987.
Giffin	Yakima	16.9	Moore, B., W. Funk. Giffin Lake restoration phase I diagnostic/feasibility study. Water Research Center. October 1992.
Goat	Snohomish	<10	Dion, N., J. Ebbert, J. Pode, B. Peck. Hydrology of Hicks Lake Watershed. U.S.G.S. Water Resources Inv. Report 88-4235. Tacoma, 1988.
Goodman	Snohomish	2.5	Entranco Eng. Inc. Seven Lakes; Water Quality Analysis and Management Plan. Kirkland, Wash. ,April 1986.

LAKE NAME	COUNTY	MEAN TP µg/L	REFERENCE
Hicks	Thurston	42	Gendron, J., R. Pedersen. Lake Hicks Post-Restoration monitoring study. King County Parks and Rec. CH2M Hill. June 1987.
Hicks	Thurston	32	Thurston County and City of Lacey. Thurston County lakes – 1978 Water Quality and Restoration Analysis.
Horseshoe	Lewis	30	Welch, E., A. Whiley, D. Spyridakis. Horseshoe Lake quality, nutrient loading and management. Water Resource Series Tech Report No. 136. Univ. of Wash., Seattle Wash., 1992.
Howard	Snohomish	9.0	Entranco Eng. Inc. Seven Lakes; Water Quality Analysis and Management Plan. Kirkland, Wash., April 1986.
Ki	Snohomish	2.5	Entranco Eng. Inc. Seven Lakes; Water Quality Analysis and Management Plan. Kirkland, Wash., April 1986.
Kitsap	Kitsap	19	Parametrix Inc. and Brown and Caldwell. A restoration analysis and watershed management plan. City of Bremerton, May 1983.
Lacamas	Clark	65	Beak Consultants Inc and Scientific Resources Inc. Lacamas - Round Lake diagnostic and restoration analysis, final report. Portland, Oreg., July 1985.
Larson	King	197	Kramer, Chin, and Mayo Inc. Phantom-Larson Restoration Assessment Phase I report. City of Bellevue, April 1987.
Lawrence	Thurston	35.5 ('79) 33 ('75 20 ('81) 21.3 ('87) 26 ('88) 24 ('89)	Thomas, G., S. Bonar, D. Beachamp. Feasibility of aquatic plant control in Lake Lawrence, using triploid grass carp; phase I base line study. Wash. Dept. of Fisheries. Univ. of Wash., October 1990.
Lawrence	Thurston	23	Jacoby, J., H. Gibbons, C. Barnes, M. Gibbons, T. Noyes, C. Patmont. Lake Lawrence phase I restoration analysis final report. Wash. Dept. of Ecology and Kramer, Chin, and Mayo. 1991.
Liberty	Spokane	14	Michael Kennedy Consulting Eng. Water quality summary report for summer 1987 monitoring of Liberty Lake. January 1988.
Lois	Thurston	38	Thurston County and City of Lacey. Thurston County lakes – 1978 Water Quality and Restoration Analysis.
Loma	Snohomish	13.8	Entranco Eng. Inc. Seven Lakes; Water Quality Analysis and Management Plan. Kirkland, Wash., April 1986.

LAKE NAME	COUNTY	MEAN TP µg/L	REFERENCE
Long	Thurston	36	Entranco Eng. Thurston County Lakes Water Quality Analysis and Restoration Plans. Volume I and II. May 1982.
Long	Thurston	25.5	Thurston County and City of Lacey. Thurston County lakes – 1978 Water Quality and Restoration Analysis.
Loon	Stevens	10.1	Singleton, L., J. Thielen, D. Kruger. An assessment of the trophic status. Ecology Water and Wastewater Monitoring. 1980.
Martha	Snohomish	5.4	Entranco Eng. Inc. Seven Lakes; Water Quality Analysis and Management Plan. Kirkland, Wash. ,April 1986.
Medical	Spokane	26 (Aeration initiated in 1987 but did not alter water quality significantly)	Soltero, R., L. Sexton, K. Merrill. Hypolimnetic aeration of Medical Lake, Washington to reduce the effects of oxygen depletion. Dept. of Biology, E. Wash. Univ. Cheney, Wash., April 1989.
Moses (diluted since 1977 with water from Columbia River)	Grant	158 (‘69-‘70) 81 (‘77) 61 (‘78) 67 (’79) 79 (’80) 70 (’81)	Welch, E., K. Carlson, R. Nece, M. Bremer. Evaluation of Moses Lake Dilution. Water Resources Series No. 77. Univ. of Wash. March 1982.
Patterson	Thurston	35	Entranco Eng. Thurston County Lakes Water Quality Analysis and Restoration Plans. Volume I and II. May 1982.
Patterson	Thurston	26.7	Thurston County and City of Lacey. Thurston County lakes – 1978 Water Quality and Restoration Analysis.
Phantom	King	27	Kramer, Chin, and Mayo Inc. Phantom-Larson Restoration Assessment Phase I report. City of Bellevue, April 1987.
Roberta	Ferry	23.3	Juul, Steve, W. Funk. A study of water quality at Curlew Lake. Water Research Center. Pullman, August 1988.
Roesiger	Snohomish	5.2	Gibbons, H. Jr., J. Jacoby, C. Barnes, S. Wagner. Lake Roesiger Phase I Restoration Analysis. Kramer, Chin, and Mayo Inc., December 1989.
Round	Clark	49	Beak Consultants Inc and Scientific Resources Inc. Lacamas - Round Lake diagnostic and restoration analysis, final report. Portland, Oreg., July 1985.
Sacajawea	Cowlitz	216(’78 pre diversion) 478(’84)	Gibbs and Olson Inc. Lake Sacagawea restoration analysis, final report and alternative water supply study. City of Longview, Wash., October 1984.

LAKE NAME	COUNTY	MEAN TP µg/L	REFERENCE
Sawyer	King	17.7	Carrol, J., G. Pelletier. Diagnostic study of Lake Sawyer; King Co. Wash. March 1991.
Scriber	Snohomish	57.2	UPS Corp. Scriber Lake Restoration, a Report to the City of Lynnwood. Seattle, Wash. November 1986.
Shoecraft	Snohomish	5.9	Entranco Eng. Inc. Seven Lakes; Water Quality Analysis and Management Plan. Kirkland, Wash., April 1986.
Silver	Cowlitz	51	Moore, B., W. Funk. Silver Lake Restoration Phase I: Diagnostic feasibility study. Water Research Center. July 1990.
Silver	Snohomish	9.4	Welch, E., J. Oppenheimer, R. Horner, D. Spyridakis. Silver Lake water quality, nutrient loading and management. Dept. of Civil Eng. Univ. of Wash. Seattle, May 1988.
Snake	Pierce	410	Entranco Eng. Snake Lake Restoration Phase I: Diagnostic and restoration feasibility study. For Metro Park District of Tacoma. Sept. 1989.
Stevens	Snohomish	13.6	Reid Middleton and Assoc. Inc., NORTEC. Lake Stevens restoration study. Nov. 1983.
Stevens	Snohomish	4.8	Kramer, Chin, and Mayo. Lake Steven Restoration Phase IIA. Seattle, Wash., December 1987.
Twin N.	Ferry	14.2	Juul, S., W. Funk, E. Broach. Twin Lake restoration analysis phase I. Water Research Center. Pullman, April 1987.
Twin S.	Ferry	21.7	Juul, S., W. Funk, E. Broach. Twin Lake restoration analysis phase I. Water Research Center. Pullman, April 1987.

Appendix B: Members of Advisory Committees

External Advisory Committee

Allison, Leroy, Grant County Health District

Barnes, Robert S., Puget Sound Power & Light Company

Beardslee, Kurt, Washington Trout

Becker, Debbie, Washington Dairy Federation

Burns, Gary, Chehalis Indian Tribe

Connor, Tom, Nisqually Indian Tribe

Degasperi, Curtis, Tetra Tech - Redmond

Faulconer, Lee, Department of Agriculture

Figlar-Barnes, Ron, Quileute Tribe

Frodge, Jonathan, Seattle METRO

Funk, Dr. William H., Washington State University

Gibbons, Harry L., Kramer, Chin and Mayo, Inc.

Ice, George, NCASI

Jacoby, Jean, Seattle University

Keniston-Longrie, Joy, Seattle METRO

Kramer, Jim, King County Surface Water Mgmt.

Lagerloef, Marcia, EPA - Region X

Lamb, Dave, The Lambert Group

Lebsack, Kent, Washington Cattlemen's Association

Leif, Bill, Snohomish County Public Works

Loehr, Lincoln C., Heller, Ehrman, White & McAuliffe

Longenbaugh, Matt, National Marine Fisheries Service

McKown, Ron, Bureau of Reclamation

McMurray, Greg, Oregon Dept. of Environmental Quality

Michaud, Joy, Envirovision

Momot, Jeff, U.S. Fish & Wildlife Service

Moore, Barry C., Washington State University

Nagel, John, Ducks Unlimited - Sacramento

Passmore, Gary W.,Colville Confederated Tribes

Rensel, Jack, Rensel Associates

Richter, Joanne, City of Olympia

Schafflein, Schafflein, Washington State Department of Transportation

Schroder, Linn, Northwest Marine Trade Association

Shumar, Mark, Idaho Dept. of Environmental Quality

Sims, Brenda, Spokane County Engineers

Stevens, Chantal, Muckleshoot Indian Tribe

Stewart, Joyce, City of Chelan

Swartout, Mark, Thurston County Water & Waste Management

Sweet, Cline, U.S. Bureau of Reclamation, Ephrata

Telders, Ed, Bass Angler Sportsman Society

Varner, Phyliss, City of Bellevue

Walrod, Rosemary, Washington Lake Protection Assoc.

Welch, Eugene, University of Washington

Wilshusen, Fran, Northwest Indian Fisheries Commission

Wishart, Bruce, Sierra Club, Olympia

Zisette, Rob, Herrera Environmental Consultants

Department of Ecology Internal Advisory Committee

Steve Butkus
Deborah Cornett
Bill Ehinger
Dave Hallock
Kathy Hamel
Allen Moore
Greg Pelletier
Joe Joy
Maria Kautz
Julie Rector
Janet Strong