An Assessment of Washington Lakes

National Lake Assessment Results

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Cover photo: The painted turtle (*Chrysemys picta*) is the most common native turtle species in Washington State. This photo was taken by Callie Meredith, Ecology staff, at Fan Lake in Pend Oreille County on September 5, 2007.

An Assessment of Washington Lakes

National Lake Assessment Results

by
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Waterbody Numbers

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Table of Contents

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List of Figures

List of Tables

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Abstract

In 2007, the Washington State Department of Ecology collected biological, chemical, and physical data at 30 randomly selected Washington lakes. Based on the survey design, the data results from these 30 lakes can be applied to a population of 620 lakes in Washington. Sample sites represented the following ecoregions of the state: Coast Range, Puget Lowland, Willamette Valley, Cascades, Northern Cascades, Columbia Plateau, and Northern Rockies. This study was part of EPA's National Lake Assessment which encompassed monitoring at 1,028 lakes in the lower 48 United States.

Measurements of environmental stress were evaluated using the reference site approach. This approach involves setting a reasonable expectation, or reference condition, for each measured parameter. Threshold criteria for reference condition were developed at both the national and regional scale, depending on the environmental parameter.

This report presents the statewide status of lakes in terms of *good*, *fair*, and *poor* condition. This study showed over 80% of the lake sample population in Washington is in *fair* or *good* condition with regard to physical habitat. The results also showed nutrients and chlorophyll-a were the parameters of highest concern. Turbidity was in poor condition at only 3% of the lakes in the lake sample population. This information could be useful for water resource managers when setting priorities for monitoring and restoring lakes.

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Introduction

Water quality monitoring in the U.S. has been conducted by many different organizations, over many decades, using a variety of techniques, for a variety of purposes. One purpose is to fulfill a federal mandate. Section 305(b) of the Clean Water Act requires the U.S. Environmental Protection Agency (EPA) to report periodically on the condition of the nation's water resources by collating information provided by the states. Yet approaches to collecting and evaluating data vary from state to state, making it difficult to compare the information across states or on a nationwide basis. Each of these monitoring efforts has yielded useful information relative to the goals of the individual programs, but integrating the data to form a nationwide assessment has been difficult.

Under section 305(b) of the Clean Water Act, the states must submit biannual reports on the quality of their water resources. According to the most recently published National Water Quality Inventory Report, 2004, the states assessed little over a third (37% or 14.8 million acres) of the nation's 40.6 million acres of lakes, ponds, and reservoirs. Of the lakes that were assessed, over half (58% or 8.6 million acres) were identified as impaired or not supporting one or more of their designated uses. The states cited nutrients, metals (such as mercury), sewage, sedimentation, and nuisance species as the top causes of impairment. The largest known sources of impairment included agricultural activities and atmospheric deposition, although the sources of impairment remain unidentified for many lakes.

In order to bring some consistency to lake data, EPA, states, and tribes collaborated in a nationwide survey called the National Lakes Assessment (NLA) during the summer of 2007 to determine the condition of the nation's lakes.

The NLA had the following goals:

- Address key questions about the quality of the nation's lakes:
  - What percentage of the nation's lakes are in good condition based on indicators of ecological integrity, trophic status, and recreational health?
  - What are the key stressors on the lake environment?
- Promote collaboration and build state and tribal capacity for lake monitoring.
- Provide a nationally consistent data set to examine lake water quality and develop baseline information in order to evaluate changes over time.

It is hoped that the NLA will serve as a scientific report card on U.S. lakes and will stimulate interest at all levels of government to increase or, in some cases, begin funding lake monitoring activities.

This report is an analysis of the data collection efforts done in Washington State by the Department of Ecology (Ecology) as part of the bigger NLA.

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Methods

Survey Design

Given that surveying every lake in the country would be cost prohibitive and beyond the reach of any program, EPA used a statistical based sampling approach, sometimes referred to as probabilistic sampling, for the NLA. This survey design, developed by EPA's research program, is based on the same statistical principles as election polls and makes it possible to sample a relatively small number of sites and make inferences about conditions across an entire population (e.g., lakes larger than 10 acres in Washington).

The theory behind the NLA sampling design was that since every lake has the same statistical chance of being chosen for sampling, the condition of the actual lakes sampled can be inferred to be the same (plus or minus a certain percentage) as other lakes sharing similar physical characteristics within the same ecoregion. Ecoregions are defined as mapped areas of general similarity in physical, chemical, and biological characteristics. They are designed to serve as a spatial framework for research, assessment, management, and monitoring (USEPA, 2006). Level III ecoregions (Omernik, 1987) were used in the NLA design.

This survey design uses a reference condition for comparing results. Setting reasonable expectations for each indicator was one of the greatest challenges for the NLA. Because of the difficulty in estimating historical conditions for many indicators, the NLA used *least disturbed condition* as the reference condition. Least disturbed condition can be defined as the best available chemical, physical, and biological habitat conditions given the current state of the landscape. Reference criteria describe the site's condition as *the best of what's left*. Data from reference sites were used to develop seven regional specific reference conditions against which data results could be compared.

Sources of Reference Sites

Reference sites sampled during the NLA, using consistent sampling protocols and analytical methods, were screened to meet regional specific physical and chemical criteria. Included were sites selected from the probability sample sites and hand-picked sites (n=124) thought to be reference by best professional judgment. Like the probability sample sites, the hand-picked sites were sampled using NLA methods. These sites were obtained from a number of sources. Some states submitted their best reference sites to be sampled as part of the NLA; other sites from the west and northeast were selected in a prescreening analysis, using land use to find least disturbed lake watersheds.

Screening NLA Site Data for Biological Reference Condition

All lakes from the NLA were grouped into distinct regional categories based on nine environmental variables. These variables took into account geographic and geologic differences such as elevation, precipitation, air temperature, longitude, latitude, and calcium concentrations. In addition to these geographic/geologic variables, other variables such as lake area, depth, and shoreline development were also used to segregate lakes. Seven regional clusters were identified during this process, and these seven regions were grouped into one of three larger regions: eastern highlands (which included the Appalachians and the Northeast), plains and lowlands (which included the coastal plains, northern and southern plains, and Midwest), and western mountains (which included the western mountains and xeric region of the west).

To identify reference sites for purposes of the NLA, chemical and physical data from both hand-picked and probability sites were used to determine whether any given site was in least disturbed condition for its region. In the NLA, ten chemical and physical parameters were used to screen for reference sites: total nitrogen (TN), total phosphorus (TP), chloride, sulfate, turbidity, euphotic zone, dissolved oxygen, acid-neutralizing capacity (ANC), shoreline disturbance by agriculture and non-agriculture, and shoreline disturbance intensity and extent.

Given that expectations of least disturbed condition vary across regions, the criteria values for exclusion varied by region. The seven reference clusters developed for the NLA used regionalized reference condition thresholds. All sites (both probability and hand-picked) that passed all criteria were considered to be reference sites for the NLA. However, if any site exceeded one or more threshold, it was not considered a reference lake.

Note that the NLA did not use data on land use in the watersheds for the final reference site screening. Sites in agricultural areas, for example, may well be considered least disturbed, provided their chemical and physical conditions are among the best for the region. Additionally, the NLA did not use data from the biological assemblages themselves because these are the primary components of the lake ecosystems being evaluated and to use them would constitute circular reasoning.

Screening NLA Site Data for Nutrient Reference Condition

Setting reference condition for nutrients required a different process than the one used for biological reference condition evaluation. Because nutrients (TN, TP) were used to select biological reference sites, the biological reference sites could not be used as nutrient reference lakes. During the development of nutrient reference sites, 11 nutrient ecoregions were used to categorize different portions of the conterminous United States. These included Coastal Plain, Temperate Plains, Southeastern Plains, Piedmont, Grass Plains, Cultivated Great Plains, Southern Glaciated, Northern Glaciated, Southern Appalachian Mountains, Xeric West, and Western Mountains.

Chemical, lake riparian, and littoral condition thresholds were used to select nutrient reference lakes. An initial screening of all ecoregions for inorganic acidity excluded all lakes with an ANC ≤ 50 µeq/L and dissolved organic carbon (DOC) < 5 mg/L. Once these lakes were excluded, selection of reference conditions by nutrient ecoregion was conducted using chloride, sulfate, shoreline disturbance by agriculture and non-agriculture, and shoreline disturbance intensity and extent. Similar to biological reference selection, a lake exceeding any one of these eight selection criteria was not considered a reference lake.

Once the nutrient reference lakes were selected, nutrient levels for separating *good*, *fair*, and *poor* were determined from the distribution of reference lake nutrient concentrations from the 11 nutrient ecoregions. Nutrient levels were determined for total phosphorus, total nitrogen, chlorophyll-a, and turbidity. The cutoff between *good* and *fair* lakes was set at the 75th percentile of reference lakes, and the cutoff between *fair* and *poor* lakes was set at the 95th percentile of reference lakes. If a nutrient ecoregion had less than 20 lakes, then the cutoff between the *fair* and *poor* lakes was the maximum nutrient concentration for reference lakes in that nutrient ecoregion.

Target Population

When conducting any statistical survey, it is important to know the size of the target population you want to characterize. The best resource for determining size of the NLA target lake population was the USGS/EPA National Hydrological Data Base (NHD). The NHD is a multi-layered series of digital maps that reveal topography, area, flow, location, and other attributes of the nation's surface waters. The NHD had 389,005 features listed that could potentially be lakes ranging in size from less than 1 hectare (2.4 acres) up to the largest lakes in the country which can be seen by satellite. Many lakes were excluded from the NLA up front for a number of reasons, e.g., being a wetland.

EPA determined there are 2,063 lakes in Washington larger than 10 acres (4 hectares). In this survey, this is referred to as the lake target population. Once the lake target population was identified, additional lake selection criteria were decided. The lake had to be:

- A natural or man-made permanent freshwater lake, pond, or reservoir.
- At least 3.3 feet (1 meter) deep.
- A minimum of a quarter acre (0.1 hectare) open water.
- Not a private aquaculture waterbody, used for disposal (e.g., tailings, gravel etc.), a sewage treatment plant or used for evaporation.

After meeting these additional criteria, 1,922 lakes were left as possible sampling candidates in Washington. This is the lake sample population. Most Washington lakes are small – between 10-25 acres. This is also the case for the rest of the country. If the selection of lakes to be sampled for the NLA from the lake sample population in Washington were entirely random, a high percentage of lakes chosen to be sampled would likely fall within the small acreage category.

The survey design addressed this issue by allocating lakes to be sampled to various size categories: 10-25 acres; 25-50 acres; 50-125 acres; 125-250 acres, and greater than 250 acres. This ensured that lakes of all sizes were equally available for the final random site selection list. In order to keep costs down, EPA decided the sampling activities conducted at each lake should be completed within one day.

The next step in the site validation process was to determine accessibility due to the following factors: owner permission to access lakes on private property, crew accessibility (e.g., safety, hazards), and the ability to complete all sampling activities within one day. These evaluations were made by Ecology staff before sampling began in the summer of 2007.

Sixty-four percent of the lakes were deleted from Washington's final sampling list based on evaluation findings (see Figure 1). These lakes could not be sampled due to site specific issues related to physical access, safety, and land owner denial of access.

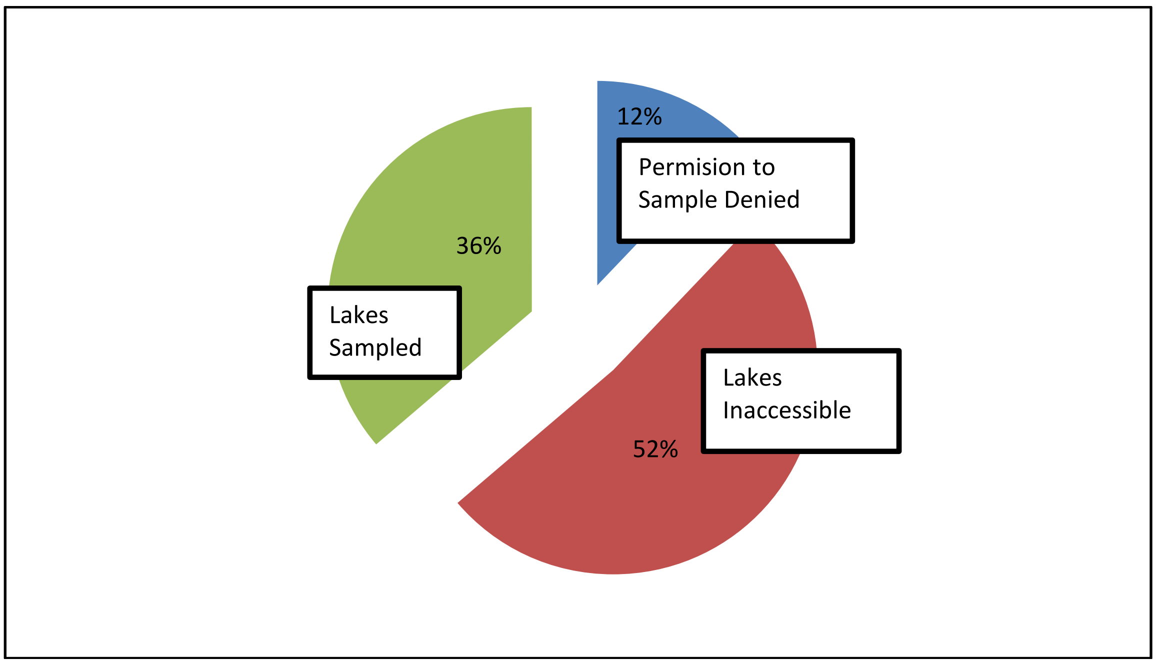

Figure 1. Fate of sites targeted for sampling.

Data Applicability

To make inferences from the sampled lakes to other lakes in Washington, a weight value was determined for each lake, based on surface area and the frequency of this lake size in the lake sample population within an ecoregion. A total of 30 lakes were chosen to be sampled; based on the weights for these 30 lakes, the final lake sample population consisted of approximately 620 lakes in Washington State. These 30 lakes were considered representative of the final lake sample population because they all meet the site criteria of adequate size, depth, and surface area.

Figure 2 shows the total number of lakes in Washington greater than 10 acres in size, and the number of lakes in the final lake sample population, broken down into the lake size categories.

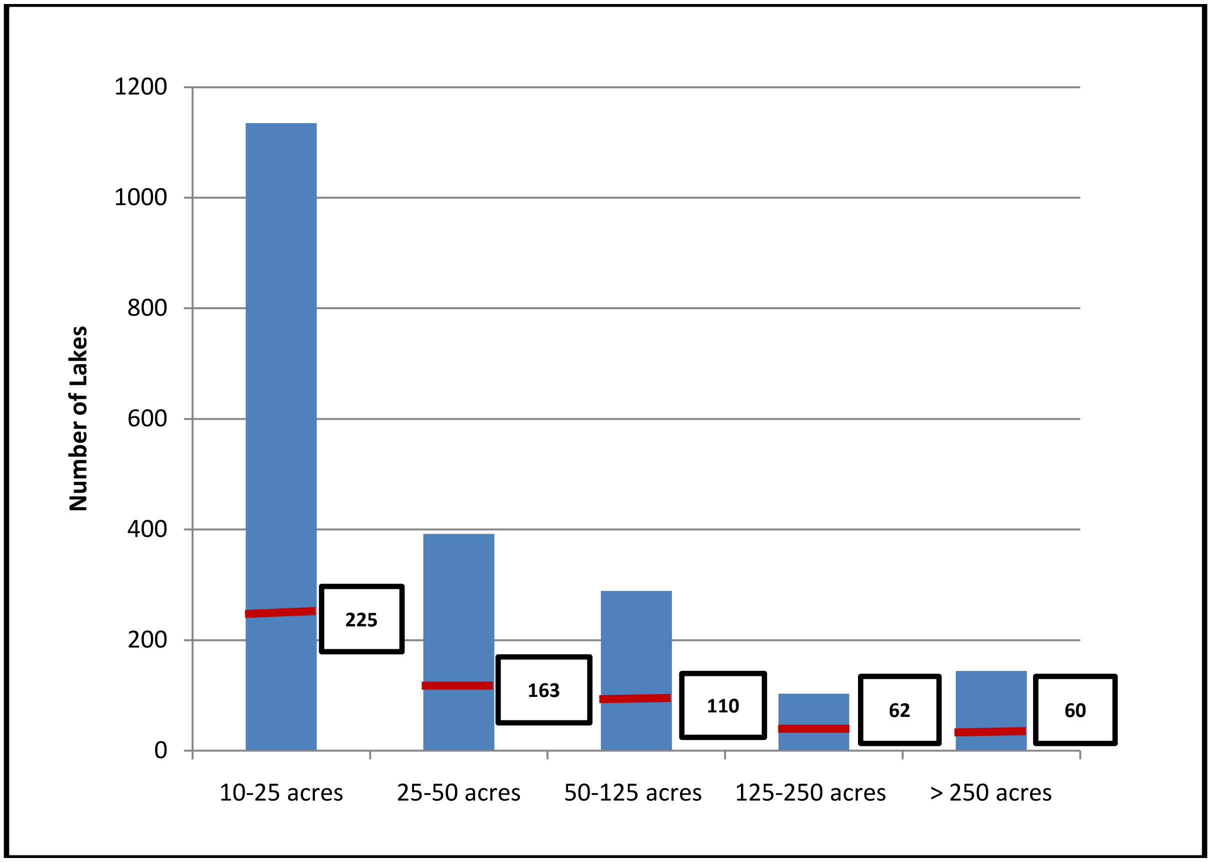

Figure 2. Total number of lakes in Washington and final lake sample population in the various lake size categories.

The blue bars show the number of lakes in Washington in each size class. The red lines within the blue bars and the numbers in the boxes both indicate the number of lakes (out of the 620 lakes which make up the final lake sample population) which the NLA data results are applied to.

For more information about probabilistic sampling, visit the EPA website:
www.epa.gov/owow/monitoring/nationalsurveys.html

EPA funded Ecology to sample 18 lakes in Washington State as part of the NLA. Ecology funded sampling of an additional 12 lakes in order to use the data for a statewide assessment. Thirty lakes was considered the minimum number needed in order to statistically analyze the data and apply the results to other lakes within the same ecoregion.

Figure 3 shows the location of the Washington lakes sampled as part of the NLA within their corresponding Level III Ecoregions.

See Appendix B for a list of the lakes sampled and associated data.

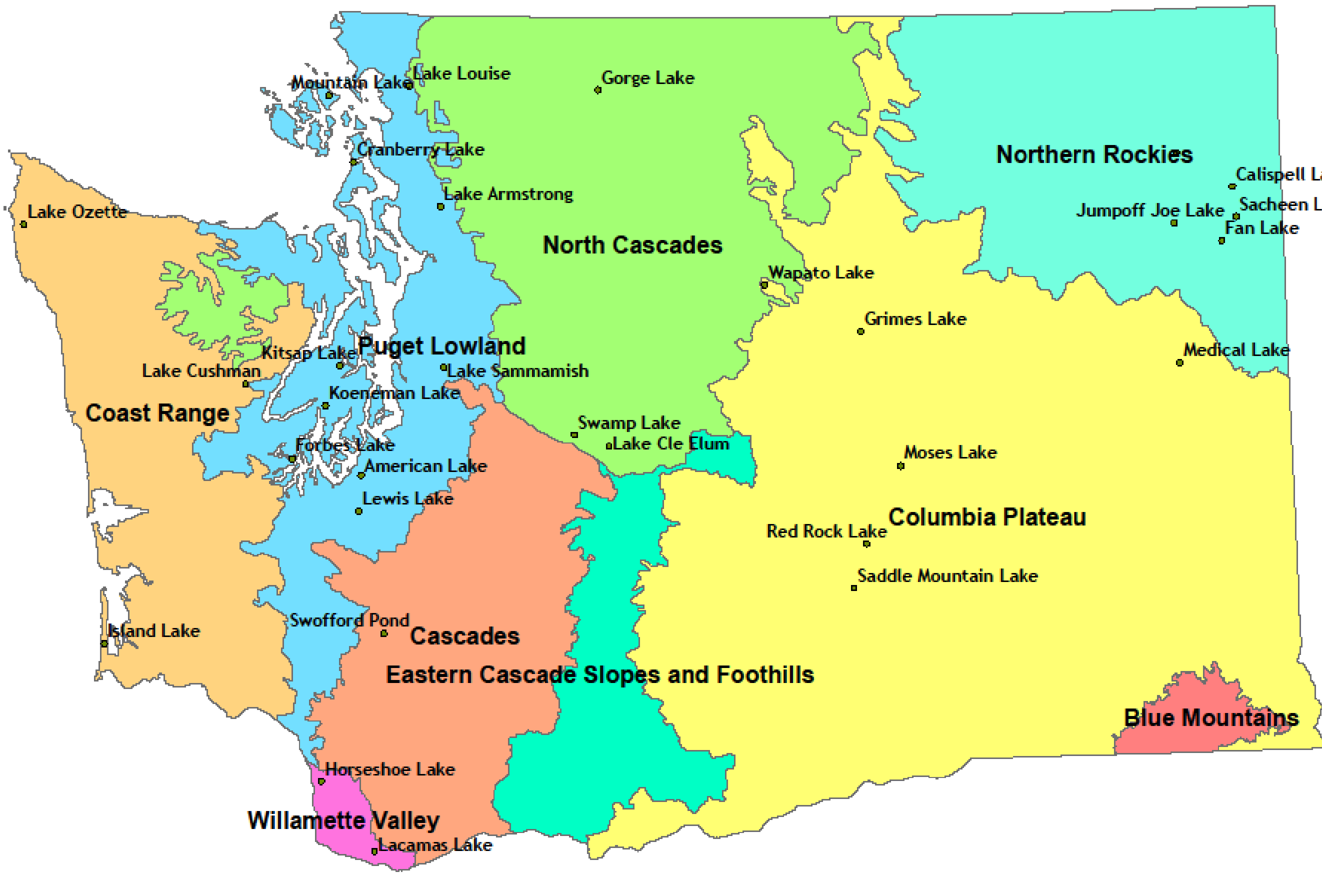

Figure 3. Map of lakes sampled within the Level III ecoregions.

Sampling Design

Environmental Indicators Selected

Environmental indicators were selected to represent a minimum of one of three categories: (1) trophic status and chemical/biological stressors, (2) recreational value, and (3) ecological integrity. Some environmental indicators provide a basis for evaluating more than one category. For example, an assessment of phytoplankton allows for an examination of ecological integrity and trophic status and, to a certain extent, recreational value.

Trophic State Indicators and Chemical/Biological Stressors

Trophic state describes the biological condition of a lake based on plant biomass. Four indicators are most often used to define the trophic state of a lake: chlorophyll-a, Secchi disk depth, total phosphorus, and total nitrogen.

In addition to these, other indicators were measured to supplement and enhance understanding of lake processes that affect the production of algal biomass. The other indicators were a variety of water chemistry parameters: basic anions and cations, alkalinity, dissolved organic carbon, total organic carbon, total suspended solids, and conductivity.

A lake profile measuring dissolved oxygen, temperature, pH, and conductivity was also taken.

Recreational Value Indicators

As recreational indicators of human health, *Enterococci* bacteria and microcystin (a cyanobacteria toxin) levels were measured.

Ecological Integrity Indicators

Indicators of ecological condition and integrity consisted of the aquatic community and their physical habitat. For the NLA Survey, these indicators were phytoplankton, zooplankton, sediment diatoms, and the physical habitat of the shoreline and littoral zone. Benthic macroinvertebrate samples were also collected at each lake but the analysis was not completed in time for inclusion in this report.

Sampling Locations and Protocols

Information detailing the selection of the sampling locations and field protocols are contained in the field operations manual for the NLA (USEPA, 2007). The Washington State survey took place in July through the end of September 2007. Ecology used a field crew of three people – two people in boats to collect the samples and measurements and one person to be the courier for getting the time sensitive samples to a FedEx office for shipping each sampling day. Figure 4 shows the two boats used for sampling.

Figure 4. A photo of the two boats used for the survey, filled with the sampling gear, ready for a day on the lake.

Figure 5 shows the location of sample collection points, the physical habitat stations, and description of plot dimensions at each physical habitat station.

An index site, located at the deepest point of the lake, was identified and used to collect water samples for the following parameters:

- Water chemistry (nutrients, basic anions and cations, alkalinity, dissolved organic carbon, total organic carbon, total suspended solids, and conductivity)
- Chlorophyll-a
- Phytoplankton
- Zooplankton
- Microcystin

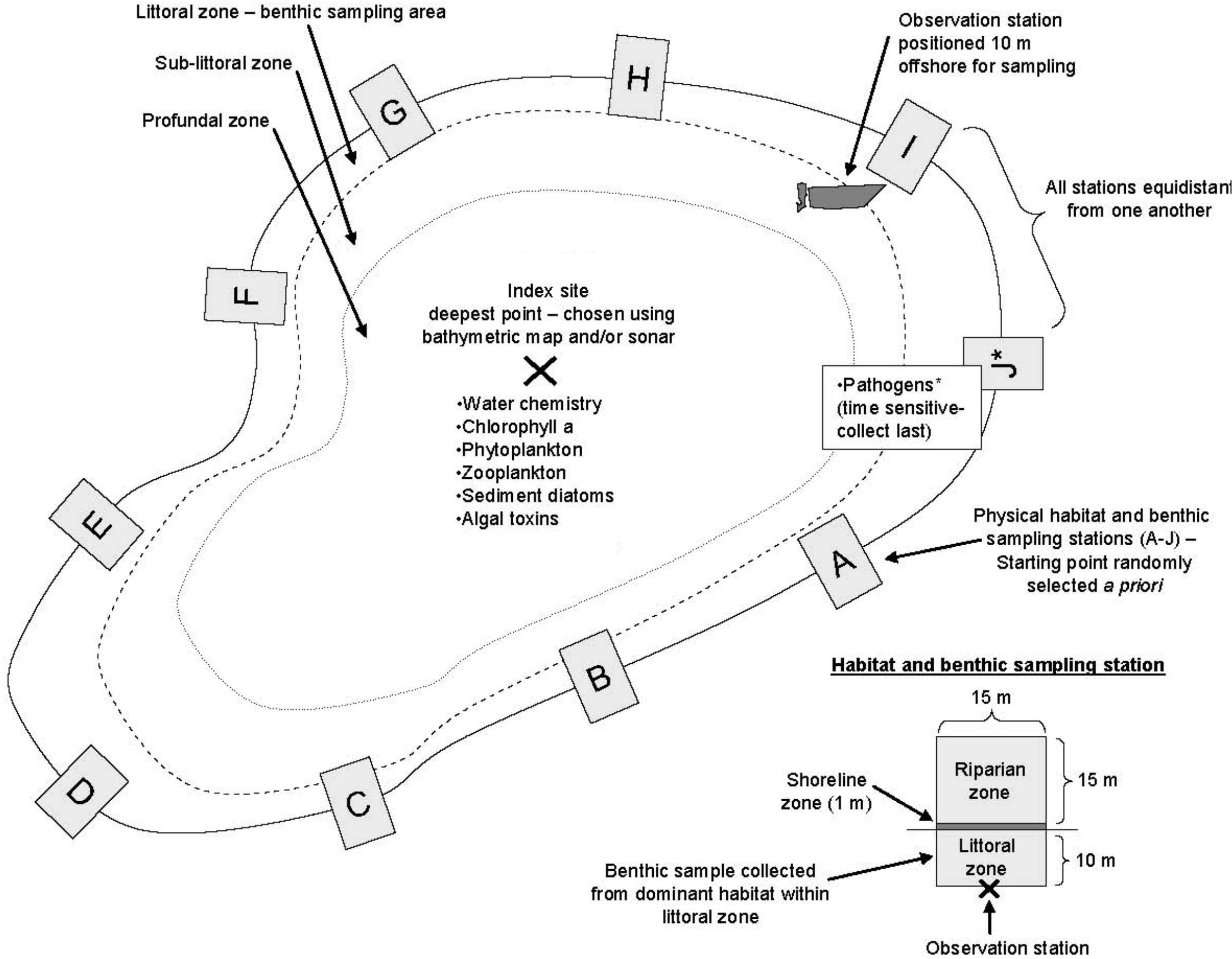

Figure 5. Location of sample collection points, physical habitat stations, and description of plot dimensions at each physical habitat station.

In addition, a lake profile (dissolved oxygen, temperature, pH, conductivity) was taken and Secchi disk transparency measured at the index site.

The water chemistry sample was collected using an integrated sampler, deposited in a 4-liter cubitainer and shipped on ice to the laboratory for analysis. The chlorophyll-a sample was also collected using the integrated sampler and filtered in the field using a Whatman GF/F filter. The filter was folded into a 50-mL centrifuge tube, covered with aluminum foil, and shipped on ice to the laboratory for analysis.

An example of the integrated sampler being used to collect water samples is shown in Figure 6.

Figure 6. Ecology staff, Callie Meredith, collecting water samples at the index site on Mountain Lake, San Juan County.

The phytoplankton sample was preserved with Lugol's solution and shipped on ice to the laboratory for analysis. Zooplankton samples were collected using a Wisconsin net sampler with fine mesh (80 µm) and coarse mesh (243 µm). Both nets were towed once vertically from near the bottom to the surface of the lake. Preserved phytoplankton and zooplankton samples were processed and enumerated, and organisms were identified to the lowest possible taxonomic level (generally genus) using specified standard keys and references.

Microcystin samples were collected using the integrated sampler and frozen within eight hours. The samples were shipped on dry ice to the laboratory for analysis.

A sediment core was also taken at the index site for analysis of sediment diatoms. Figure 7 shows a sediment core being collected at Lake Ozette in Clallam County.

Figure 7. Callie Meredith, Ecology staff, collecting a sediment core from Lake Ozette/Clallam County.

To evaluate the impact of habitat alteration on biological integrity, the NLA assessed the physical habitat of each lake. The physical habitat of a lake includes the environment at the bottom of the lake (substrate), the vegetation along its shoreline and away from the lake water edge (riparian zone), the biological community (aquatic plants, fish, and benthic organisms), and non-biological structure (e.g., fish cover, human structures) of the near shore water area (littoral zone). All of these biological and non-biological components make up the biological integrity of a lake.

The goal of the NLA physical habitat survey was to characterize the lakeshore based on 55 observations made at each of 10 randomly selected and evenly distributed physical habitat stations located around the perimeter of the lake. These stations were determined using GIS software and mapped onto a Trimble® GPS prior to each lake visit. See Figure 8 for an example of the location of the physical habitat stations at one of the lakes sampled.

Figure 8. Location of the ten physical habitat stations, labeled A through J, on Fan Lake/Pend Oreille County.
(X marks the index site - the deep spot of the lake.)

At each physical habitat station, site plot dimensions were established (see Figure 5). In the riparian zone, observations of vegetation structure, human disturbances, and bank substrate were recorded. In the littoral zone, observations of water depth, bottom substrate type, aquatic macrophyte cover, nearshore fish cover type, and scums were recorded. Figure 9 shows Ecology staff recording physical habitat information.

Figure 9. Callie Meredith, Ecology staff, recording physical habitat survey information on Swamp Lake/King County.

Benthic macroinvertebrates samples were also collected at each physical habitat station. However, the analysis of these samples was not completed in time in order for those results to be included in this report. Figure 10 shows benthic macroinvertebrates being collected by Ecology staff at Moses Lake in Grant County.

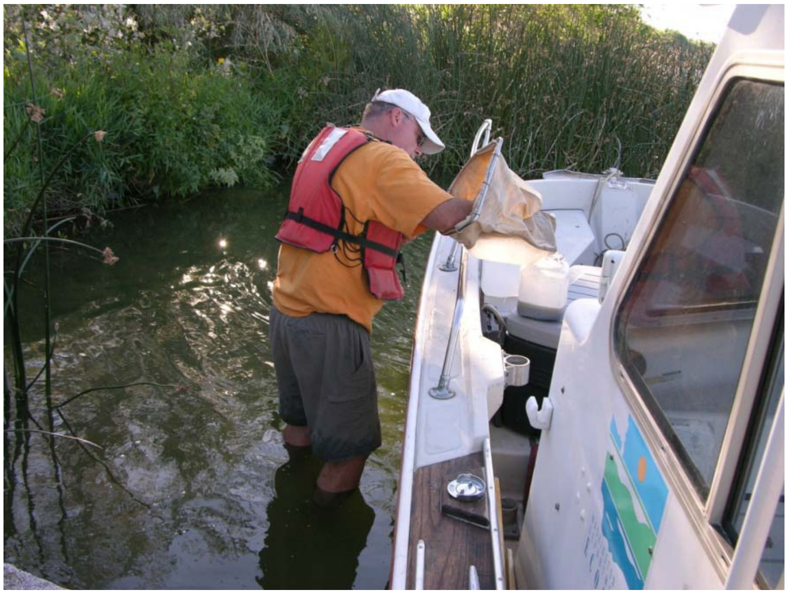

Figure 10. Glenn Merritt, Ecology staff, collecting macroinvertebrate samples from Moses Lake/Grant County.

Because the *Enterococci* bacteria sample was time sensitive with regard to collection, the water sample for analysis was collected at the last physical habitat station within the littoral zone at one foot below the surface of the lake. Once on shore, the samples were filtered and shipped on dry ice to the laboratory for analysis.

A number of different laboratories conducted the analysis of the parameters sampled. For a complete list of the laboratories, see USEPA, 2009.

In addition, the Quality Assurance Project Plan for the NLA, describing the analytical procedures and data quality information, can be found at this site:
www.epa.gov/owow/lakes/lakessurvey/pdf/qualityassuranceplan_draft.pdf

Results

The data collected for the NLA was used to generate many metrics that have potential use as indicators of stress in the lake environment. This report examines the most relevant metrics for identifying the stressors affecting ecological condition of lakes in Washington. As stated in the discussion under *Survey Design* in the *Methods* section, the data results can be applied to the lake sample population of 620 lakes.

Trophic State Indicators

Lakes are always changing. The fate of all lakes is to eventually fill in with plants and sediment and become part of the terrestrial environment, commonly referred to as succession. However, that process can take centuries, if not millennia, depending on many factors. Humans can influence the rate of succession in a lake by increasing nutrient input (which can increase plant biomass), changing shorelines, and planting non-native fish. These actions change the natural balance of a lake ecosystem and accelerate the succession process.

Lakes can be described in many ways, for example, by depth, water chemistry, and size. Trophic state is one way of classifying lakes. According to Robert Carlson, noted limnologist, the most basic definition of the trophic state of a lake is the amount of plant biomass. Biomass is an approximate measure of some of the most common problems that plague lakes, for example, too many plants and too much algae. These in turn can interfere with the more desirable lake uses such as swimming, boating, and fishing.

Carlson's Trophic State Index (TSI) is on a scale from 0-100 and characterizes a lake's trophic state by measuring Secchi transparency, chlorophyll-a, total phosphorus and total nitrogen. Table 1 shows the thresholds of each of these four metrics in relation to Carlson's four trophic state classes:

Table 1. Parameter thresholds for trophic state classes.

Trophic State	Total Phosphorus (µg/L)	Total Nitrogen (mg/L)	Secchi Transparency (M)	Chlorophyll-a (µg/L)
Oligotrophic	< 10	<0.35	>4	<2
Mesotrophic	10 - <25	0.35 - <0.75	4 - >2	2 - < 7
Eutrophic	25 - <100	0.75 - <1.4	2 - 0.7	7 - <30
Hypereutrophic	>100	≥1.4	<0.7	≥30

Oligotrophic lakes are characterized by having low plant biomass and low levels of nutrients. They generally do not support large fish populations. Eutrophic lakes are high in nutrients and support a large plant biomass. They are usually either weedy, subject to frequent and persistent algae blooms, or both. Eutrophic lakes often support large fish populations but are also susceptible to oxygen depletion. Hypereutrophic lakes have the highest plant biomass, and levels of nutrients. Mesotrophic lakes lie between the oligotrophic and eutrophic states in terms of plant biomass and nutrient levels.

Figure 11 shows the breakdown of the percentage of the lake sample population in each trophic class, based on Secchi transparency, chlorophyll-a, total phosphorus, and total nitrogen values.

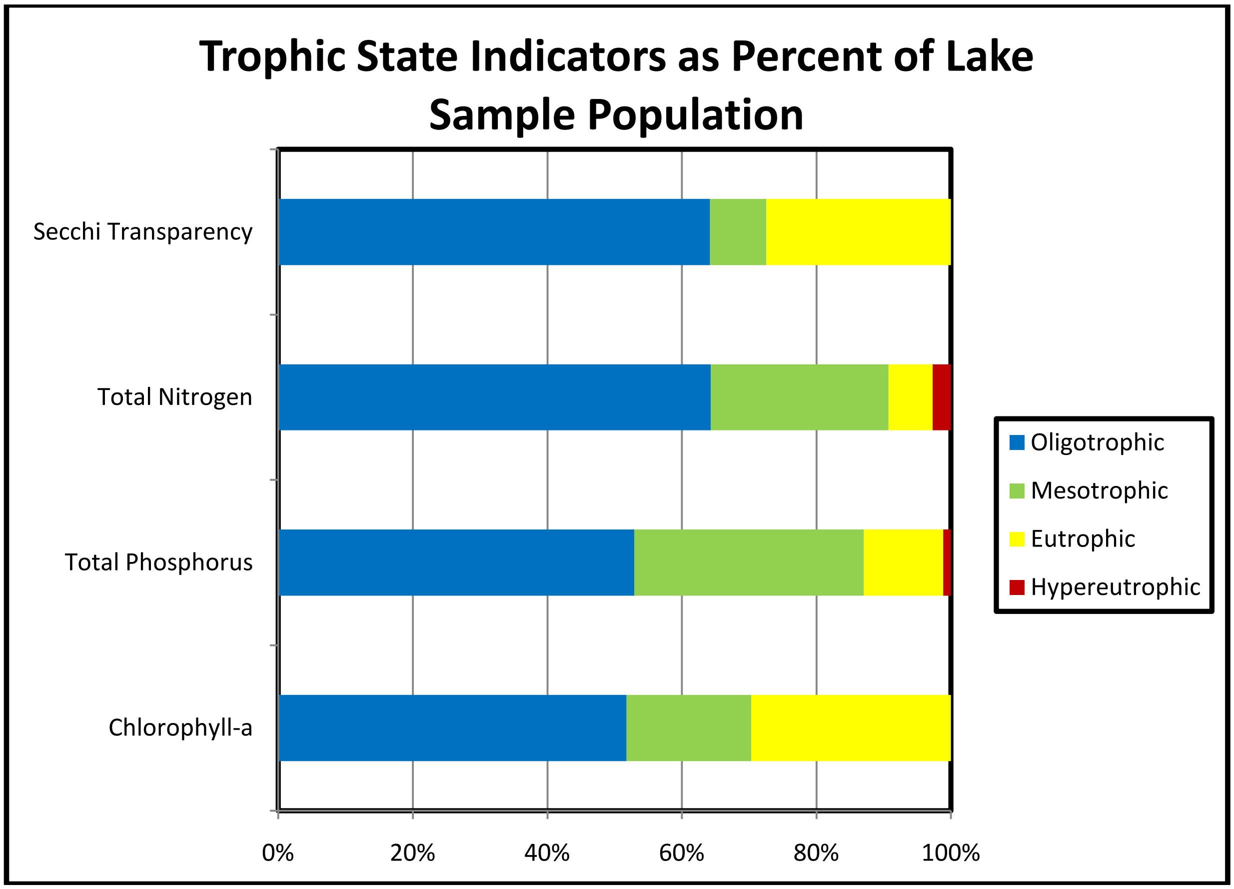

Figure 11. Percentage of Washington lakes in each trophic state index class as calculated for Secchi transparency, total nitrogen, total phosphorus, and chlorophyll-a.

Using these trophic state classes, the sample results for Secchi transparency, total nitrogen, total phosphorus, and chlorophyll-a estimate that approximately 50% of the lakes are oligotrophic. Figure 11 shows all four metrics with similar percentage values for this trophic state. There is more metric variability in the percentages for the mesotrophic class; the percentages range from 8% to 34%. There is also metric variability shown in the eutrophic class – values range from 7% to 30%. The hypereutrophic class values ranged from 0% to 3% (the hypereutrophic state is very rare in lakes).

For comparison, 1999 data from Ecology's Lake Monitoring Program showed out of the 43 lakes sampled that year, 37% percent of the lakes were oligotrophic, 40% mesotrophic, 16% eutrophic, and 7% hypereutrophic.

One reason for having higher trophic state scores in Ecology's 1999 dataset could be that the lakes chosen for the 1999 sampling tended to be ones that either already exhibited problems associated with higher trophic states or had the potential for increased human impact. The lakes for the NLA were chosen randomly.

The trophic state indicators were also calculated for the 11 reference lakes located in EPA Region 10. Figure 12 shows the breakdown of the percentage of the EPA Region 10 reference lake population in each trophic class, based on Secchi transparency, chlorophyll-a, total phosphorus and total nitrogen.

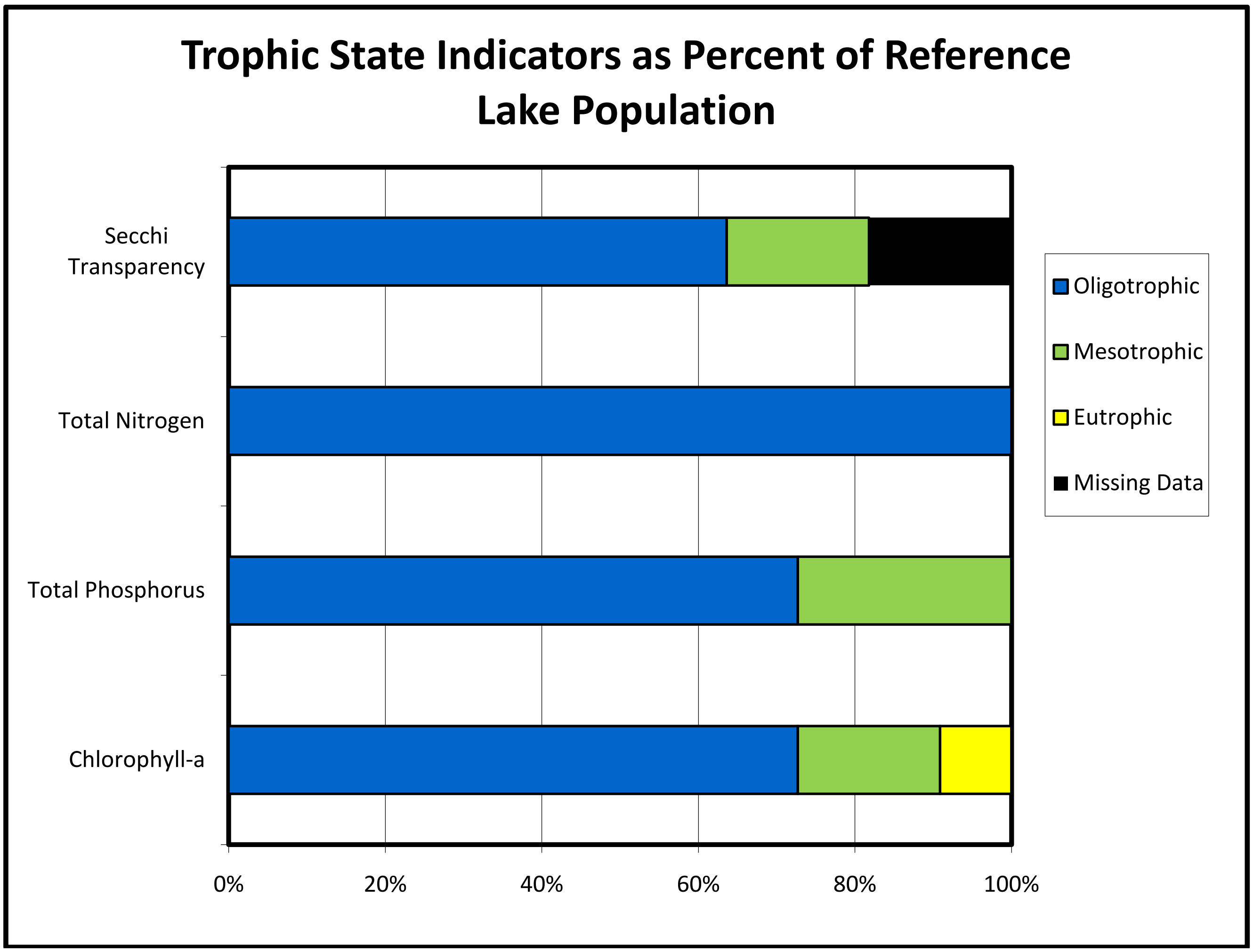

Figure 12. Percentage of EPA Region 10 reference lakes in each trophic state index class.

The expectation for the reference lakes would be that they are all in a relatively unproductive (oligotrophic) state; i.e. low nutrient levels, low levels of chlorophyll-a and high Secchi transparency. Figure 12 shows most of the lakes to be in the oligotrophic class with more or less agreement between all four metrics. There is less agreement in the mesotrophic class between all four metrics. Unfortunately, almost 20% of the reference lakes were missing Secchi transparency data.

A surprising result is that approximately 10% of the reference lakes were in the eutrophic class for chlorophyll-a. A possible explanation is that the chlorophyll-a samples were taken during an algal bloom, which was not reflected in the nutrient (total phosphorus and total nitrogen) results.

It should be noted there is a potential for error in trying to characterize a lake's trophic state based on a single data result. Nutrient concentrations and algal biomass can vary throughout the summer productive season. Accurate trophic state assessment is best accomplished with numerous data points.

Chemical/Biological Stressors

For this report, total phosphorus, total nitrogen, turbidity and chlorophyll-a will be evaluated as indicators of lake stress. Phosphorus and nitrogen are required to support aquatic life in lakes. Excessive levels of phosphorus or nitrogen in lakes can lead to frequent and persistent algal blooms which in turn can affect the beneficial uses of a lake (e.g., swimming, boating, and fishing). Chlorophyll-a levels are a surrogate measurement for the presence of algal biomass in a lake.

Turbidity is a measurement of suspended material in a lake, both organic (algae and other living organisms) and inorganic (suspended soil particles and other inorganic material). High turbidity levels can negatively affect the lake environment in many ways, including lowering light levels which affect algal growth and depositing sediment in nearshore habitats.

Regional specific thresholds were developed for total phosphorus, total nitrogen, turbidity and chlorophyll-a. These regional thresholds were developed based on data collected from a set of reference lakes (see *Survey Design* under the *Methods* section of this report). Categories of *good*, *fair*, and *poor* were constructed from these thresholds and were used to evaluate the study data. Deviation from the reference condition is a measure of stressor effects on the lake ecosystem. In this way, *good*, *fair*, and *poor* is defined relative to the expectations for a particular ecosystem.

Tables 2 and 3 show the parameter thresholds for the Western Mountain and Xeric West nutrient ecoregions.

The Washington results show over 60% of the lakes were *good* for turbidity (see Figure 13). Over 50% of the lakes were in *good* condition for total nitrogen and total phosphorus. Only 20% of the lakes were in *good* condition for the parameter of chlorophyll-a.

Table 2. *Good*/*fair*/*poor* class thresholds for total phosphorus and total nitrogen.

Nutrient Ecoregion	Total phosphorus (µg/L) *Good*	Total phosphorus (µg/L) *Fair*	Total phosphorus (µg/L) *Poor*	Total Nitrogen (mg/L) *Good*	Total Nitrogen (mg/L) *Fair*	Total Nitrogen (mg/L) *Poor*
Western Mountains	<15	15-19	>19	<0.27	0.27-0.38	>0.38
Xeric West	<48	48-130	>130	<0.51	0.51-2.28	>2.28

Table 3. *Good*/*fair*/*poor* class thresholds for chlorophyll-a and turbidity.

Nutrient Ecoregion	Chlorophyll-a (µg/L) *Good*	Chlorophyll-a (µg/L) *Fair*	Chlorophyll-a (µg/L) *Poor*	Turbidity (NTU) *Good*	Turbidity (NTU) *Fair*	Turbidity (NTU) *Poor*
Western Mountains	<1.8	1.8-2.7	>2.7	<1.4	1.4-5.5	>5.5
Xeric West	<7.8	7.8-29.5	>29.5	<3.7	3.7-24.9	>24.9

Appendix C summarizes the results for all the chemical data analyzed.

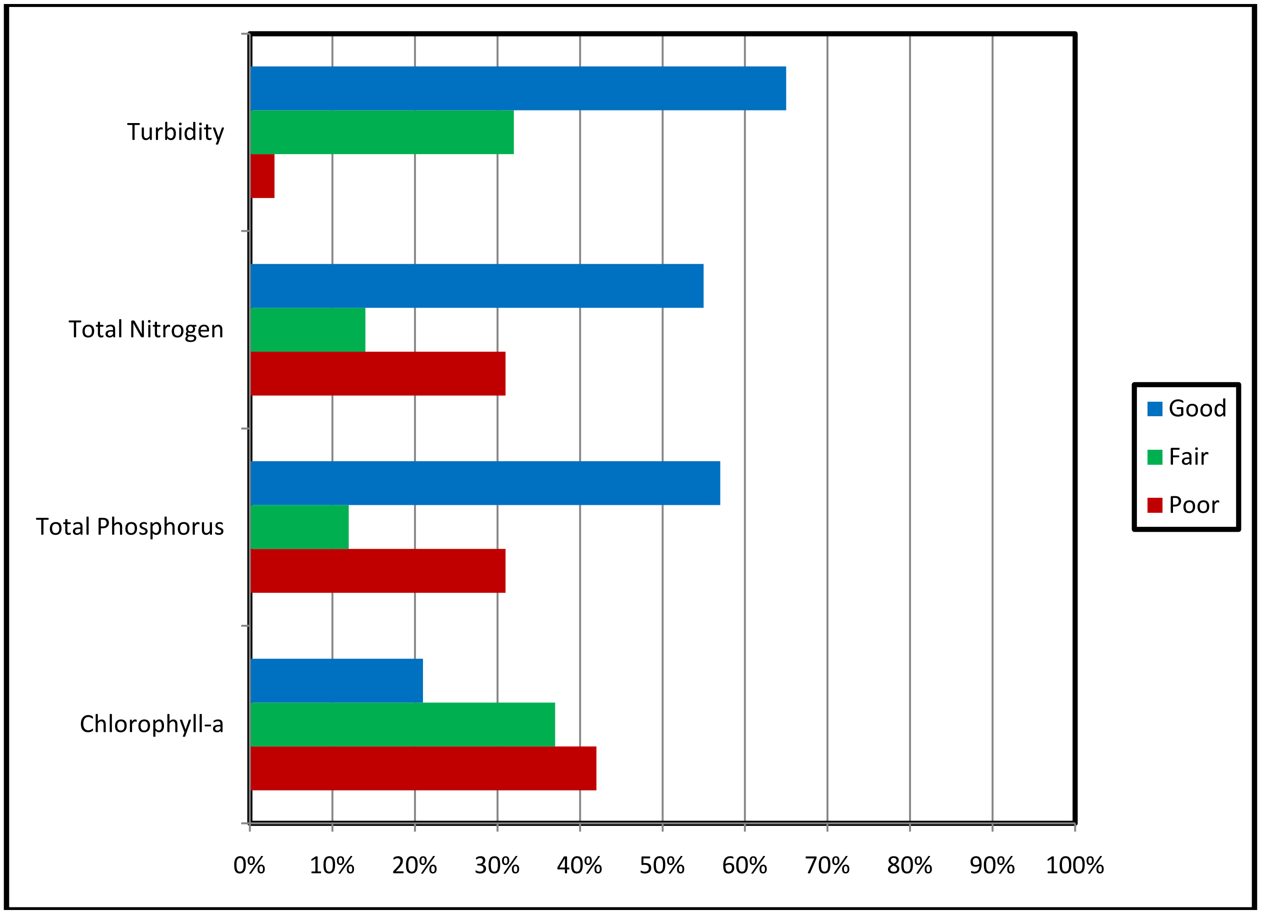

Figure 13. Percentage of Washington lakes in *good*, *fair* or *poor* condition for turbidity, total nitrogen, total phosphorus, and chlorophyll-a.

Comparison to Washington State Nutrient Criteria

As part of the Water Quality Standards for Surface Waters of the State of Washington (Chapter 173-201A WAC), total phosphorus action values were established to aid in the development of nutrient criteria for lakes. If a lake exceeds the total phosphorus action value, a lake specific study is recommended to evaluate the lake and establish a total phosphorus criteria specific to that lake.

These action values were established for the different ecoregions within Washington State. For lakes in the Coast Range, Puget Lowland, and Northern Rockies Ecoregions, the total phosphorus action value is 20 µg/L. For the Cascades Ecoregion, the total phosphorus action value is 10 µg/L. For the Columbia Basin Ecoregion, the total phosphorus action value is 35 µg/L. Lakes in the Willamette, East Cascade Foothills, and the Blue Mountain Ecoregions do not have total phosphorus action values established in the water quality standards.

The results from the NLA were compared to the Washington State guidelines for total phosphorus (see Table 4). Almost 80% of the lake sample population in the Coast Range, Puget Lowlands and Northern Rockies Ecoregions would show total phosphorus values below the Ecology recommended action value of >20 µg/L. In the Columbia Basin Ecoregion, over 70% of the lakes would show total phosphorus values below the Ecology recommended action value of >35 µg/L.

However, in the Cascades Ecoregion, only 29% of the lakes would show total phosphorus values below the Ecology recommended action value of >10 µg/L. Over 71% of the lakes in the Cascades Ecoregion would exceed the Ecology recommended action value of >10 µg/L.

Table 4. Percent comparison of lakes above and below recommended total phosphorus action values.

(The number of lakes these results are applied to are in parentheses.)

Ecoregion(s)	Coast Range, Puget Lowlands, and Northern Rockies	Cascades	Columbia Basin
Below action value	78% (387)	29% (17)	72% (25)
Above action value	22% (111)	71% (41)	28% (10)
Action value	>20 µg/L	>10 µg/L	>35 µg/L

The results from the Cascades Ecoregion could indicate the recommended total phosphorus action value is too low. The Cascade Ecoregion contains a number of volcanoes whose past activity may have contributed soils higher in phosphorus than other ecoregions. Ecology staff who conducted stream surveys in the Cascade Ecoregion found a very strong correlation between streams which had higher turbidities to higher total phosphorus values (Merritt, personal communication).

Recreational Indicators

Recreational indicators address the ability of a lake to support recreational uses such as swimming, fishing, and boating. Two indicators of recreational condition used in the NLA were the indicator bacteria *Enterococci* and the algal toxin microcystin.

Bacteria

Enterococci are bacteria that live in the intestinal tracts of warm-blooded creatures, including humans. They are most frequently found in soil, vegetation, and surface water because of contamination by animal excrement. Most species of *Enterococci* are not considered harmful to humans. However, the presence of *Enterococci* in the environment indicates the possibility that other disease-causing agents also carried by fecal material may be present.

Epidemiological studies of marine and freshwater beaches have established a relationship between the density of *Enterococci* in the water and the occurrence of gastroenteritis in swimmers. *Enterococci* is believed to provide a better indication of the presence of pathogens than fecal coliform which was previously used as an indicator of potential pathogens.

Bacteria analysis for the NLA was performed using the quantitative Polymerase Chain Reaction (qPCR) method, which quantifies a DNA target via a fluorescently tagged probe. The units of measure are cell equivalents, shown as ceq/100 mL. The reporting limit for this method is calculated for each sample. For our sample analysis, the reporting limits ranged from 127 to 197 ceq/100 mL.

Figure 14 shows only 27% of the lakes in the lake sample population produced detections in excess of their reporting limit. This means 73% of the lake sample population showed no measurable levels of *Enterococci* bacteria.

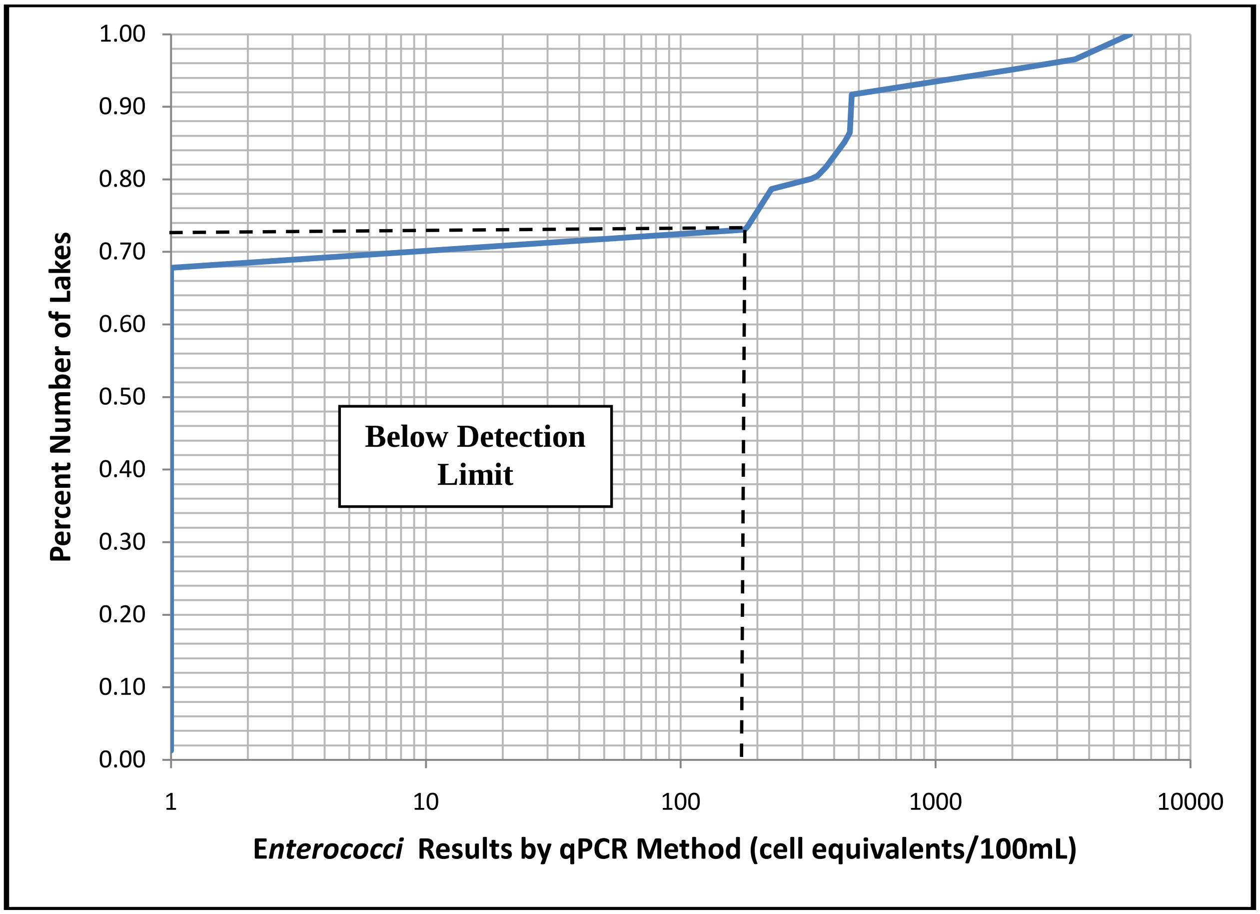

Figure 14. Cumulative distribution of *Enterococci* bacteria results by percentage of lakes.

Of the 11 reference lakes in EPA Region 10, all had *Enterococci* values below the reporting limit except for one lake: Fish Lake in Oregon. This lake had a value of 332 ceq/100 mL.

The qPCR analysis is a new method that does not rely on live organisms to assess concentrations of *Enterococci*. It is important to note the unit of measure used in the qPCR analysis – cell equivalents/100 mL (ceq/100 mL) – is not the same as counting individual bacteria colonies. As stated above, the reporting limit for this analysis ranged from 127-197 ceq/100 mL. For comparison, the Washington State water quality standards for *Enterococci* in marine waters is not to exceed a geometric mean of 70 colonies/100 mL and not more than 10% of all samples exceeding 43 colonies/100 mL. There is no Washington water quality standard for *Enterococci* in freshwaters.

The method used in the NLA has the advantage of rapid turnaround and extended hold times relative to traditional bacteria culture methods. At present, there are no water quality standards for *Enterococci* analyzed by qPCR. EPA research is still underway to develop health based thresholds for interpreting qPCR results.

Microcystin

Microcystins are known liver toxins produced by several genera of cyanobacteria (blue-green algae) and are currently believed to be the most commonly occurring class of cyanobacteria toxins in freshwaters. Exposure to microcystins can produce allergic reactions such as skin rashes, eye irritations, and respiratory symptoms. In extreme cases, microcystins have been implicated in human illness and the death of livestock and pets.

As a result, several states have issued guidelines for recreational use advisories. In July, 2008, the Washington State Department of Health published a document titled *Washington State Recreational Guidance for Microcystins (Provisional) and Anatoxin-a (Interim/Provisional)* (Hardy, 2008). In this document, a provisional recreational guidance value of 6 µg/L of microcystin was recommended.

In addition, the World Health Organization (WHO) has established recreational exposure guidelines for microcystins of low risk (<10 µg/L), moderate risk (10 - <20 µg/L), high risk (20 - <2000 µg/L), and very high risk (>2000 µg/L).

Samples for the NLA were analyzed by the United States Geological Survey (USGS) using an Enzyme-Linked Immunosorbent Assay (ELISA) method. A total of 90% of the lakes sampled in Washington for this survey and all of the reference lakes in EPA Region 10 had levels of microcystin toxin less than 0.1 µg/L, the reporting limit. The other 10% of the lakes sampled had levels less than 3.5 µg/L, lower than the Washington State Department of Health guidance value of 6 µg/L.

Because microcystin toxin levels can vary considerably over a short period of time, NLA analysts decided the best indicator of human health risk for this survey would be based on cyanobacteria cell counts. This indicator would not underestimate the potential risk of human health impacts by only relying on the actual presence of microcystin.

Using cyanobacteria cell count thresholds developed by the WHO, Figure 15 shows 80% of the Washington lake sample population in the low risk category with the remaining lakes in the moderate risk category. No lakes were found to be in the high risk category (cell count greater than 100,000 cells/mL). All of the reference lakes in EPA Region 10 were in the low risk category.

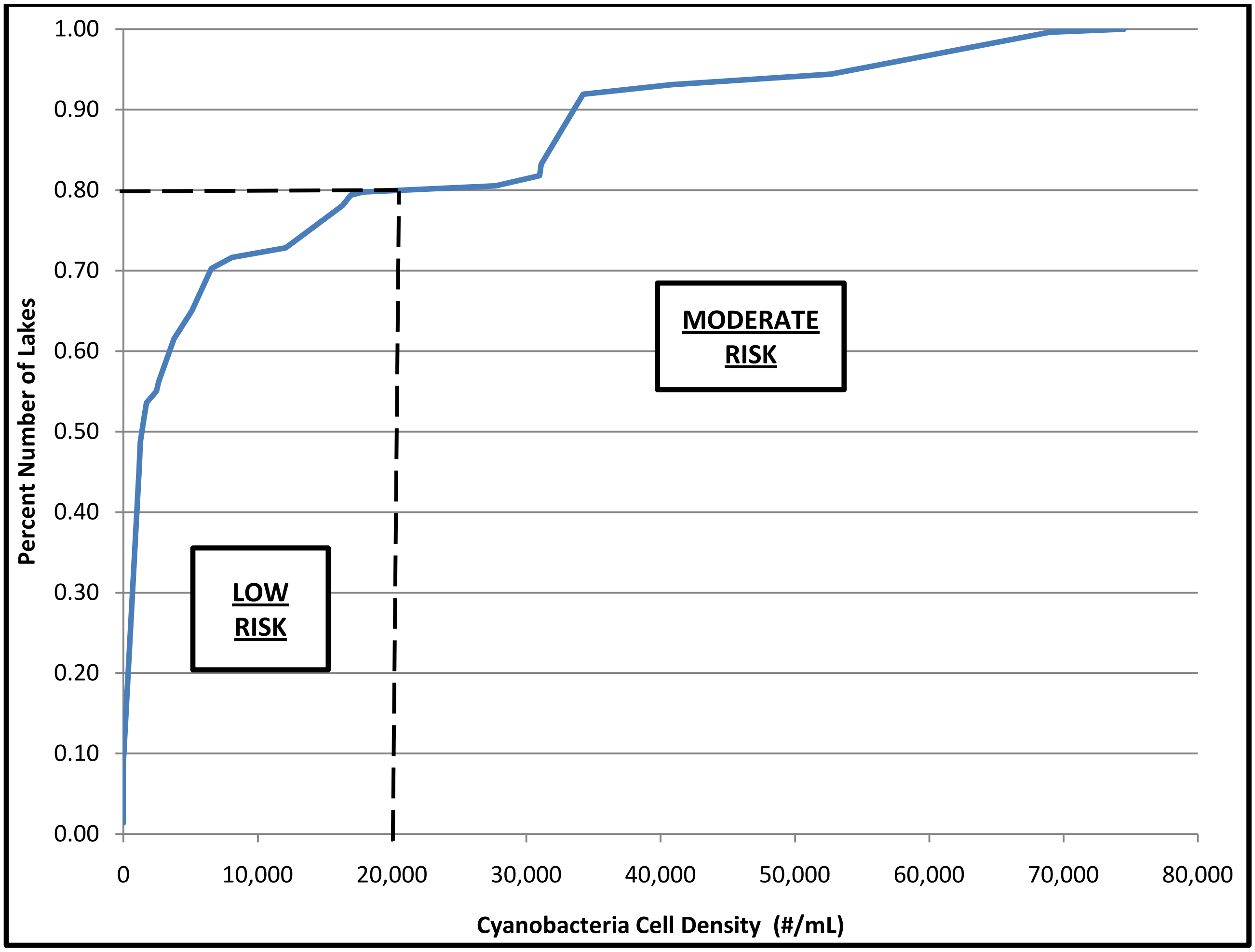

Figure 15. Percentage of Washington lakes in cyanobacteria risk categories.

Typically, large windblown accumulations of cyanobacteria may occur at nearshore areas around the perimeter of a lake. It is well documented that cell counts and cyanobacteria toxin concentrations in these accumulations are greater than in open water areas. In the NLA, samples were collected in the open water areas of the lake. As such, results may underestimate certain types of recreational exposure when accumulations or scums are present.

Ecological Integrity Indicators

Phytoplankton and Zooplankton

Phytoplankton and zooplankton assemblages are key elements of the lake biota and provide two indicators of the ecological integrity of lakes.

Phytoplankton are free-floating, mostly microscopic plants suspended in the water column. They are the base of most lake food webs. Phytoplankton species composition and abundance respond to changes in nutrients, pH, alkalinity, temperature, metals, and water column mixing.

Zooplankton are very small, often microscopic, animals that float in water and consist of crustaceans (copepods and cladocerans), rotifers (wheel-animals), pelagic insect larvae (phantom midges), and aquatic mites. The zooplankton assemblage is an important element of the food web; zooplankton transfer energy from phytoplankton (typically primary producers) to larger invertebrate predators and fish. The zooplankton assemblage responds to changes in the phytoplankton community and is also directly impacted by certain chemical conditions such as acidification or metals toxicity.

NLA analysts used a predictive taxa loss model to assess the condition of the planktonic community (phytoplankton and zooplankton). Predictive modeling estimates the expected occurrence of the taxa – in this case phytoplankton and zooplankton species - at each lake. This is done by developing a list of species that commonly occur at least disturbed, or reference lakes.

The list of species generated from the reference lakes is known as the *Expected* taxa list or *E*. This *E* list is compared to the phytoplankton and zooplankton taxa collected or *Observed* (O), at each lake.

The predictive model output is the observed to expected (O/E) taxa ratio. Scores less than one have fewer taxa at a site than were predicted by the model. Scores greater than one are either equivalent to the reference condition or the lake may have an enhanced phytoplankton community as a result of some type of enrichment or other environmental effect.

Another way to think of the score is in terms of the percentage of taxa loss or gain. Values less than 1.0 represent a loss of common native reference taxa. Percent taxa loss or gain is defined as:

$$(1.0 - O/E) * 100$$

For the phytoplankton and zooplankton data, three regionally specific O/E models were developed by NLA analysts to predict the extent of taxa loss in lakes across the country. Three categories of taxa loss were defined for each model: low (<20% taxa loss); moderate (20%-40% taxa loss); and severe (> 40% taxa loss).

Figure 16 shows the results of this O/E taxa loss model for the sampled lakes. Almost 50% of the lake sample population showed low taxa loss and, consequently, strong ecological integrity.

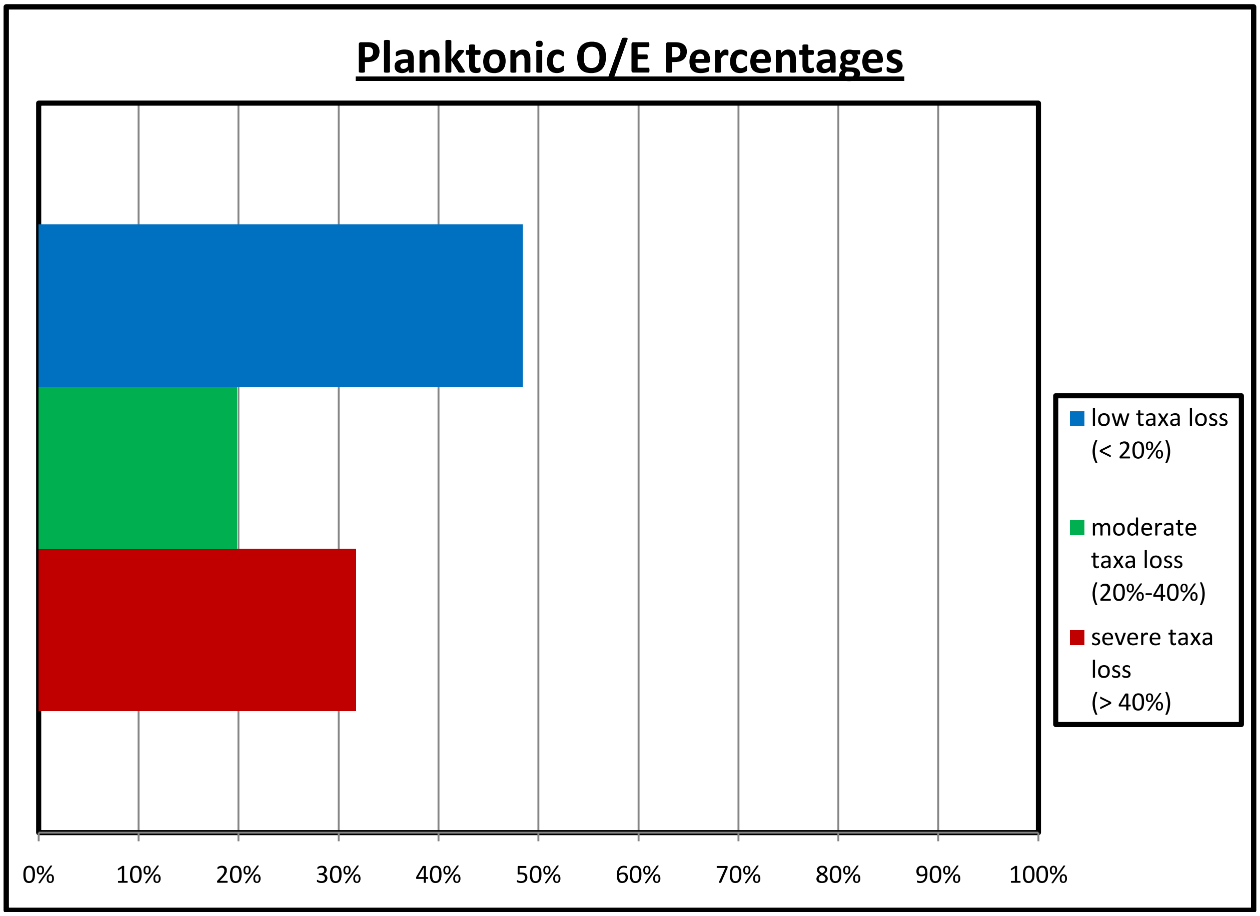

Figure 16. Percentage of Washington lakes showing low, moderate, or severe combined phytoplankton and zooplankton taxa loss.

Sediment Diatoms

Diatoms are one of the most common types of phytoplankton. They come in a wide variety of shapes, for example, filaments, fans, and colonies. A characteristic feature of diatom cells is that they are encased within a unique cell wall made of silica. These silica cell walls are able to survive in sediment and are one of the most powerful water quality indicators used in paleolimnological studies. They colonize virtually every freshwater habitat and many diatom species have well defined tolerances for environmental variables such as pH, nutrient concentration, water salinity, and color (Stoermer and Smol, 1999). Based on previous research, variations in fossil diatom species composition were used to assess the amount of nutrient change (specifically total phosphorus and total nitrogen) that has occurred in the lakes sampled as part of the NLA (Smol, 1992; Charles et al., 1994).

Sampling Methodology

In order to accurately date a sediment core, Pb-210 (a naturally occurring radioactive element) levels are measured. From the accumulation rate, the age of sediment from a particular depth in the sediment core can be estimated. Since Pb-210 dating of the NLA bottom cores was not performed, an alternative approach was used to evaluate whether or not the bottom slice of the cores represent pre-European settlement conditions. A core length of between 35-45 centimeters was recommended as one that would include lake sediments from the pre-European settlement era. A slice was taken from the top of the core representing present day conditions, and the bottom of the core representing pre-disturbance condition.

The top-bottom approach provides two snapshots of environmental conditions: one before and one after European settlement impacts. The change in the composition and relative abundance of the diatom assemblages between the top and the bottom of the sediment cores can be quantified and the results used to infer historical concentrations of various water quality parameters. For this survey, the diatom community structure was used to infer concentrations of total phosphorus, total nitrogen, conductivity, and pH. For more detail on the methodology of the model development, see the EPA website: www.epa.gov/owow/lakes/lakessurvey/

Sediment Core Analysis

For the NLA, each sediment core was assigned to one of three categories based on the confidence that the bottom interval represented time prior to European settlement disturbance typical for the region. This categorizing system is called *core confidence*. The category *Yes* indicates confidence that the bottom core slice represents a pre-disturbance time period. Usually these are from longer cores or from lakes with lower sedimentation rates. The category *No* indicates it is unlikely that the core is sufficiently deep to represent pre-disturbance time. These are usually from shorter cores or from lakes with presumed high sedimentation rates. *Uncertain* indicates that it was difficult to make a determination. This category was used for lakes officially designated *man-made,* e.g., reservoirs, oxbow lakes. The *Uncertain* category was also used for lakes that were borderline in terms of core length, presumed sedimentation rate, and disturbance history.

Core confidence category assignments were based on several factors, including sediment core dates from previous studies and evaluation of lake and watershed characteristics that can have a strong influence on sedimentation rates. Key variables considered were nutrient ecoregion, total percent watershed disturbance, total phosphorus, lake depth and surface area, and watershed area.

A longer core would be required to reliably represent pre-European disturbance condition especially in the following cases:

1. Lake watersheds with highly erodible soils and high watershed disturbance - especially agricultural disturbance - tend to have greater input of inorganic particles due to erosion.
2. Watersheds with a higher percent of agricultural and urban land use tend to have higher algal growth stimulated by increased nutrient inputs.
3. Sediments in shallower lakes might be mixed to a greater depth than deeper lakes.

Sediment Core Results

Results for the lakes are shown in Figure 17 (difference in inferred total phosphorus concentrations) and Figure 18 (difference in inferred total nitrogen concentrations). The values indicate the difference in inferred nutrient concentrations between the top and bottom slices of the sediment cores.

Cores were collected from 23 of the 30 lakes sampled. A core was also collected at one of the reference lakes – U-Lake. Two lakes, Red Rock and Medical, fell into the *No* category for core confidence. Six lakes – Louise, Sammamish, Bayley, Moses, Wapato, and Grimes – fell into the *Uncertain* core confidence category. It is interesting to note both lakes in the *No* category and three out of the six lakes in the *Uncertain* category all occur in the Xeric Ecoregion of Eastern Washington.

The Xeric Ecoregion is typically highly agricultural (cropland as well as rangeland) with a high amount of human/animal disturbance. Using GIS analysis, four of the nine lakes (Moses, Red Rock, Grimes, and Medical) showed high levels of watershed disturbance, including agricultural activities and sedimentary soils which can be highly erodible. Both of these conditions could indicate the sediment core length was insufficient to show pre-European settlement total phosphorus conditions.

Figure 17 shows the difference in inferred total phosphorus concentrations. Eight of the nine lakes (89%) sampled in Eastern Washington showed negative values for the difference in total phosphorus concentrations between the top and bottom slice of the sediment core. Based on the diatom community analysis, this indicates higher phosphorus levels in the bottom slice of the core which is supposed to represent the pre-European settlement period. Most of the negative values were 50 µg/L or less although Grimes Lake had a negative value of 1500 µg/L and Medical Lake had a negative value of 3200 µg/L.

Eight out of 15 lakes (53%) in Western Washington showed negative values for the difference in total phosphorus concentrations between the top and bottom slice of the sediment core. Most of these eight lakes had negative values of 10 µg/L or less. Kitsap Lake in Kitsap County had the highest negative value – a difference of 40 µg/L of total phosphorus.

Figure 18 shows the difference in inferred total nitrogen concentrations. Seven of the nine lakes (78%) sampled in Eastern Washington had negative values for the difference in total nitrogen concentrations between the top and bottom slice of the sediment core. Most of these negative values were less than 0.2 mg/L of total nitrogen. Wapato Lake had a negative value of 1.0 mg/L; Grimes Lake, a negative value of 3.98 mg/L; and Medical Lake, a negative value of 15.6 mg/L.

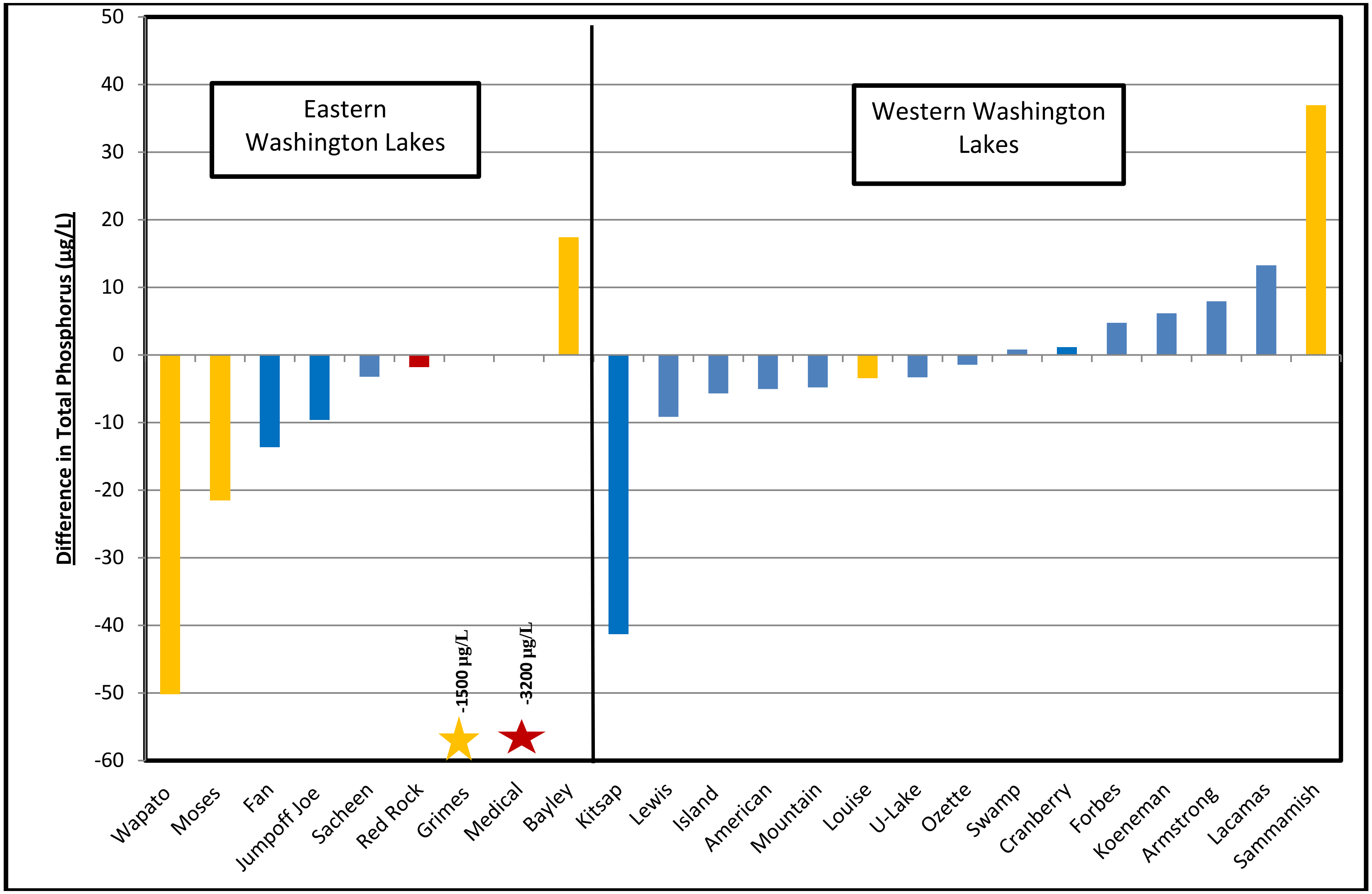

Figure 17. The difference between inferred total phosphorus concentrations (based on sediment diatom community structure) in the top and bottom slices of the sediment cores.

U-Lake is a reference lake. The orange bars and star represent cores at lakes that were in the Uncertain core confidence category. The red bars and star represent cores at lakes in the No core confidence category. The blue bars represent cores in the Yes core confidence category.

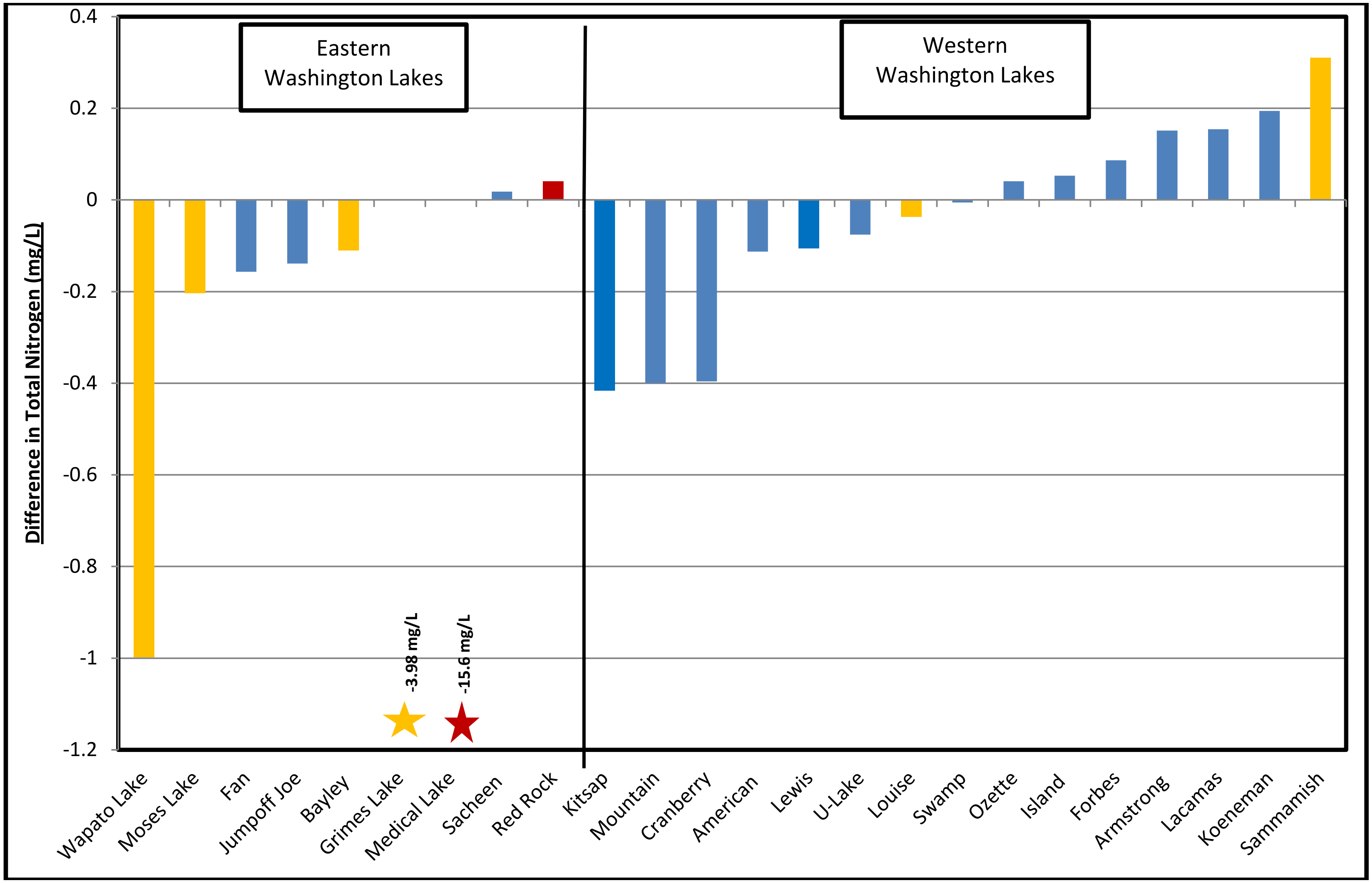

Figure 18. The difference between inferred total nitrogen concentrations (based on sediment diatom community structure) in the top and bottom slices of the sediment cores.

U-Lake is a reference lake. The orange bars and star represent cores at lakes that in the Uncertain core confidence category. The red bars and star represent cores at lakes that were in the No core confidence category. The blue bars represent cores in the Yes core confidence category.

Eight of 15 lakes in Western Washington had negative values for the difference in total nitrogen concentrations between the top and bottom slice of the sediment core. Most of the negative values were less than 0.4 mg/L. Kitsap Lake had the highest negative value at just over 0.4 mg/L of total nitrogen.

One possible explanation for the negative nutrient values could be that the core length for these lakes was not sufficient to show pre-European settlement nutrient conditions. Closer analysis of the individual lake environment, e.g., sedimentation rates and land use history, could also help explain the negative values.

Physical Habitat

Physical habitat condition is critically important to aquatic insects, fish, and other aquatic organisms. Habitat alteration can affect biological integrity even where chemical stressors, like increases in total phosphorus, are absent. Littoral and riparian habitats provide refuge from predation, living and egg-laying substrates, and food. Shoreline structure affects nutrient cycling and sedimentation rates. Human activities along lakeshores often adversely affect a lake's physical habitat by reducing habitat complexity. For example, in the presence of human activity, lake habitat complexity (in the form of woody snags, overhanging trees, and aquatic plants) can become markedly reduced.

The physical habitat portion of the NLA generated a large amount of data. All of the physical habitat information was combined into the following four descriptive metrics of lake physical habitat condition:

- **Lakeshore Disturbance** is a metric which incorporates the extent and intensity of human land use activities that were observed within and adjacent to each physical habitat station. Lakes where most stations contained no disturbance of any type would score low for this metric. Lakes where many stations had only a small number of disturbances would score in the moderate category. Lakes with many disturbance types occurring both within and adjacent to the physical habitat stations would score high for this metric.
- **Riparian Habitat** is a metric which incorporates the structure and cover in three layers of riparian vegetation observed in the riparian zone.
- **Shallow Water Habitat** is a metric which combines cover measure including both living and non-living material observed in the littoral zone. This includes large woody snags, brush, overhanging vegetation, aquatic macrophytes, boulders, and rock ledges.
- **Lake Habitat Complexity** is a metric which combines riparian vegetation cover and littoral cover observed in both the riparian and littoral zones. This metric results in an assessment of overall habitat structural complexity and integrity.

Figure 19 shows the percentage of *good*, *fair*, and *poor* lakes in each of the above mentioned categories. Over 90% of the lakes showed *good* shallow water habitat. Over 70% of the lakes showed *good* riparian habitat. Over 75% of the lakes were *good* in the category of lake habitat complexity.

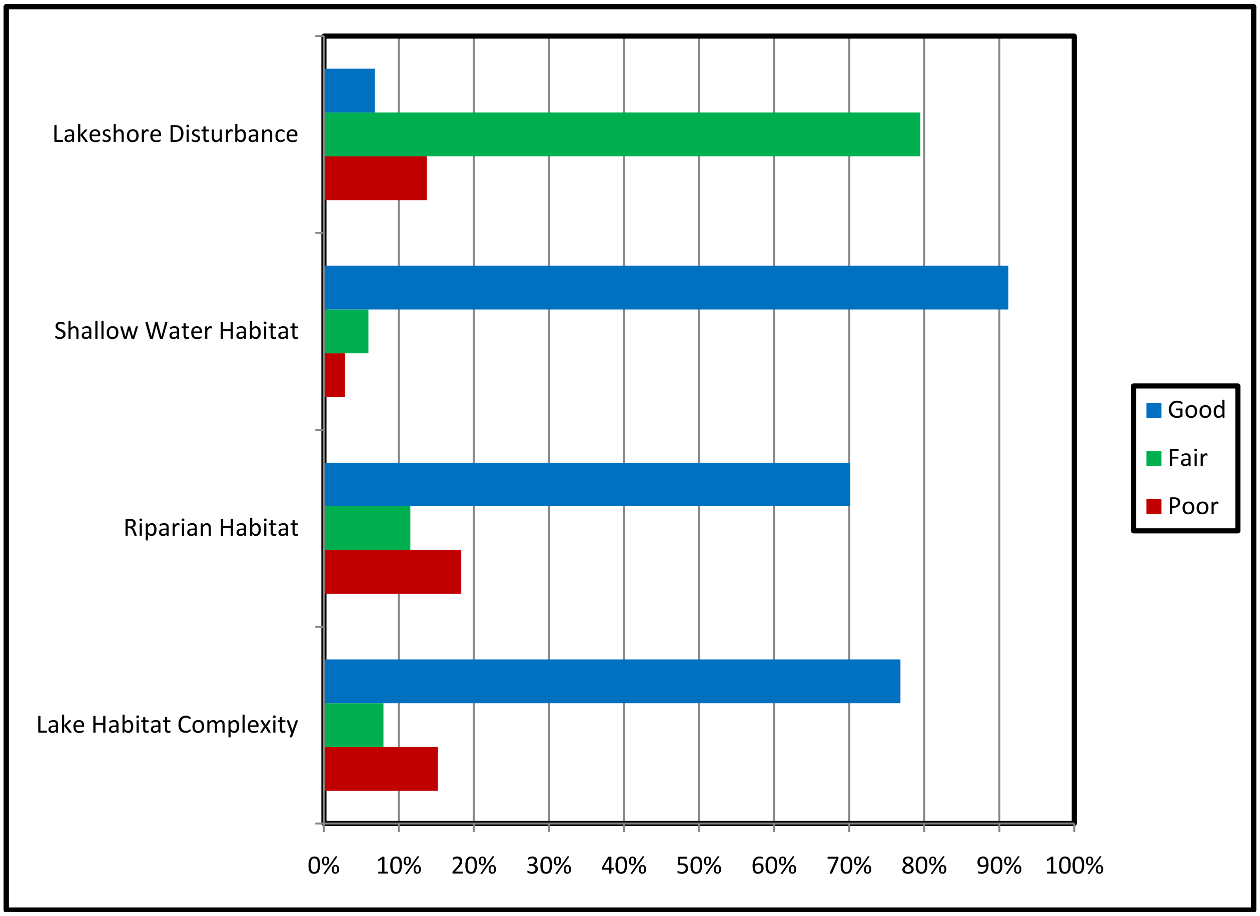

Figure 19. Percentage *good*, *fair*, or *poor* lakes with regard to physical habitat indicators.

In spite of all the lakes having good riparian vegetation and littoral cover, less than 10% of the lakes are in the *good* category for the lakeshore disturbance metric. These results are interesting: they show the consistency between the habitat quality indicators (riparian habitat, shallow water habitat, and lake habitat complexity) yet the lakeshore disturbance metric results do not seem strongly related. A correlation analysis further shows the weak relationship with R values less than 0.03 for all three metrics (see Table 5).

Table 5. Summary of analysis showing R correlation coefficient values.

Physical Habitat Indicator	Lakeshore Disturbance
Shallow Water Habitat	0.08
Riparian Habitat	0.28
Lake Habitat Complexity	0.24

Part of the explanation for this might be that the *good*, *fair*, and *poor* condition criteria for lakeshore disturbance were developed at a national scale for all the lakes in the NLA. The condition criteria for the other physical habitat indicators were developed on a regional basis. Statistically, this could lead to more stringent thresholds for the condition criteria for lakeshore disturbance, putting more lakes in *fair* and *poor* categories in Washington. The small Washington lake sample size (30 lakes sampled) could also be a factor in the weak relationship between the physical habitat metrics.

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Discussion

Indicator Outcomes

An important key function of the NLA was to provide a perspective on key stressors impacting lakes. One way to accomplish this is to see how extensive or widespread any particular stressor is, e.g., what percentage of lakes are in poor condition with regard to excess phosphorus concentrations. *Relative extent* is the term used in the NLA to describe the ranking of lake stressors in poor condition. This is simply a way of evaluating how widespread and common a particular stressor is among lakes.

Figure 20 ranks the eight key stressor indicators by the percentage of lakes in poor condition. The stressors are assessed and reported independently and as such do not sum to 100%. Most lakes are likely to experience multiple stressors simultaneously which can result in cumulative effects rather than those shown by a single stressor.

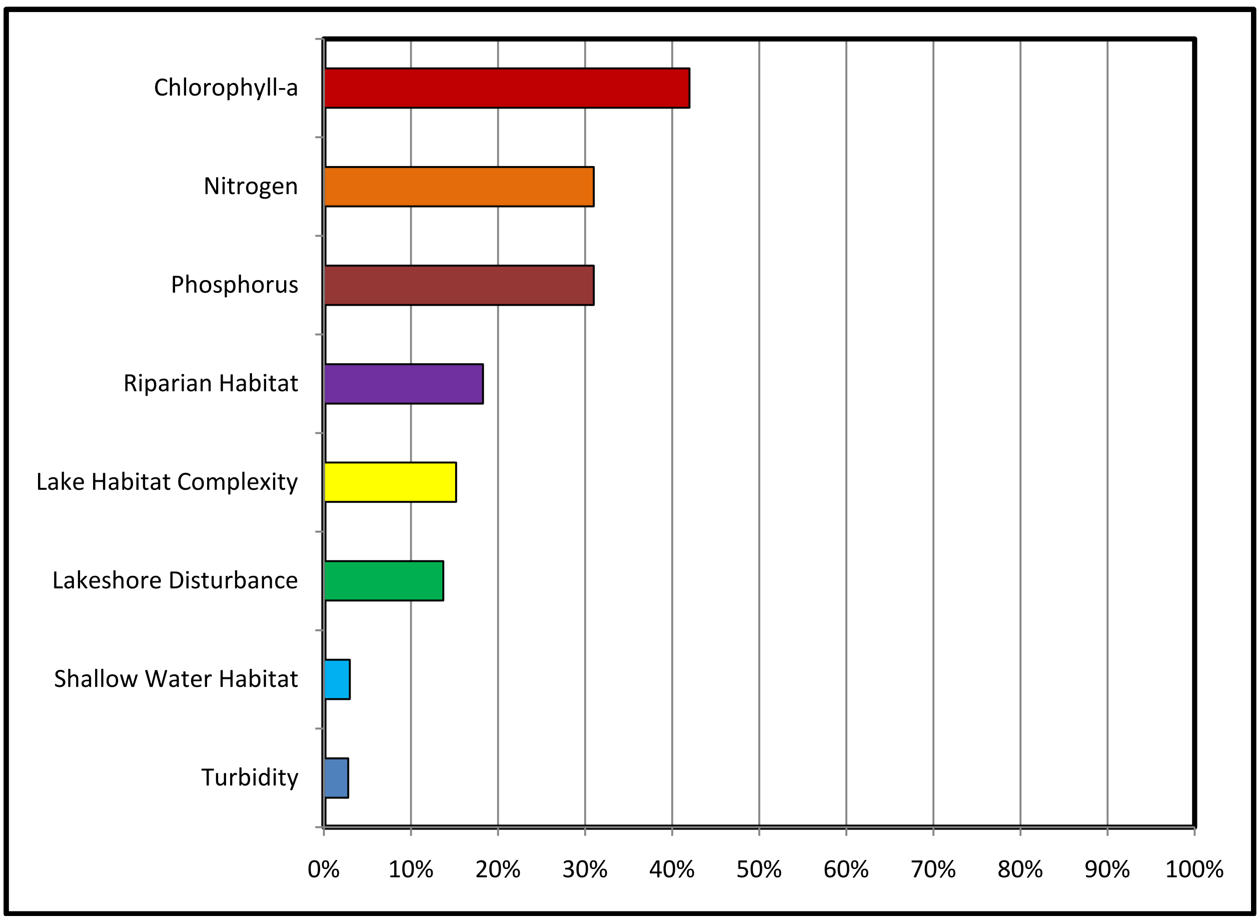

Figure 20. Relative extent of stressor parameters in poor condition, expressed as percentage of lakes in Washington.

In Washington, chlorophyll-a and nutrients account for the highest number of lakes in poor condition. Chlorophyll-a is in poor condition in 42% of the lake sample population. At 31% of the lake sample population, total phosphorus and total nitrogen are the second and third highest ranked stressor.

The physical habitat metrics in poor condition range from 3% for shallow water habitat, 14% for lakeshore disturbance, 15% for lake habitat complexity, and 18% for riparian habitat. This tells us over 80% of the lake sample population in Washington is *fair* or *good* with regard to physical habitat.

Turbidity was in poor condition at only 3% of the lakes in the lake sample population.

The results in Washington show nutrients and chlorophyll-a are the parameters of highest concern. It is important for water resource managers to take into account the extent of stressors when setting lake priority actions.

Statistical Confidence and Sample Size

Determining sample size for any project is always a dilemma. Available funds and staff time are two of the biggest factors to consider in any project design. The common assumption is the larger the sample size, the more confidence in the final data results. One way to convey confidence in data is to calculate confidence intervals, or error bars.

For probability surveys conducted by EPA (such as the National Lake Assessment), it is generally accepted that 30 lakes was the minimum number of lakes needed to be sampled in order to be statistically valid in applying the results to a larger lake population with a 95% confidence interval of approximately ±15%. For comparison, 1,028 lakes were sampled in the lower 48 states and the average 95% confidence interval for all the parameters sampled was ±4%.

Survey Design

The NLA design stipulated all the sampling activity at a lake was to be done in one day. Unlike other parts of the country, many lakes in the western United States are often inaccessible. Fifty-two percent of the lakes on the Washington sampling list were identified as inaccessible and therefore not sampled. In most cases these lakes were not accessible by road and required backpacking the equipment into the site, either on foot or with animals. Some lakes were only accessible by aircraft. Obviously these sites would not meet the criteria of accessing and sampling the lake in one day. These types of sites would require more resources in terms of time, staff, and money in order to be included in the survey.

Even though Ecology followed the NLA design, the high number of lakes not sampled because of accessibility issues may have skewed the data results.

Conclusions

The National Lakes Assessment (NLA) was the first attempt by EPA to collect information on lakes in the lower 48 states using identical sampling methodologies. The resulting national report will allow an understanding of the nation's lakes and establish a baseline for future monitoring efforts.

The NLA survey had the following goals:

- Address key questions about the quality of the nation's lakes:
    - What percentage of the nation's lakes are in good condition based on indicators like ecological integrity, trophic status, and recreational health?
    - What are key stressors on the lake environment?
- Promote collaboration and build state and tribal capacity for lake monitoring.
- Provide a nationally consistent data set to examine lake water quality and develop baseline information in order to evaluate changes over time.

By its participation in the NLA, Ecology was able to describe the condition of 620 lakes and report on the percentage of lakes in *good*, *fair*, and *poor* condition in a number of environmental categories. The results of this survey indicate nutrients and chlorophyll-a are the most important stressors in Washington lakes.

Many of the lakes sampled as part of this survey required permission for access and cooperation from other natural resource agencies. The potential for future collaboration for lake monitoring has been established as a result of this survey.

Finally, a baseline of lake information has been established. If Washington lake managers agree lakes are in need of continued monitoring activity, this survey could act as a template for future action.

The NLA survey design is built upon comparing data results to a set of reference conditions. This design depends on a large enough set of established reference conditions for the parameters of concern in order to statistically apply the results of the sampled lakes to a larger population with confidence. In future studies, this could be improved by increasing the number of reference lakes identified and sampled.

Statewide, Washington lakes have a large degree of heterogeneity. As evidenced in this survey, with a small number of reference lakes, it is difficult to capture that heterogeneity. Increased sample size could compensate for the inherent lake heterogeneity, yielding higher confidence in the data.

Recommendations

Results of this study support the following recommendations.

- Before participating in the next NLA, Ecology should conduct sampling on a selected number of lakes to try to verify the validity of the NLA results. The parameters sampled could be limited to the top three stressors identified in the NLA.
- If Ecology participates in the next National Lakes Assessment survey (scheduled for field work in 2012), a minimum of 50 lakes should be sampled to ensure higher levels of confidence in the data results.
- In order to avoid skewing the data results, we need to include lakes for sampling which require backpacking or means of access other than driving to the site. This will require additional monetary resources, staff, and a change in the requirement of completing each lake's sampling activity within one day.
- Additional resources should be allocated to work on correlations between land use and the findings of this report.
- Sediment cores taken for diatom analysis need to be dated in order to ensure they are of sufficient length to reach a depth indicative of pre-European settlement.
- Additional statewide located reference lakes need to be identified and sampled.

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Appendices

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Appendix A. Glossary, Acronyms, and Abbreviations

Glossary

Clean Water Act: A federal act passed in 1972 that contains provisions to restore and maintain the quality of the nation's waters. Section 303(d) of the Clean Water Act establishes the TMDL program.

Conductivity: A measure of water's ability to conduct an electrical current. Conductivity is related to the concentration and charge of dissolved ions in water.

Parameter: Water quality constituent being measured (analyte). A physical, chemical, or biological property whose values determine environmental characteristics or behavior.

Pathogen: Disease-causing microorganisms such as bacteria, protozoa, viruses.

pH: A measure of the acidity or alkalinity of water. A low pH value (0 to 7) indicates that an acidic condition is present, while a high pH (7 to 14) indicates a basic or alkaline condition. A pH of 7 is considered to be neutral. Since the pH scale is logarithmic, a water sample with a pH of 8 is ten times more basic than one with a pH of 7.

Pollution: Such contamination, or other alteration of the physical, chemical, or biological properties, of any waters of the state. This includes change in temperature, taste, color, turbidity, or odor of the waters. It also includes discharge of any liquid, gaseous, solid, radioactive, or other substance into any waters of the state. This definition assumes that these changes will, or is likely to, create a nuisance or render such waters harmful, detrimental, or injurious to (1) public health, safety, or welfare, or (2) domestic, commercial, industrial, agricultural, recreational, or other legitimate beneficial uses, or (3) livestock, wild animals, birds, fish, or other aquatic life.

Riparian: Relating to the banks along a natural course of water.

Surface waters of the state: Lakes, rivers, ponds, streams, inland waters, salt waters, wetlands and all other surface waters and watercourses within the jurisdiction of Washington State.

Watershed: A drainage area or basin in which all land and water areas drain or flow toward a central collector such as a stream, river, or lake at a lower elevation.

303(d) list: Section 303(d) of the federal Clean Water Act requires Washington State to periodically prepare a list of all surface waters in the state for which beneficial uses of the water – such as for drinking, recreation, aquatic habitat, and industrial use – are impaired by pollutants. These are water quality limited estuaries, lakes, and streams that fall short of state surface water quality standards, and are not expected to improve within the next two years.

Acronyms and Abbreviations

Following are acronyms and abbreviations used frequently in this report.

ANC	Acid neutralizing capacity
Ecology	Washington State Department of Ecology
EPA	U.S. Environmental Protection Agency
NLA	National Lake Assessment
USGS	U.S. Geological Survey

Units of Measurement

ceq/100 mL	cell equivalents per 100 milliliters
mg	milligrams
mg/L	milligrams per liter
mL	milliliters
NTU	nephelometric turbidity units
PCU	platinum cobalt units
qPCR	quantitative polymerase chain reaction
µg/L	micrograms per liter (parts per billion)
µeq/L	microequivalents per liter

Appendix B. Lake Information

Table B-1. List of lakes sampled in Washington as part of the National Lakes Assessment survey.

County	Lake	Area (acres)	Longitude	Latitude	Ecoregion
Pierce	American	1104	-122.547	47.135	Puget Lowland
Snohomish	Armstrong	25	-122.123	48.225	Puget Lowland
Stevens	Bayley	68	-117.662	48.420	Northern Rockies
Pend Oreille	Calispell	486	-117.321	48.290	Northern Rockies
Kittitas	Cle Elum	4541	-121.110	47.277	North Cascades
Island	Cranberry	130	-122.656	48.396	Puget Lowland
Mason	Cushman	3880	-123.225	47.451	Coast Range
Pend Oreille	Fan	71	-117.407	48.056	Northern Rockies
Mason	Forbes	36	-122.972	47.190	Puget Lowland
Whatcom	Gorge	204	-121.155	48.714	North Cascades
Douglas	Grimes	188	-119.591	47.729	Columbia Plateau
Cowlitz	Horseshoe	80	-122.749	45.898	Willamette Valley
Pacific	Island	44	-124.036	46.422	Coast Range
Stevens	Jump-off Joe	120	-117.688	48.138	Northern Rockies
Kitsap	Kitsap	233	-122.703	47.576	Puget Lowland
Kitsap	Koeneman	18	-122.785	47.410	Puget Lowland
Clark	Lacamas	253	-122.432	45.621	Willamette Valley
Pierce	Lewis	56	-122.560	46.987	Puget Lowland
Whatcom	Louise	26	-122.328	48.708	Puget Lowland
Spokane	Medical	124	-117.687	47.569	Columbia Plateau
Grant	Moses	6439	-119.340	47.120	Columbia Plateau
San Juan	Mountain	185	-122.816	48.660	Puget Lowland
Clallam	Ozette	7590	-124.621	48.100	Coast Range
Grant	Red Rock	127	-119.577	46.873	Columbia Plateau
Pend Oreille	Sacheen	301	-117.335	48.148	Northern Rockies
Grant	Saddle Mountain	548	-119.646	46.692	Columbia Plateau
King	Sammamish	4836	-122.083	47.576	Puget Lowland
Kittitas	Swamp	38	-121.301	47.311	North Cascades
Lewis	Swofford Pond	210	-122.405	46.499	Cascades
Chelan	Wapato	192	-120.164	47.919	Columbia Plateau

Appendix C. Chemical Data

Table C-1. Data results for lab analyzed parameters and Secchi depth.

Metric	Lake Sample Population	Min.	Max.	Range	Mean	Median	Variance	Standard Deviation	Standard Error	Confidence Interval (-95%)	Confidence Interval (+95%)
pH - field	620	5.10	9.50	4.40	7.75	7.50	0.92	0.96	0.04	7.68	7.83
pH - lab	620	5.12	9.34	4.22	7.57	7.35	0.60	0.77	0.03	7.51	7.63
Conductivity (µS/cm)	620	34.20	4217.00	4182.80	138.56	50.86	204492.66	452.21	18.18	102.87	174.25
ANC (ueq/L)	620	1.50	17949.45	17947.95	916.27	357.17	4378013.33	2092.37	84.10	751.11	1081.43
Turbidity (NTU)	620	0.42	12.20	11.78	1.91	0.72	7.50	2.74	0.11	1.70	2.13
Color (PCU)	620	2.00	61.00	59.00	20.18	14.00	232.02	15.23	0.61	18.97	21.38
Total organic carbon (mg/L)	620	0.66	22.06	21.40	5.32	3.26	13.28	3.64	0.15	5.03	5.61
Dissolved organic carbon (mg/L)	620	0.76	19.01	18.25	4.98	3.30	10.28	3.21	0.13	4.72	5.23
Total nitrogen (mg/L)	620	0.03	2.62	2.59	0.41	0.21	0.14	0.38	0.02	0.38	0.44
Total phosphorus (µg/L)	620	1.00	190.00	189.00	18.41	7.00	626.19	25.02	1.01	16.44	20.39
NH4N (mg/L)	620	0.01	0.07	0.06	0.01	0.01	0.00	0.02	0.00	0.01	0.02
NO3N (mg/L)	620	0.01	2.23	2.23	0.05	0.01	0.06	0.25	0.01	0.03	0.07
NO3_NO2 (mg/L)	620	0.01	2.30	2.30	0.05	0.01	0.07	0.26	0.01	0.03	0.07
SO4 (mg/L)	620	0.13	899.48	899.36	13.52	1.35	9042.18	95.09	3.82	6.02	21.03

Metric	Lake Sample Population	Min.	Max.	Range	Mean	Median	Variance	Standard Deviation	Standard Error	Confidence Interval (-95%)	Confidence Interval (+95%)
CL (mg/L)	620	0.38	347.01	346.62	8.04	1.93	1392.34	37.31	1.50	5.09	10.98
SIO2 (mg/L)	620	0.18	32.76	32.58	8.20	7.01	42.33	6.51	0.26	7.68	8.71
CA (mg/L)	620	0.54	35.77	35.23	7.48	3.70	61.96	7.87	0.32	6.86	8.10
MG (mg/L)	620	0.91	35.16	34.25	3.91	1.23	36.46	6.04	0.24	3.43	4.39
NA (mg/L)	620	0.81	796.70	795.90	13.87	2.62	7313.03	85.52	3.44	7.12	20.62
K (mg/L)	620	0.10	79.54	79.44	1.68	0.39	71.99	8.48	0.34	1.01	2.35
Chlorophyll-a (µg/L)	620	0.15	26.08	25.93	5.86	1.91	37.20	6.10	0.25	5.38	6.34
Secchi Depth (M)	620	0.70	9.16	8.46	3.83	4.72	3.40	1.84	0.08	3.68	3.98