science for a changing world

Prepared in cooperation with the National Park Service

Sources and Sinks of Nitrogen and Phosphorus in a Deep, Oligotrophic Lake, Lake Crescent, Olympic National Park, Washington

Scientific Investigations Report 2012–5107

U.S. Department of the Interior
U.S. Geological Survey

Cover: Photograph looking southeast over Lake Crescent, Washington. (Photograph taken by Steve Fradkin, National Park Service.)

Sources and Sinks of Nitrogen and Phosphorus in a Deep, Oligotrophic Lake, Lake Crescent, Olympic National Park, Washington

By P.W. Moran, S.E. Cox, S.S. Embrey, R.L. Huffman, T.D. Olsen, and S.C. Fradkin

Prepared in cooperation with the National Park Service

Scientific Investigations Report 2012–5107

U.S. Department of the Interior
U.S. Geological Survey

U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2013

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1–888–ASK–USGS.

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov

Suggested citation:
Moran, P.W., Cox, S.E., Embrey, S.S., Hufffman, R.L., Olsen, T.D., and Fradkin, S.C., 2013, Sources and sinks of nitrogen and phosphorus to a deep, oligotrophic lake, Lake Crescent, Olympic National Park, Washington: U.S. Geological Survey Scientific Investigations Report 2012–5107, 56 p., http://pubs.usgs.gov/sir/2012/5107/.

Contents

Contents—Continued

Figures

Figures—Continued

Tables

Conversion Factors, Datums, Abbreviations and Acronyms

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
inch (in.)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
cubic meter (m^3)	10,000	liters (L)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
acre-foot (acre-ft)	325,900	gallons (gal)
acre-foot (acre-ft)	1,234,000	liters
acre-foot (acre-ft)	0.8104	megaliters
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
hectare (ha)	0.003861	square mile (mi^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
square centimeter (cm^2)	0.001076	square foot (ft^2)
	Volume	
cubic meter (m^3)	0.0008107	acre-foot (acre-ft)
liter (L)	0.2642	gallon (gal)
megaliter	1.234	acre-foot (acre-ft)
milliliter (mL)	0.03381	ounce (oz.)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)

Conversion Factors, Datums, Abbreviations and Acronyms

Conversion Factors—Continued

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F=(1.8×°C)+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C=(°F-32)/1.8$$

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (µg/L).

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (µS/cm at 25°C).

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations and Acronyms

AMLE	Adjusted Maximum Likelihood Estimation
CCAL	Oregon State University Cooperative Chemical Analytical Laboratory
DL	detection limit
DO	dissolved oxygen
GIS	geographic information system
HDPE	high-density polyethylene
IG	inorganic grade
KCl	potassium chloride
NADP	National Atmospheric Deposition Program
NHDPlus	National Hydrologic Dataset-Plus software
NLCD	National Land Cover Dataset
NO_3	dissolved nitrate
NOx	nitrogen oxide
ONP	Olympic National Park
PETE	polyethylene terephthalate copolymer
RL	reporting level
RO	reverse osmosis
SE	standard error
SEP	standard error of prediction
SM	standard methods
TN	total nitrogen
TP	total phosphorus
TSI	Trophic Status Index
USGS	U.S. Geological Survey
WSDOT	Washigton State Department of Transportation

This page is intentionally blank

Sources and Sinks of Nitrogen and Phosphorus in a Deep, Oligotrophic Lake, Lake Crescent, Olympic National Park, Washington

By P.W. Moran[1], S.E. Cox[1], S.S. Embrey[1], R.L. Huffman[1], T. D. Olsen[1], and S.C. Fradkin[2],

Abstract

Lake Crescent, in Olympic National Park in the northwest corner of Washington State is a deep-water lake renowned for its pristine water quality and oligotrophic nature. To examine the major sources and sinks of nutrients (as total nitrogen, total phosphorus, and dissolved nitrate), a study was conducted in the Lake Crescent watershed. The study involved measuring five major inflow streams, the Lyre River as the major outflow, recording weather and climatic data, coring lake bed sediment, and analyzing nutrient chemistry in several relevant media over 14 months. Water samples for total nitrogen, total phosphorus, and dissolved nitrate from the five inflow streams, the outlet Lyre River, and two stations in the lake were collected monthly from May 2006 through May 2007. Periodic samples of shallow water from temporary sampling wells were collected at numerous locations around the lake. Concentrations of nutrients detected in Lake Crescent and tributaries were then applied to the water budget estimates to arrive at monthly and annual loads from various environmental components within the watershed. Other sources, such as leaf litter, pollen, or automobile exhaust were estimated from annual values obtained from various literature sources. This information then was used to construct a nutrient budget for total nitrogen and total phosphorus. The nitrogen budget generally highlights vehicle traffic—diesel trucks in particular—along U.S. Highway 101 as a potential major anthropogenic source of nitrogen compounds in the lake. In contrast, contribution of nitrogen compounds from onsite septic systems appears to be relatively minor related to the other sources identified.

[1]U.S. Geological Survey.

[2]National Park Service, Olympic National Park.

Introduction

Lake Crescent lies along the northern edge of the rugged mountainous core of Olympic National Park (ONP) in the northwest corner of Washington State (fig. 1). The deep-water monomictic lake is renowned for its pristine water-quality and is home to a trout fishery that is unique for its large size, life history, and appearance (National Park Service, 2011). Lake Crescent, on the northern end of the Olympic Peninsula, is 17 km long, including the northeastern basin with a maximum depth of 190 m (Wolcott, 1973) and a surface area of 2,030 hectares (ha) (as delineated from geographic information system [GIS] calculations). The park and surrounding area is noted for its remote wilderness, which includes glacier-capped mountains, stands of old-growth and temperate rain forest, and clear streams and lakes.

Visitors have been drawn to Lake Crescent since the early 1900s when a health sanatorium and at least six other resorts were on the north and south shores (Kirk and Alexander, 1990). The number of visits to the park and to the lake has steadily increased from 40,650 visits in 1939 to 4.2 million in 2001 (Jenkins and others, 2003).

Because of its pristine quality, disturbances from natural and anthropogenic sources could adversely affect the water quality of the lake and alter its ecosystem condition. Chief among these disturbances are increases in nutrient loading that can change the algal community structure and result in the growth of nuisance algae. Over the past decade, ONP employees have observed an apparent increase in the algal community typical of nutrient-poor waters. Additionally, a difference in the algal community has occurred along developed and undeveloped shorelines (Rosenberger and others, 2008). Of particular concern to ONP employees are results from surveys in 2001 of algal mats on the cobble and gravel substrates around the Lyre River, which is an important spawning area for an endemic and genetically unique species of trout. The nuisance algal mats likely are the result of nutrient enrichment, possibly from old, failing onsite septic systems and sewage treatment facilities near the lakeshore (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002).

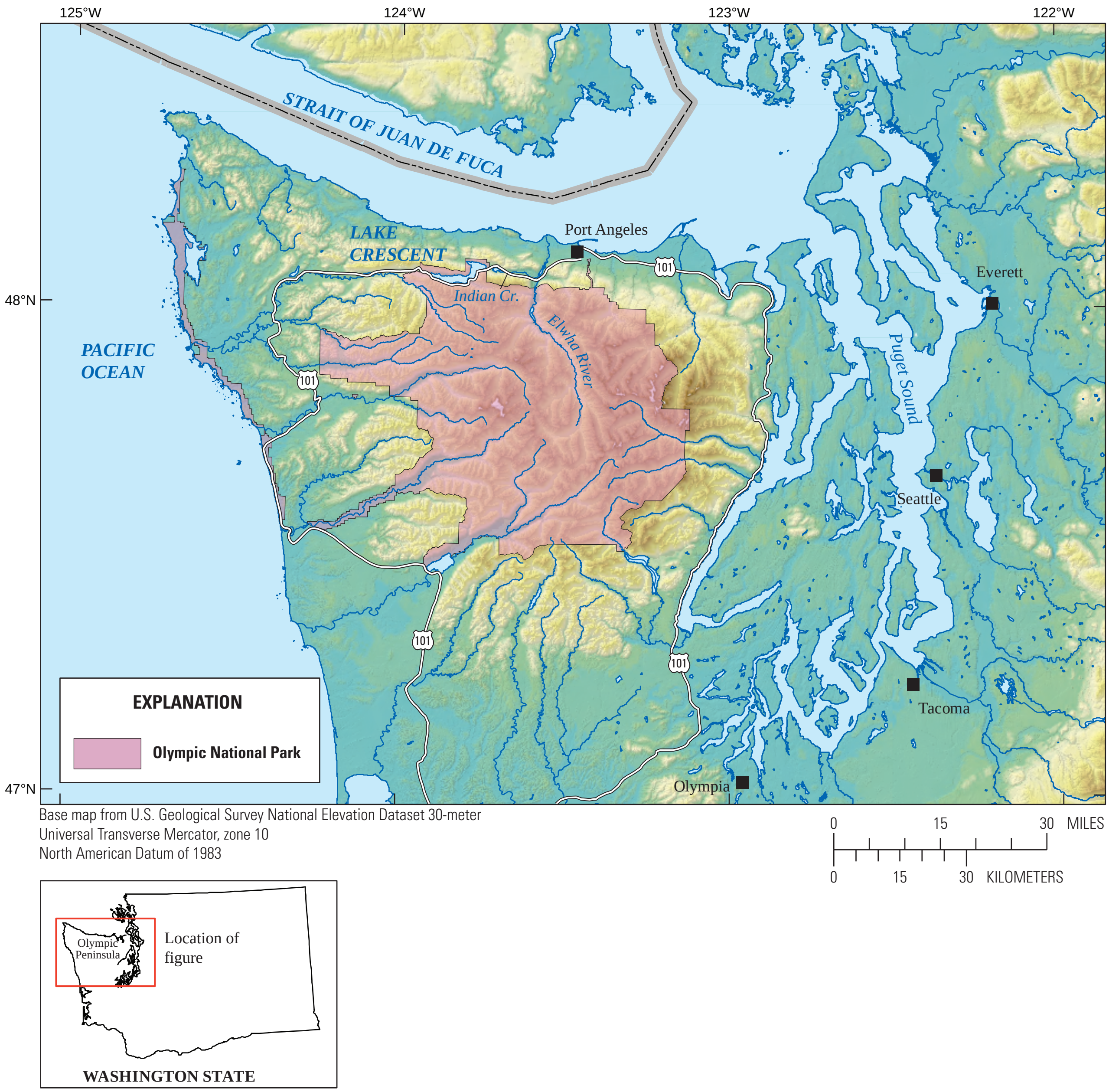


Figure 1. Location of Lake Crescent and Olympic National Park, western Washington.

In 2002, ONP convened a scientific review panel consisting of ONP scientists, U.S. Geological Survey (USGS) hydrologists, and other scientists to discuss current conditions and potential anthropogenic affects on the quality of water and fisheries of Lake Crescent. The panel also addressed issues of management, habitat protection and restoration, and research needs for the lake. Protection and management of the water quality and habitat of Lake Crescent, especially for endemic and unique aquatic species, are priorities for ONP.

Improved understanding of the nutrient dynamics of Lake Crescent was identified as a significant need for effective management of Lake Crescent. Nutrient enrichment is consistently ranked as one of the top causes of water resource impairment nationally (U.S. Environmental Protection Agency, 2000). Nutrient dynamics and, in particular, nutrient limitation is widely recognized as critical to understanding nutrient-poor ecosystems and the onset of eutrophication (Goldman, 1988; Wetzel, 2001). Nutrients from agricultural and urban sources often are considered a primary cause of eutrophication in aquatic ecosystems (Carpenter and others, 1998); however, these sources are largely absent in the Lake Crescent watershed. In the absence of widespread human land use activities that contribute large amounts of nutrients, small nutrient sources such as vehicle exhaust, litterfall

(Triska and others, 1984), and nitrogen fixing red alder (*Alnus rubra*) (Compton and others, 2003) may provide a larger fraction of input of the total nitrogen to Lake Crescent than is usual for other lakes. In addition, atmospheric deposition is widely recognized as a major source of nutrients to lake systems (Bergstrom and others, 2005; Fenn and others, 2011).

Following the scientific review panel and documentation written by ONP scientists, a conceptual model was developed which indicated that the system was oligotrophic, had primarily natural inputs of nutrients from sources like precipitation, streamflow, and organic matter, and may be vulnerable to anthropogenic activities, particularly onsite septic system use along the shoreline (fig. 2). In response, the USGS in cooperation with ONP, conducted a study to identify and quantify estimates of loadings and losses of nutrients to and from the lake. Field data collected for this investigation included field measurements needed to construct a water budget for the lake along with water-quality samples to determine the input of nutrients through those sources. Additional information for several sources of nutrients to Lake Crescent was estimated from values reported for similar settings. Information from this study will assist park managers in making decisions concerning the activities of park visitors and residents within the watershed.

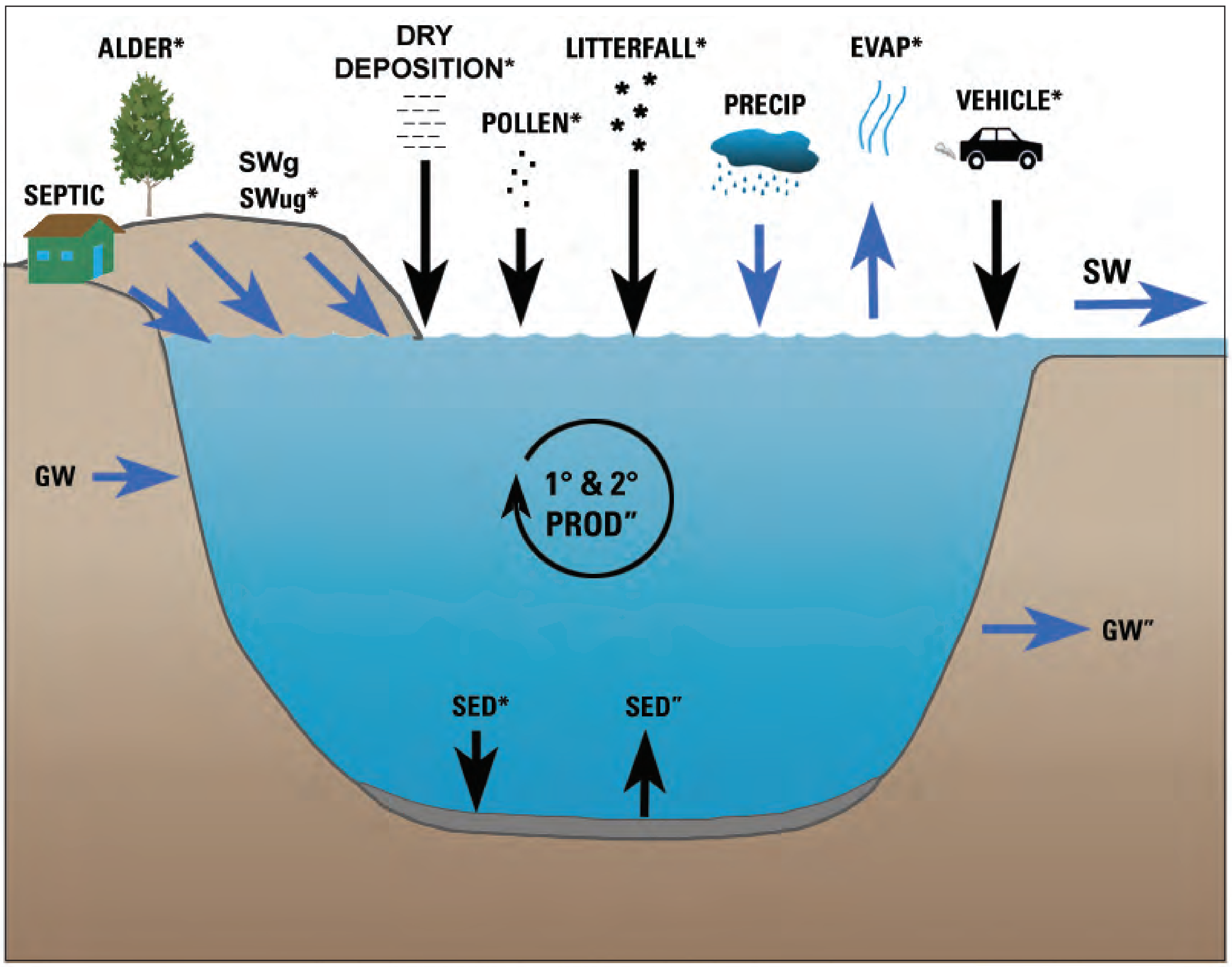


Figure 2. Pathways of the nutrient and hydrologic budgets for Lake Crescent, Washington. Blue arrows are hydrologic pathways; black arrows are particulate pathways; asterisks (*), components estimated based on literature values; quotes ("), components not measured or estimated in this study. All other components were directly measured as part of this project. GW, groundwater; SED, sedimentation; SEPTIC, septic tank inputs; ALDER, nitrogen fixation inputs from alders; SWg, surface water from gaged streams; SWug, surface water from ungaged streams; POLLEN, pollen inputs from trees; LITTERFALL, leaf-litter from waterhsed trees; PRECIP, precipitaiton; EVAP, evaporation; VEHICLE, automobile emissions; 1° and 2° PROD, primary and secondary productivity.

Purpose and Scope

This report presents an evaluation of major sources and sinks of nitrogen and phosphorus used to construct a mass budget for these nutrients. A conceptual model was assembled that classified the likely sources of nutrient inputs into Lake Crescent. These included commonly described and studied sources, such as dry deposition, rainfall, surface water and groundwater, as well as sources particular to Lake Crescent, such as pollen from coniferous trees, vehicle exhaust from adjacent Highway 101, and local septic systems. Data collected from the study area used to construct the water and nutrient budgets for Lake Crescent were collected from 2006 to 2008. Additional information used in the evaluation of sources and sinks of nutrients were values obtained from various literature sources. This report also describes the quality of water in streams entering Lake Crescent during 2006 to 2008, summarizes ancillary data used in constructing the budgets, and identifies potential nutrient sources. The objective of the study was to describe and quantify the major contributions of nutrients to Lake Crescent in order to better facilitate management of nutrient issues in the watershed.

Description of Lake Crescent and the Watershed

Lake Crescent is located along the northern boundary of the rugged mountainous core of ONP about 24 km west of Port Angeles on U.S. Highway 101 (fig. 1). Lake Crescent is a deep lake with exceptionally clear and nearly pristine water. The elongated lake is 17.7 km long and typically varies from 1 to 4 km wide. Highway 101 borders the south shore of the lake and provides a transportation corridor from the populous regions east of the lake to the Pacific Ocean. The lake occupies an area of 2,030 ha with the surrounding watershed of 11,000 ha; making the lake area approximately one-fifth of the entire watershed. The elevation of Lake Crescent is 176.4 m, with a mean depth of 101 m, and a maximum depth of 190.5 m (Wolcott, 1973; Pierce, 1984). About 50 percent of the surface area overlays waters deeper than 95 m (fig. 3).

The crescent shape of the lake is formed by two elongated subbasins that are connected through a narrow reach. The western basin is in a steep V-shaped valley bounded by east-west trending ridges that rise to elevations of 762–1,219 m above NAVD 88. Slopes in excess of 30 degrees cover as much as 50 percent of the valley walls. Steep valley sides extend below the lake surface creating a precipitous shoreline along much of the roughly 40 km perimeter of the lake. Shallow beach areas are only near the lake outlet (Lyre River), at Barnes Point, and at the east and west ends of the lake. Geographic names and sampling locations within the watershed are shown in figure 4.

Geologic and Glacial History

Lake Crescent is situated along the northern extent of the geologically complex Olympic Peninsula. The steep mountainous features of this area were formed from a combination of tectonic processes at a convergent continental margin over much of the last 15 million years, and more recently by glacial sculpting and scouring during the Pleistocene period (1 million to 11,000 years ago). The elongated lake consists of two connected basins that occupy deep, narrow troughs formed between west-northwest trending blocks of steeply dipping and thrust-faulted marine sedimentary and basaltic rocks (Schasse, 2003; fig. 5). The western lake basin follows the Crescent fault from Fairholm to Barnes Point, and the eastern basin follows the Boundary Creek Fault along its northern shore line (Schasse, 2003; fig. 5). Measurement of the dip in the bedding planes of thrusted blocks that make up the valley walls of Lake Crescent indicated that the blocks have been tilted 50–75 degrees from their original depositional position. Glacial recessional outwash deposits are predominant in the far western end of the lake, whereas landslide deposits composed of clay, silt, sand, gravel, and larger rocks border the northeastern end (fig. 5).

Following retreat of the glaciers, the Lake Crescent valley filled with water forming a large ancestral lake that emptied into Indian Creek and then into the Elwha River (fig. 1). Several large landslides split this ancestral lake into Lake Crescent and Lake Sutherland (Logan and Schuster, 1991). The last of the large landslides left a rock-debris dam that raised the surface of Lake Crescent 24 m higher than Lake Sutherland (Logan and Schuster, 1991) and rerouted the outflow to the Lyre River, which drains northward into the Strait of Juan de Fuca.

Climate

The Lake Crescent area generally has a moderate, maritime climate that lacks the extremes in air temperature, precipitation, and snowfall that characterize the higher elevations and western slopes of the Olympic Mountains (National Park Service, 2012). Summers are mild with high temperatures ranging from 65 to 75°F (18.3 to 23.9°C). Winters are wet with temperatures ranging from about 33 to 48°F (1 to 9°C). The driest months of the year are July through September. Precipitation is variable across the watershed, west to east across the surface of Lake Crescent, and varying with elevation into the upper watershed areas, particularly in the Barnes Creek drainage basin. Average precipitation varies from about 190 cm (75 in.) at the west end of the lake to 140 cm (55 in.) at the east end (National Atlas of the United States, 2011).

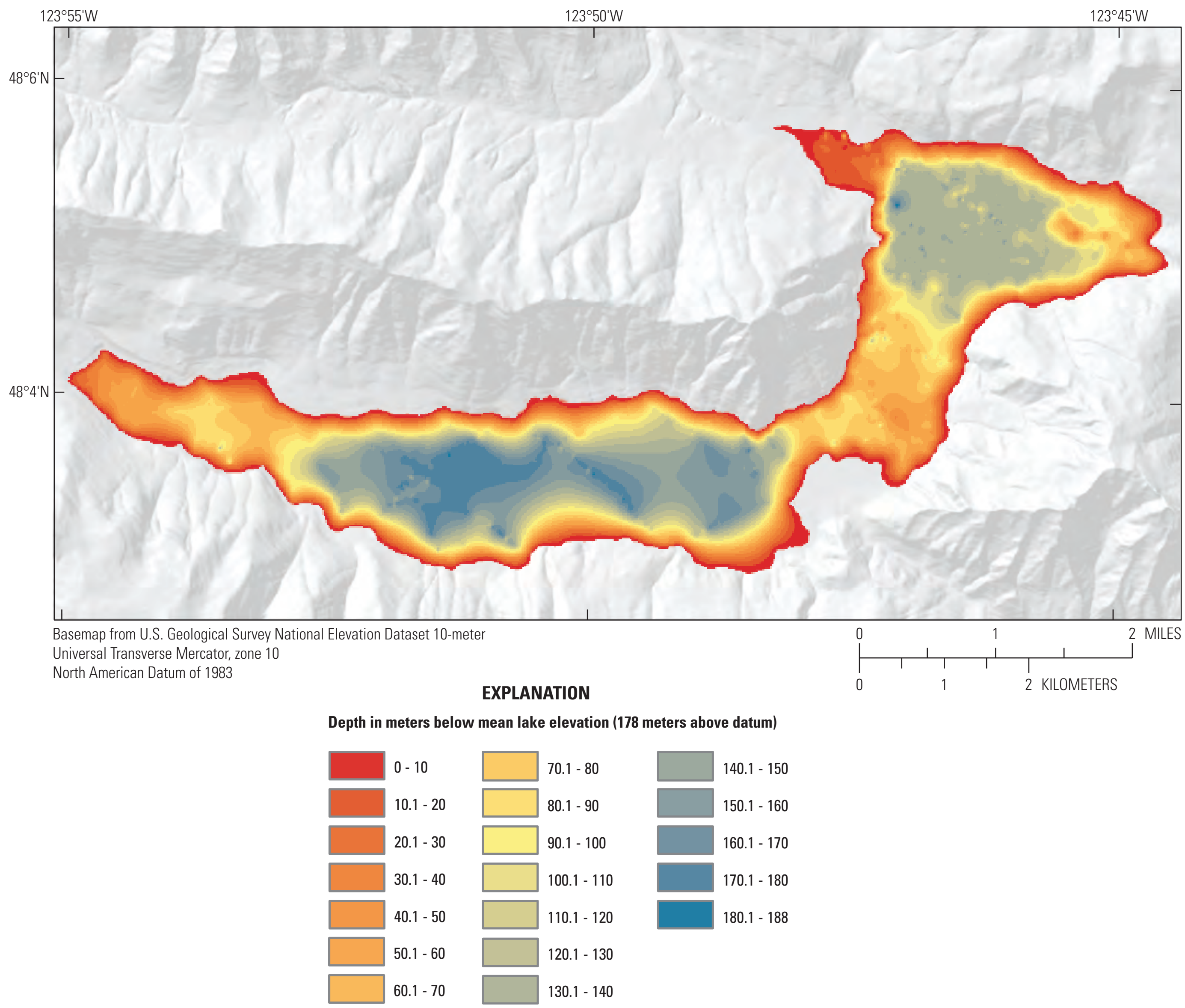


Figure 3. Bathymetry of Lake Crescent, Washington, 2008. Bathymetry provided by Olympic National Park.

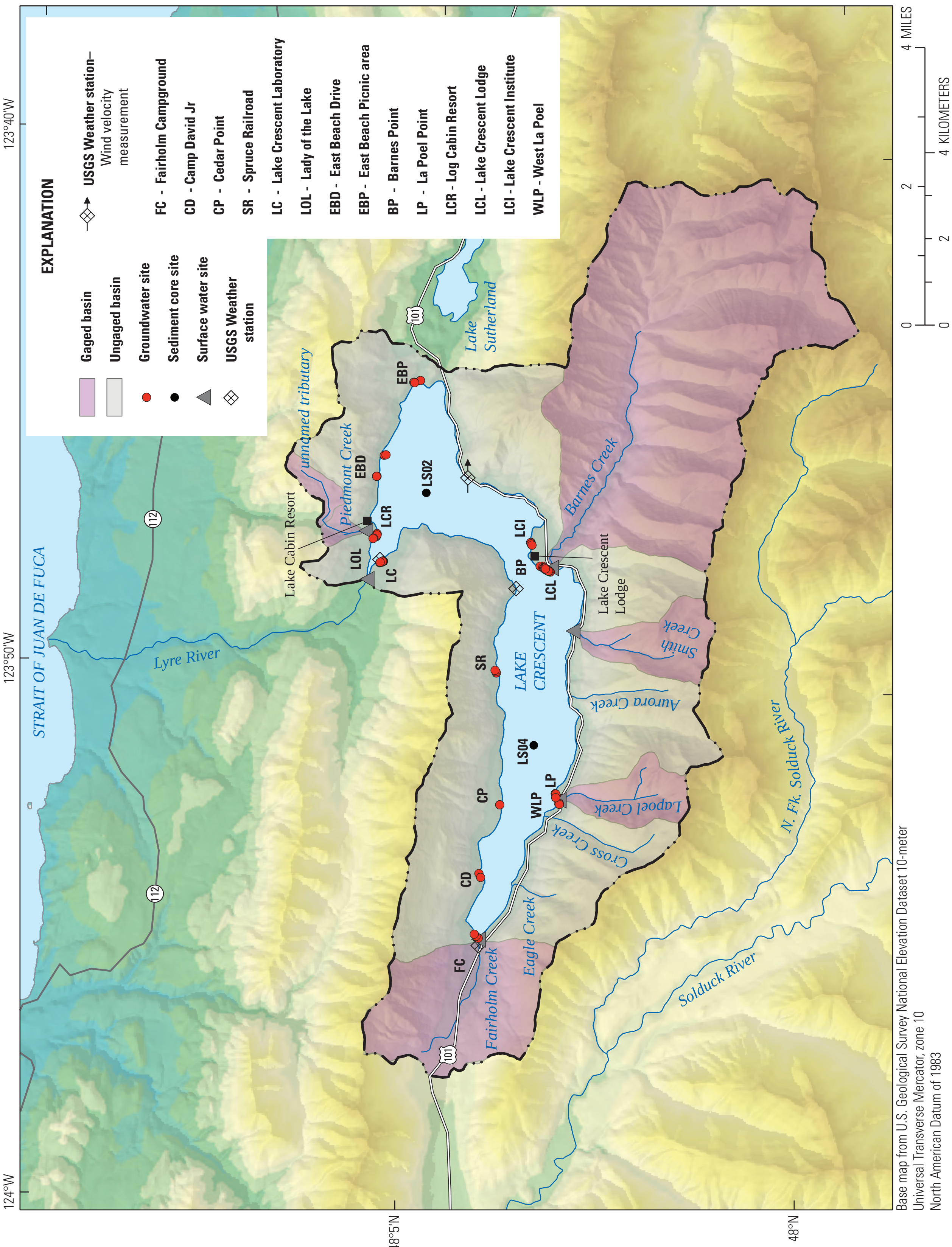
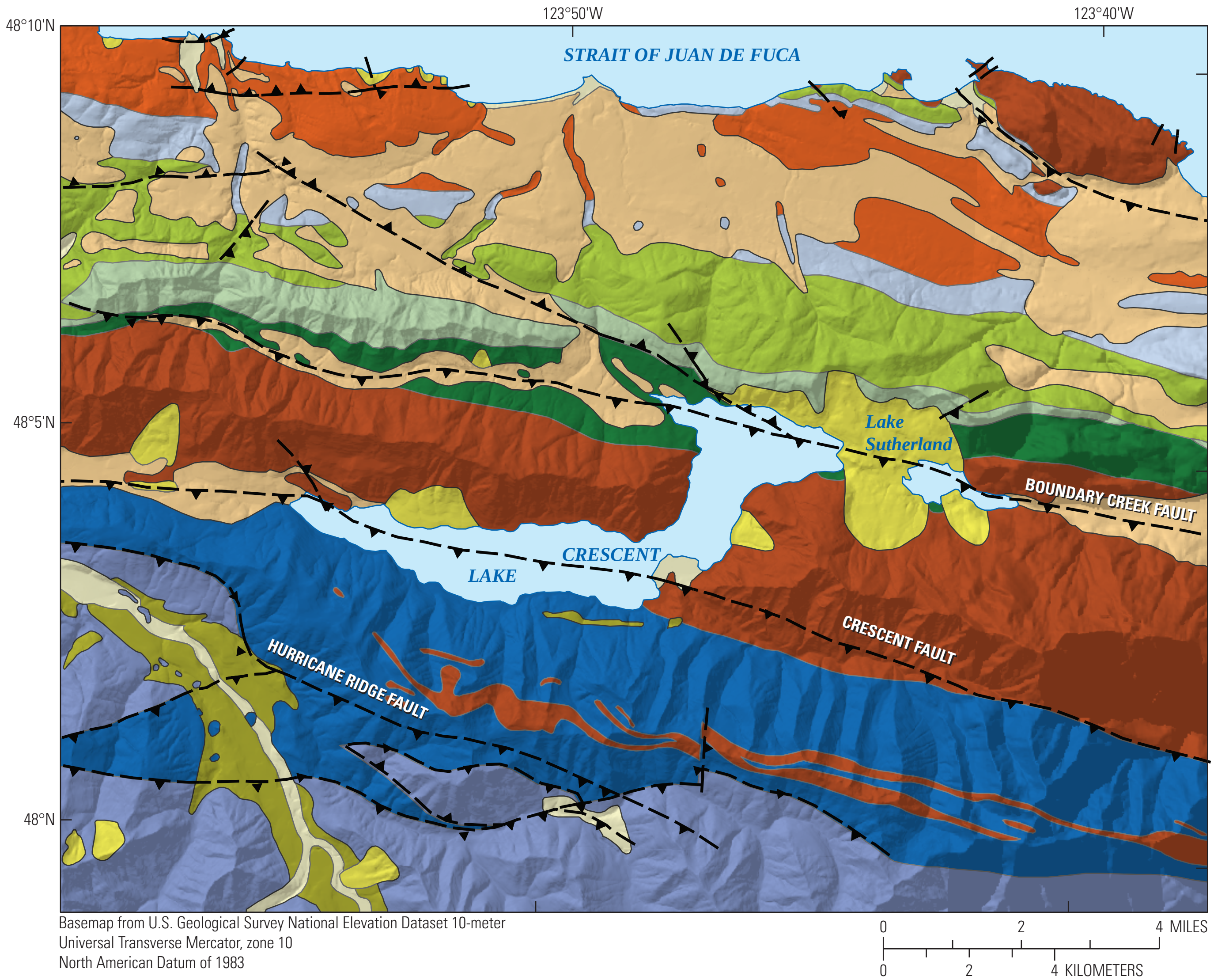


Figure 4. Geographic reference points and sampling sites, Lake Crescent, Washington.



Basemap from U.S. Geological Survey National Elevation Dataset 10-meter
Universal Transverse Mercator, zone 10
North American Datum of 1983

EXPLANATION

Quaternary surficial deposits

- Recent alluvium and beach deposits
- Landslide deposits
- Vashon outwash and till
- Alpine outwash and till

Tertiary sedimentary and volcanic rock

- Pysht formation
- Makah formation
- Hoko river formation
- Lyre formation
- Aldwell formaton
- Crescent formation
- Blue mountain unit
- Olympic subduction complex

Thrust fault

Figure 5. Simplified geology of Lake Crescent, Washington.

Land Cover and Land Use

Conifer trees dominate the vegetation of the Lake Crescent watershed; however, the predominant species and the abundance of deciduous species changes with elevation. Below about 610 m elevation, Douglas fir and western hemlock dominate, but western red cedar, grand fir, red alder, big leaf maple, Pacific madrone, Pacific dogwood, and Douglas maple also are at lower elevations. Red alder trees are prominently along the shoreline of Lake Crescent in areas where disturbance and development have occurred. The extensive forests of the Olympic Peninsula have been an economic resource since the mid-1800s with the establishment of sawmills and the exportation of wood from communities such as Port Angeles (Kirk and Alexander, 1990). Prior to the incorporation of ONP into the National Parks system in 1938, logging likely occurred within the Lake Crescent watershed or near the lake itself (Pierce, 1984; Rector and Hallock, 1991).

Shoreline Development

Although shoreline alteration, logging, and mining have occurred (Rector and Hallock, 1991), Lake Crescent and its watershed remain largely undeveloped. In 1989, about 100 houses were on the lakeshore, with about 14 houses occupied year-round (Rector and Hallock, 1991). As of 2002, 121 private residences, of which 19 were occupied year-round, 3 large resort facilities, a National Park Service campground, several picnic areas, and 3 modern boat launch facilities occupied the shoreline and provided access to the water (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002). The lakeshore is partially sewered and numerous storm drains, particularly off U.S. Highway 101, flow into the lake (Rector and Hallock, 1991).

During the 2000 season, there were 12,730 visitor-use days at Fairholm Campground. (A “visitor-use day” is defined as one person entering the park for any part of the day. For campgrounds, this number is primarily based on registrations at a given campground, presumably with intent to stay overnight.) Four septic drain fields service the campground and the Fairholm store. During 2000, use of Lake Crescent Lodge, Log Cabin Resort, and Rosemary Inn was 15,017, 13,247, and 5,730 visitor-use days, respectively. Virtually all homes and developments use either onsite septic systems or outhouses, except the Lake Crescent Lodge complex on Barnes Point and the Log Cabin Resort. These facilities use a 25,000-gallon-capacity sewage treatment plant and a package plant, respectively (Mike Kalahar, Olympic National Park, oral commun., March 2006, John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002).

During the low-use winter months, sewage from Barnes Point facilities is collected in a septic tank and pumped to Bovies Meadow drainfield behind the Lake Crescent Lodge. During the summer, sewage is treated at the plant and effluent released to the Bovies Meadow drainfield, and solids are removed offsite mechanically. The Log Cabin Resort package plant releases effluent through a mounded drain field near the East Beach Road. An outflow pipe near the mouth of Piedmont Creek (fig. 4), was installed during construction and monitored during its first year of use, but monitoring of the outflow pipe revealed no effluent release, and subsequent monitoring was discontinued (Mike Kalahar, Olympic National Park, oral commun., March 2006; John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002). There is no known direct release of effluent from these treatment plants to Lake Crescent.

Built in the 1910s, the Rosemary Inn resort served for decades as private lodging for vacationers in the Barnes Point area. Seeking to improve services to the public and find an adaptive re-use of this site, in 1987, Olympic National Park invited NatureBridge to establish an educational institute on Barnes Point. In 1987, the Olympic Park Institute was established by NatureBridge as an educational institute to improve public services and provide science education about ONP. More than 6,000 grade school students visit annually for residential field science programs.

Hydrology

The Lake Crescent watershed encompasses about 13,000 ha with 32 tributary inflows into the lake and one outflow from the lake. The Lake Crescent watershed is on the margin of the rain shadow created by the bulk of the Olympic Mountains. Many of the tributaries to Lake Crescent are intermittent and tend to be short in length, high gradient over steep colluvial material, and because they drain areas with little groundwater storage are dry in late summer (Walters, 1970). Of these tributaries, only 5–6 were substantial, (greater than 0.03 m^3 [or 1 ft^3/s]) and perennially flowing, and these perennial streams were measured in this study. (Note: Although metric units are used predominantly in this report, water management parameters of flow and volume also are provided in cubic feet per second [ft^3/s] and acre-feet [acre-ft], respectively, because these units are most common to local water managers, and in this study, are generally more appropriately matched to the scale of measurements presented.)

During summer, flow in some creeks is not present at the shoreline of the lake, but significant flow can be observed several hundred meters upstream, indicating that drainage from these creeks discharges to the lake as underflow below the creek bed surface. Barnes Creek is the largest of the tributaries in area with a drainage area of 4,066 ha and mean discharge of 1.75 m^3 (61.7 ft^3/s). The next largest drainage areas are Fairholm Creek (986 ha), Smith Creek (356 ha), Lapoel Creek (298 ha), Cross Creek (238 ha), Lake Crescent Tributary near Piedmont (204 ha), Aurora Creek (149 ha), Eagle Creek (148 ha), and Piedmont Creek (137 ha) (table 1).

The Lyre River exits the lake at the northwest corner and flows north to the Strait of Juan de Fuca. Mean discharge was 6.06 m^3 (214 ft^3/s) for the Lyre River during the 2006–07 study.

Groundwater in the Lake Crescent area is not plentiful and is limited to areas of relatively thick accumulations of unconsolidated sediments, such as at Barnes Point and the Fairholm shoreline. Groundwater is used as a source of water in these areas. Most of the rock surrounding Lake Crescent is marine basalts and sedimentary rocks which may yield groundwater where fractures have not been occluded by weathering products; however, no wells were drilled in these rocks. Groundwater springs at various locations have been used as water supplies in the past.

Table 1. Hydrology of major tributary drainage basins in the Lake Crescent watershed, Washington, 2006–07.

[**Abbreviations**: mi^2, square mile; ha, hectare; ft^3/s, cubic foot per second; acre-ft/ha, acre-foot per hectare measured; acre-ft/mi^2, acre-foot per square mile measured; acre-ft/ha NHDPlus, acre-foot per hectare from National Hydrologic Dataset-Plus, version 2; GIS, geographic informations system; NA, not applicable; –, no data]

Station No.	Site name	Drainage area		Site monitored for this study	Period of record	Mean discharge for period of record (ft^3/s)	Runoff per drainage area per year		
		(mi^2)	(ha)				(acre-ft/ha)	(acre-ft/mi^2)	(acre-ft/haNHDPlus)
12043445	Fairholm Creek at Fairholm	[1]3.81	986	Yes	April 21, 2006–June 1, 2007; June 17, 2007–June 26, 2007	2.17	449	1.74	NA
NA	Eagle Creek	[2]0.6	148	No	–	–	–	–	NA
12043450	Cross Creek near Fairholm	[3]0.92	238	No	–	–	–	–	[5]614
12043454	Lapoel Creek near Fairholm	[1]1.15	298	Yes	April 22, 2006–August 1, 2007	5.01	3,236	12.5	–
NA	Unnamed tributary near Lapoel Point	[4]1.8	464	No	–	–	–	–	[5]4,365
NA	Aurora Creek	[2]0.6	149	No	–	–	–	–	[5]4,077
12043467	Smith Creek near Fairholm	[1]1.38	356	Yes	April 6, 2006–September 30, 2007	2.29	1,213	4.7	[5]465
12043470	Lake Crescent Tributary near Piedmont	[3]0.79	204	No	–	–	–	–	NA
12043530	Barnes Creek near Piedmont	[3]15.7	4,066	Yes	April 22, 2006–June 26, 2007	61.7	2,990	11.6	–
12043950	Piedmont Creek at Piedmont	[4]0.53	137	Yes	April 21, 2006–June 26, 2007	2.61	3,960	15.3	–
12044000	Lyre River at Piedmont	[4]50.2	13,000	Yes	October 1, 1917–September 30, 1927; April 20, 2006–February 4, 2008	214	2,490	9.61	–

[1] From U.S. Geological Survey, 2012 (http://waterdata.usgs.gov/wa/nwis).

[2] From Pierce, 1984.

[3] From Richardson, 1962.

[4] From GIS coverages.

[5] Significant underflow was observed at these sites; therefore runoff per area from NHDPlus hydrologic model also was considered.

Previous Limnology and Water-Quality Studies

Limnology and chemical data for Lake Crescent are available from only a few studies. Scientists at ONP compiled these data and information from previous investigations and summarized them into a reference document (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002) for the scientific review panel when it met to discuss current conditions and potential anthropogenic effects on the quality of water and fisheries.

Trophic Status

The trophic status of Lake Crescent is consistently described as oligotrophic (low level of primary productivity) or ultra-oligotrophic using measures of water clarity (Secchi-disk depth), nutrient concentrations, or chlorophyll *a* concentrations. The trophic status of the lake was classified using the Trophic Status Index (TSI; Carlson, 1977), which considers values less than 40 to be oligotrophic. Using a Secchi-disk depth of 18.3 m in his August 1982 study of Lake Crescent, Pierce (1984) calculated a TSI of 18. Boyle and Beeson (1991) identified the lake as an oligotrophic system on the basis of TSI values of 13–42, 17–26, and 39 using 1986–87 measurements of total nitrogen concentrations. At that time, nitrogen ranged from 0.007 to 0.116 mg/L, Secchi-disk depths ranged from 12 to 22 m, and chlorophyll *a* concentrations ranged from 0.078 to 0.673 µg/L. Smith and others (2000) also assigned an oligotrophic classification on the basis of TSI values of 20 and 24 using TP concentrations of about 3 µg/L, and chlorophyll *a* concentrations of 0.5 µg/L. The investigators, however, qualify these TSIs because the concentrations were near the analytical detection limits (DLs) of the laboratory.

Water Temperature and Dissolved Oxygen

The few water-temperature and dissolved-oxygen profiles made of Lake Crescent by Kemmerer and others (1924), Pierce (1984), Boyle and Beeson (1991), Smith and others (2000), and ONP staff in 1960 and 2000–01, are described in ONP's 2002 Summary Report. Pierce's (1984) monthly data collected during 1982–83 to a depth of 131 ft (40 m) showed Lake Crescent to be a monomictic lake (water layers mixing from top to bottom once each year) with summer through early autumn stratification. Winter through spring mixing seems to extend to at least 50 m; however, it is not known if the deepest parts of the lake completely mix (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002). The earliest and deepest profiles were those by Kemmerer and others (1924). Their profiles from August reached a depth of 574 ft (175 m) and showed a stratified lake having an epilimnion (surface layer) extending to about 66 ft (20 m), a metalimnion (middle layer) from 66 to 164 ft (20 to 50 m), and a hypolimnion (bottom layer) at least 410 ft (125 m) thick. The dissolved-oxygen profile showed relatively constant concentrations with depth through the epilimnion and increasing concentrations through the metalimnion in the shape of an orthograde curve. Monthly water-temperature profiles measured from May through September 1998 by Smith and others (2000) indicated an epilimnion that ranged from about 12 to 20 m, and a metalimnion to about 30 m. Corresponding dissolved-oxygen profiles also described orthograde curves that are characteristic of oligotrophic lakes (Wetzel, 2001).

Scientists from ONP monitored water temperatures during 1999–2001 in Barnes Creek, at the lake outlet just upstream of the Lyre River Bridge and in the Lyre River. These data indicated that the mean daily temperature of Barnes Creek was cooler than the water at the outlet and in the Lyre River, and temperatures at the lake outlet matched surface temperatures (Meyer and Fradkin, Olympic National Park, written commun., January 2002).

Water-Quality Characteristics and Nutrients

Near-surface values of pH and specific conductance vary by study, location, and date of measurement. The ONP 2002 Summary Report indicates that pH values average 7.22 units and range from a low of 6.38 units to a high of 8.58 units for measurements at as many as seven locations during studies conducted by Boyle and Beeson (1991) and ONP staff (T.A. Hagan and J. Aho, Olympic National Park, written commun., 1989; Meyer and Fradkin, Olympic National Park, written commun., January 2002). For these same data sets, specific conductance averaged 120 µS/cm and ranged from 100 to 160 µS/cm. These data indicate mostly neutral pH conditions and water with low concentrations of dissolved inorganic constituents.

In a 1998 trophic assessment, Smith and others (2000) determined that nutrient concentrations at two sampling locations ranged from less than 0.003 to 0.0082 mg/L for TP, and from less than 0.01 to 0.41 mg/L for TN. Because of the pristine nature of Lake Crescent, Smith and others (2000) recommended setting a TP criterion to the Cascades ecoregion/ultra-oligotrophic action value of 0.004 mg/L (4 µg/L). Similarly low concentrations of TP (many of which are less than laboratory DLs) in samples collected during 2000–2001 at 4 lake sites and 2 two stream sites (Lyre River and Eagle Creek) are listed in the ONP 2002 Summary Report. Median TP concentration for these samples is 0.0075 mg/L and ranges from 0.003 to 0.021 mg/L. Median total dissolved nitrogen is 0.001 mg/L and ranges from non-detected (less than 0.001 mg/L) to 0.021 mg/L.

Using the 10-year mean discharge for the Lyre River and the volume of the Crescent Lake watershed, Pierce (1984) estimated an exchange rate for the lake of 9.8 years per cycle. Pierce (1984) considered the rate to be sufficient for available nutrients to be completely cycled within the lake; however, he noted that the hypolimnion might act as a nutrient sink during much of the year. Indeed, ONP's 2002 Summary Report recreates the only known deep profile of nitrate concentrations, which shows nitrate is essentially absent at the water surface, but increases in concentration to 0.04 mg/L at a depth of 590 ft (180 m) in the hypolimnion. These data also suggest that the hypolimnion acts as a nitrogen pool during lake stratification (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002). Nitrogen was indicated as the limiting nutrient for primary production by Boyle and Beeson (1991), who reported ratios of TN to TP concentrations of less than 10. A calculated mean total dissolved nitrogen to total phosphorus ratio of 0.85 was derived by Peter Nelson, Oregon State University, written commun. (2002). Nelson concluded that by being substantially less than the Redfield ratio of 16:1, the calculated ratio strongly indicated nitrogen as the limiting nutrient.

As part of their study, Boyle and Beeson (1991) assessed nutrient enrichment from non-point sources at six near-shore sites using TSI calculated with chlorophyll *a*, periphyton community growth and structure on artificial substrate, an algal assay with *Selenastrum capricornutum*, and lake water from each site. Test results indicated that the periphyton community in Lapoel Creek has greater densities and productivity and less diversity than communities at the other five sites. Results also showed that water from the Lapoel Creek site and, to a lesser extent, the Barnes Point site, stimulated algal growth. The researchers suggested that leachate from old landfills or a septic system from a resort that was active from the 1930s to early 1950s was having a local effect on the algal communities off Lapoel Point. However, they concluded that there was no evidence for non-point nutrient enrichment at the near-shore sites despite the apparently different conditions at the Lapoel site.

Aquatic Ecology

Lake Crescent supports a cold-water fishery consisting of five native species—Kokanee (*Oncorhynchus nerka*), which is a resident sockeye salmon, prickly sculpin (*Cottus asper*), pygmy whitefish (*Prosopium coulteri*), and two unique forms of trout—the Beardslee rainbow trout (*Oncorhynchus mykiss*) and Crescenti cutthroat trout (*Oncorhynchus clarki*). Of particular interest to the ONP are the two unique trout species. These fish presumably originated from the anadromous forms of the species; however, the landslide that separated Lake Crescent from the Elwha River drainage isolated some of these trout from the parent stocks. These isolated populations of rainbow and cutthroat trout subsequently adapted into the Beardslee and Crescenti trout, respectively (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002). Historically, Pacific lamprey also might have been in the lake, but no lampreys have been seen in recent years (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002). Fish have not been stocked since 1989 (Rector and Hallock, 1991); however, past hatchery programs and releases of native and non-native trout meant to enhance recreational fishing did occur over a period of 62 years (Pierce, 1984). In addition to these fishes, freshwater mussels and crayfish are in Lake Crescent (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002).

Lake Crescent also contains various aquatic plants, algae, and cyanobacteria. Three species of macrophytes—western quillwort (*Isoetes occidentalis*), water lobelia (*Lobelia dortmanna*), and Illinois pondweed (*Potamogeton illinoensis*) are considered rare, sensitive, or special by the Washington State Natural Heritage Program and ONP (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002).

The periphyton algal communities of Boyle and Beeson's (1991) artificial substrates were typical of cold, oligotrophic or meso-oligotrophic water, and were composed of green algae (Chlorophyta), yellow-brown algae (Chrysophyta), dinoflagellates (Pyrrophycophyta), and diatoms (Bacillariophyceae class of Chrysophyta; Bacillariophyta), as well as cyanobacteria such as *Oscillatoria* sp. and *Lyngbya* sp. Rosenberger and others (2008) used data on algal biomass, macroinvertebrate communities, and periphyton communities in a study of effects of shoreline development on nearshore environment of Lake Crescent. The data showed that the aquatic communities shifted in composition to more detritivores and filamentous green algae at developed sites, and substantial nearshore changes in the basal food web are detectable even with low levels of shoreline development (Rosenberger and others, 2008).

Methods of Investigation

Geographic Information System Methods

Several tools and existing databases within GIS software were used during this study to arrive at some input values discussed below. Basin delineations upstream of the sampling sites for six basins (Fairholm Creek, Lapoel Creek, Smith Creek, Barnes Creek, Piedmont Creek, and the Lyre River (the entire Lake Crescent watershed) were created by using the Washington StreamStats web application (U.S. Geological Survey, 2010a). The surficial geology for the study area was compiled and simplified from the digital

1:100,000 scale geologic map of the Port Angeles quadrangle (Schasse, 2003). The area around Lake Crescent, classified as developed, was computed using the impervious surface land cover classification from the National Land Cover Dataset 2001 (Homer and others, 2007). A 100 m buffer was created around the lake polygon using a GIS. A developed land cover classification was extracted within the buffer to calculate the buffer area. A smaller 20-m buffer area around the lake, classified as undeveloped, also was calculated using the same land cover dataset.

The percentage of red alder, broadleaf, and coniferous trees within the 100-m buffer around Lake Crescent was calculated using a digital vegetation classification of dominant tree and plant species grids of the study area supplied by the ONP (Katherine Beirne, Olympic National Park, written commun., January 2008). It should be noted that there is significant uncertainty in the estimate of nitrogen contribution from alder trees. Specifically, the estimate of alder abundance and density, and the somewhat arbitrary designation of what buffer width (100 m in this case) to consider as contributing to the lake versus contributing to groundwater, are areas of considerable uncertainty in the alder estimate. Although alder trees beyond the buffer are also assumed to be a nitrogen source, it is expected that this upslope production would be consumed locally or reflected in the shallow groundwater concentrations. It could be argued that alder not be included separately, as their total contributions should be reflected in the groundwater sampling. However, because of the great abundance and density of alder immediately along the rocky shoreline it was decided that this 'alder proximity' needed special consideration in the budget.

The length of U.S. Highway 101 within the 100-m buffer of the lake was digitized from the USGS 1:24,000 topographic quadrangles of the lake. The highway segments that were within the 100-m buffer were extracted and summed to calculate the length. The volume of Lake Crescent was calculated using a digital 10-m resolution depth grid of the lake (supplied by National Park Service) and the lake surface elevation was extracted from the National Elevation Dataset (U.S. Geological Survey, 2010b) with the same 10-m resolution. A lake bathymetric elevation GIS grid (fig. 3) was created by subtracting the depth grid from the lake surface grid.

Water-Quality Data Collection

Field data collection began in 2006 and focused on defining the hydrology of the watershed and on key components for constructing a nitrogen balance over an annual cycle. The key components for the balance included measurements of streamflows and nutrient concentrations in the major tributaries to the lake (fig. 4), collecting and compiling data on the two sewage treatment facilities, atmospheric wet and dry deposition, and groundwater. Estimates of nutrient cycling and nutrient loss involved sampling from the water column of the lake, at the lake outlet (Lyre River), and coring of bottom sediments for chemical and age-dating analyses. Ancillary data to assist in constructing and interpreting the balance included lake levels, land use, vehicular traffic, and potential contributions from onsite septic systems, pollen, and nitrogen fixing vegetation (in particular, red alder).

The surface water streamflow-gaging stations also served as locations for collection of monthly water-quality samples. These monthly samples were used to characterize the physical and chemical properties of the water and determine nutrient concentrations. Monthly water samples also were collected from two lake sampling locations; typically at five depths at each location. Near each of the two lake-sampling locations, a deep (greater than 1 m) bottom-sediment core was obtained for estimating sedimentation rates and losses of nutrients from the water column. Two new weather stations were installed at various locations along the lakeshore, in addition to the existing station at the Lake Crescent Laboratory (fig. 4) to obtain continuous climatic data, used primarily to estimate evaporation from the lake surface.

Additionally, ONP staff contributed limnological data consisting of quarterly depth profiles of dissolved-oxygen concentrations, water temperature, specific conductance, and pH. The profile data were collected with a YSI model 600 data sonde.

Chemical analyses of nutrient concentrations in water (as TN, TP, and dissolved nitrate [NO_3]) in this study were provided by the Oregon State University Cooperative Chemical Analytical Laboratory (CCAL). This laboratory is approved by the USGS Branch of Quality Systems for USGS project work, and specializes in low nutrient concentrations in natural waters. Analytical methods used by CCAL primarily follow those published in Eaton and others (2005). Descriptions of these standard methods (SM), along with CCAL modifications, are available from Cooperative Chemical Analytical Laboratory (2012). Analyses of surface-water and groundwater samples consisted of low-level determinations of filtered nitrite plus nitrate nitrogen (hereafter referred to as nitrate) by automated cadmium reduction (SM4500-NO_3 F); whole-water (but occasionally filtered-water) TN by persulfate digestion and cadmium reduction (SM4500P-J and SM4500-NO_3 F); and whole-water phosphorus (referred to as TP) by persulfate digestion (SM4500P-B modified with a 60-minute microwave digestion on 50-mL aliquot) and colorimetric ascorbic acid reduction (SM4500-P E). Several samples also were analyzed for filtered orthophosphate phosphorus (SM4500P-E) by colorimetric ascorbic acid reduction.

Hydrologic Data Collection

Streamflow-gaging stations for recording water-level stage were established near the mouths of five tributaries (Fairholm, Lapoel, Smith, Barnes, and Piedmont Creeks) and also on the Lyre River. Collectively, the five creek basins (fig. 4) account for 53 percent (5,840 ha) of the 11,000 ha in the terrestrial Lake Crescent watershed. Stage readings were obtained with data-logging devices (water level data logger, Onset Corporation, 2000 version) equipped with pressure sensors for measuring the water level in the stream, and a separate logger placed at 2 m height for measuring barometric pressure and correcting local barometric pressure. Logging intervals were set to 15 minutes. Instantaneous discharges were measured at each of the gaging station sites to develop stage-discharge relations, which were used to create time-series records of daily mean discharges.

Water-Quality Data

The selection and preparation of equipment used in water-quality sample collection and processing generally followed standard USGS practices as described in U.S. Geological Survey (variously dated), hereafter referenced as Field Manual. Prior to going to the field, sample-collection bottles, compositing containers, caps and nozzles used in the USGS DH-81 depth-integrating sampler, and filtration equipment used in processing were washed with a phosphate-free detergent solution, rinsed with tap water, rinsed with 5 percent hydrochloric acid (HCl) solution, and given a final rinse with deionized water. The cleaned equipment was transported to the field in clean plastic bags. The Van Dorn point sampler used for sampling at various depths through the water column of the lake was thoroughly rinsed with either deionized water from the ONP laboratory or water from the USGS Washington Water Science Center reverse-osmosis system. At the sampling site, all collection bottles and equipment were rinsed three times with native water before sample collection and all sample bottles submitted to the laboratories were rinsed with whole or filtered water before filling.

Samples from streams were obtained mostly by grab or dip methods using a 1 L high-density polyethylene (HDPE) or 2-L polyethylene terephthalate copolymer (PETE) bottle. When stream depths and flows warranted its use, a DH-81 equipped with a 1 L bottle, and a polypropylene cap and nozzle assembly was used to collect samples at multiple verticals across the stream. Water-column samples from five depths at the two locations on the lake were collected with a polycarbonate acrylic Van Dorn point sampler equipped with polyurethane resin stoppers and a cable messenger to activate the closure of the stoppers. The Van Dorn sampler was lowered through the water column to the target depth for collection, filled, brought to the surface, and emptied into various sample bottles.

Sample-water filtration took place in the field and typically was done using a Pall Aquaprep® disk filter (0.45 micron nominal pore size) and a peristaltic pump with C-flex® tubing. Occasionally, a small-diameter syringe-tip filter (Millipore™) with a 0.45 micron nominal pore size attached to a new, disposable 50 mL syringe was used instead of the larger Aquaprep® disk filter. Sample bottles were chilled soon after filling, then frozen at approximately –15°C prior to submission to the laboratory. Frozen samples generally were shipped to the analytical laboratory 1–2 weeks after collection. Field parameters measured during sampling events consisted of water temperature in the stream or in the lake and specific conductance of the sample water. Concentrations of dissolved oxygen in the stream were measured early in the project, but the measurements were then discontinued because values indicated saturation at all times (data not shown). Prior to measurements, the meter used for specific conductance was checked against potassium chloride (KCl) standards and adjusted if needed. The KCl standards selected for calibrations bracketed the range of expected values for the streams and the lake. The specific conductance meter thermistor was used for reading the water temperature, which was typically measured in the centroid of streamflow. Water temperatures for the point samples in the lake were measured from the deployment of a YSI multiparameter sonde, following methods of the Field Manual (U.S. Geological Survey, variously dated).

Groundwater Data

Samples of shallow groundwater discharging to Lake Crescent were collected from near the water table adjacent to the lakeshore at 12 sites selected around Lake Crescent where alluvial or colluvial deposits were present (fig. 4). Samples of groundwater from fractured bedrock were not obtained. The shallow water samples were collected at or near the water table using temporary drive-point wells in an effort to evaluate groundwater potentially affected by nearshore land use. The sites include residential land use likely to be influenced by onsite septic systems, as well as sites where no land development was apparent and considered undeveloped. From 3 to 12 individual samples were collected from each site, totaling 52 water samples from the temporary wells. The locations of the drive point wells often were within 2–10 m of the lake water line at the time of sampling. The objective of using these sampling site locations was to obtain groundwater samples representative of the range of nutrient concentration of groundwater discharging to the lake. Specific site conditions included sites that might be affected by influences of onsite septic systems and sites influenced by nitrogen-fixing microbes, such those detected with red alder.

The temporary drive point wells were constructed using Schedule 80 black-iron pipe (1.25 cm inside diameter). Constructing the groundwater access part of the pipe consisted of crimping closed the lower 2–3 cm of each pipe, then drilling a series of 20–25 3-mm-diameter holes to allow groundwater entry into the pipe in the 15 cm length immediately above the crimped end. The pipes were driven into the ground to a depth just below the water table using a slide hammer. Well water was developed using a surge block and peristaltic pump. After driving a well into position, the casing (pipe) was filled with clean water and a surge block used to move water through the casing perforations. A peristaltic pump then was used to extract more than 10 times the volume of water that filled the well during the surge-block development process.

Depth to water below a point at the top of the exposed casing was measured in the wells using a steel tape. After measuring depth to water, the wells were purged of about 3 casing-volumes of water. During the purge, specific conductance and dissolved oxygen (DO) concentrations were monitored for readings to stabilize to within 5 percent and 0.3 mg/L, respectively. Measurements of water temperature, specific conductance, and water level were made to check for differences between the groundwater sample and the adjacent lake-water quality. Water samples from the temporary wells were collected after purging with a low-flow peristaltic pump equipped with single-use polyethylene tubing. The final, stabilized readings of specific conductance and DO concentrations were recorded and water samples were collected for laboratory analyses. Specific conductance was measured using a sensor that was checked against KCl standards. Dissolved-oxygen concentrations ranging from 0 to 1 mg/L were measured using CHEMets® Rhodazine-DTM colorimetric ampoules. The ampoules were filled directly from the sampling tube after well purging was complete. The whole- and filtered-water samples for nutrient analyses were processed and handled as described previously for the lake and stream water samples and shipped to the CCAL laboratory.

Nutrient contributions from a limited number of residences and both sewage treatment facilities were investigated using a drain field rather than direct discharge into the lake. No outfalls were located or reported that could be directly sampled. Rather, shallow groundwater sampling piezometers were used to evaluate concentrations downgradient of drain fields but prior to entering the lake. However, from visual and conductivity surveys along the shoreline, clear signs of nutrient sources, as increased periphyton abundance or changes real-time conductivity, or both, were not observed.

Lake Sediment Coring

Sediment cores were collected from a central location in each of the two lake basins to determine the nitrogen content of lake sediments that serve as a sink for nutrients deposited in the lake. The University of Washington’s 3 m, 13 by 13 cm square, Kasten Core was used to obtain accumulated-bottom-sediment cores of approximately 258 cm at location LS04, and 155 cm at location LS02 (figs. 4 and 6). The recovered cores were sectioned into 2.5-cm increments; however, the upper 30 cm of both of the Kasten cores recovered were disturbed because the upper 20 cm slumped when the vertical Kasten Core was placed on its side for sectioning following the recovery process. Surface sediment grabs using a 50 cm box core (courtesy of Washington State Department of Ecology) also were collected for undisturbed samples of the sediment-water interface. The box core was sectioned at 1-cm intervals. Selected subsections were dried at 60°C, sieved for a particle-size fractional piece smaller than 62.5 microns, and shipped to the USGS National Water Quality Laboratory (NWQL) in Denver, Colo., to determine concentrations of trace elements, cesium-137, lead-210, and radium-226. Samples from the subsections also were analyzed by the Utah State University laboratory in Logan, Utah, for total carbon and total nitrogen content. A nearly intact conifer cone was collected from sediment 254 cm below the sediment-water interface in the core extracted at site LS04. Additional discrete plant fragments were found at depths of 178 cm in the same core and at 148 cm depth in the core extracted from site LS02. Carbon-14 analysis by University of Waterloo, Ontario, Canada, of these plant fragments was used to estimate the linear sediment accumulation. Selected sections of the core were analyzed for nitrogen and carbon content, trace elements, and radionuclides.

Photograph taken by Steve Cox, U.S. Geological Survey.

Core photograph taken by Florence Bigot-Comier, University of Washington.

Core LS04 – Lake Station 04 15 to 37 centimeters	Core LS04 – Lake Station 04 90 to 130 centimeters	Core LS04 – Lake Station 04 210 to 250 centimeters

Figure 6. Collection of accumulated bottom sediments and sediment cores from Lake Crescent, Washington, using a Kasten core.

Quality Control, Method Detection Limits, and Reporting Levels

During the data-collection period, quality-control samples consisted of field blank-water, control-solution blank-water, sequentially collected field-replicate, split-sample field-replicate, and reference-material samples. Field blank-water samples were prepared using either reagent-grade reverse-osmosis (RO) water from the USGS Washington Water Science Center laboratory, or as certified inorganic-grade (IG) reagent water purchased from the USGS NWQL. Field blanks that test for positive bias in the data might result from handling of equipment and supplies, preparation, collection, and handling of samples, or other factors such asenvironmental conditions, reagents, or instrumentation. Field blanks consist of passing blank water through all collection and processing equipment onsite and into sample bottles submitted to the laboratory. Collection bottles were filled with blank water which was then pumped through the C-flex tubing directly into a sample bottle representing the whole-water fraction and then through the tubing and filter into a sample bottle representing the filtered fraction. Blank-water samples prepared with RO water during lake sample collection primarily tested for carryover of target constituents in the Van Dorn point sampler. Control-solution blanks were prepared in the field and in controlled laboratory environments by adding unfiltered IG blank water directly into sample bottles without passing it through sampling equipment or filters. Control-solution blanks provided baseline data for target constituents for comparison of field-blank and environmental data.

Field replicate samples test for total variability in the data due to collection, processing, and laboratory analysis. Sequentially-collected replicate samples from streams consisted of filling two collection bottles one after the other by dip or depth-integrating methods. For the lake, split replicate samples consisted of filling the Van Dorn sampler at the target depth, then splitting the sample into two collection bottles. Each replicate sample was processed as whole water and filtered water into the appropriate sample bottles for the laboratory.

In addition to testing for potential positive bias, analytical results for the control-solution blanks and the field blanks were used to establish detection limits (DLs) and reporting levels (RLs) for the nutrient-concentration data used in this study. Long-term reporting limits from blank samples were provided by the CCAL laboratory for nutrient data using their standard methods. From these raw data, censoring levels for low-level concentrations and non-detects were established. Calculating the DLs (for estimated low-level concentrations) and RLs (for censoring non-detects) for this study followed methods described by Childress and others (1999) and guidelines provided by USGS Branch of Quality Systems (U.S. Geological Survey, 2009). From April 2006 to February 2008, 41 blank-water samples were prepared at stream- and lake-sampling sites for nutrient analyses (appendix A). For establishing the study DLs, the data set was first examined by Grubbs test for outlier concentrations, which were removed from the data set at a significance level of 0.05. The standard deviations of the blank-water concentrations in the revised data set were calculated and multiplied by the Student's t-distribution of 1, at a p-value of $\alpha = 0.01$, to give the upper 99th percentile. The resulting DLs were multiplied by 2 for the RLs (table 2). Concentrations ranging from the DL to the RL are reported as estimated; non-detects and concentrations less than the DL are reported as less than the RL.

Nitrate nitrogen was not detected in stream and lake field-blank samples at concentrations greater than the DL, but was present in 2 of 12 control-solution samples at concentrations greater than 0.002 mg/L (table 3). Total nitrogen was detected in only 1 stream field blank, but was present in 4 of 14 lake field blanks and 5 of 15 control-solution blanks at concentrations ranging from the estimated DL of 0.02 mg/L to the estimated RL of 0.05 mg/L (table 3). Total phosphorus was not detected in stream field blanks, but detections in lake field-blank and in control-blank samples ranged from an estimated 0.004 to 0.046 mg/L. The results for the blanks indicate that concentration data for streams are free of positive bias. However, results from control-solution blanks and lake-field blanks indicate a generally low-level, positive bias due to one or more unknown factors. Because the DLs and RLs were constructed using these water data blanks (see appendix A1–A3) estimations and censoring of environmental data accommodates for this low-level of positive bias. For consistency and as a conservative approach, all data from streams and lakes were censored with the same DLs and RLs.

Table 2. Calculated detection limits and reporting levels for nutrient samples collected from Lake Crescent, Washington, April 2006 to February 2008.

[All values are in milligrams per liter. Detection limits and reporting levels are from Oregon State University Cooperative Analytical Laboratory. All values are in milligrams per liter. **Reporting level:** Standard deviation × Student's t (n–1, 1–α = 0.99). Total values reported on a nitrogen or phosphorous equivalence. **Abbreviation**: OSU, Oregon State University]

Constituent	OSU detection level	Reporting level
Total nitrogen	0.01	0.02
Nitrite-plus-nitrate nitrogen	0.001	0.002
Total phosphorus	0.002	0.004

Table 3. Summary of detections and ranges of concentrations in blank samples, Crescent Lake, Washington, April 2006 to February 2008.

[Total values reported on a nitrogen or phosphorous equivalence. **Abbreviations**: mg/L, milligram per liter; E, estimated; NA, not applicable]

Type of blank sample	Nitrate nitrogen		Total nitrogen		Total phosphorus	
	Number of detections/ Number of samples	Range of detected concentrations (mg/L)	Number of detections/ Number of samples	Range of detected concentrations (mg/L)	Number of detections/ Number of samples	Range of detected concentrations (mg/L)
Stream field blank	0/12	NA	1/12	E0.02	0/12	NA
Lake field blank	0/14	NA	4/14	E0.02–E0.03	4/14	E0.004–[1]0.012
Control-solution	2/12	E0.004–[1]0.014	5/15	E0.02–[1]E0.05	2/15	E0.005–[1]E0.046

[1] Outlier concentration; Grub's Outlier test with alpha = 0.05

During the data-collection period from April 2006 to February 2008, nine replicate samples consisting of pairs of samples bottles were collected. Of the 9 sample pairs, 6 were from the lake and 3 were from the streams (appendix A). Relative percent differences in the pairs of concentrations ranged from 0 to 26.7 percent for nitrate nitrogen, 0 to 20 percent for total nitrogen, and 0 to 23.1 percent for total phosphorus, which indicates relatively good agreement and low variability considering the low-level nature of the nutrient concentration data.

Sources and Sinks of Nitrogen and Phosphorus

Hydrology of the Lake Crescent Watershed

Hydrographs of the six gaging stations from April 2006 to September 2007 are presented in figure 7; daily values for measured streamflow are also provided in appendix B.

As is typical of streamflow in the Olympic Mountain range, a generally slowly falling stage occurs from the early spring months to the late summer/early autumn months of 2006 (fig. 7). Some variation on this trend is apparent in Smith Creek, which contributed the least amount of flow and has a steep gradient with large substrate size and significant underflow not recorded by the gaging station (see notation of "dry streambed" in figure 7) and Fairholm Creek west of the lake that drains a considerably lower elevation catchment with no summertime snowmelt. Conversely, Lapoel, Smith, and Barnes Creeks, which all drain the higher elevations of the southern watershed, show an increase in streamflows from April to early June 2006 indicative of snowmelt at higher elevation. All hydrographs show a dramatic increase in streamflow at the beginning of November 2006 when a series of storms arrived after an unusually dry September and October (fig. 7).

Water Chemistry

Water samples collected during 2006–08 were analyzed for concentrations of nutrients in Lake Crescent, (see appendix C for the raw data by sampling location). The samples were collected from five tributary streams, the Lyre River outflow, and at two stations from the water column of Lake Crescent (fig. 4). Results of chemical analyses on subsamples of bottom materials obtained from cores of lakebed sediments are presented in appendix D.

Of the sites sampled, the highest nutrient concentrations were in Piedmont Creek with median values of total nitrogen and nitrate nitrogen one order of magnitude higher, and total phosphorus about two times higher than the other five streams (fig. 8). Concentrations of total nitrogen at Piedmont Creek were 75 percent of the total nitrogen values exceeding 0.25 mg/L, whereas most values in the other five streams were less than 0.25 mg/L. Concentrations of total nitrogen in Piedmont Creek were followed in magnitude by concentrations in Fairholm Creek. The lowest concentration of nitrogen of all six streams was in samples collected from the Lyre River (fig. 8; table 4).

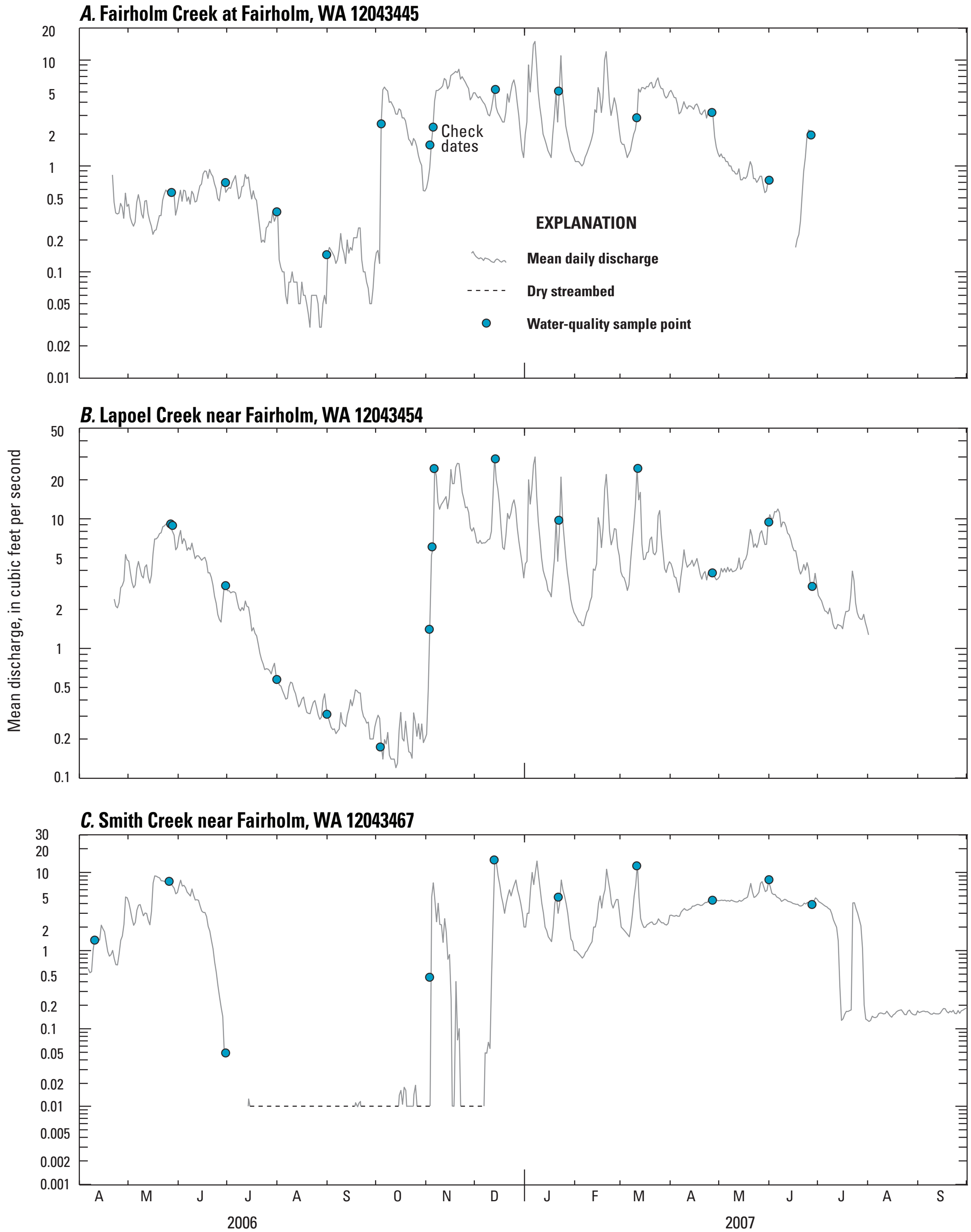


Figure 7. Mean daily discharge and water-quality sample collection points for (*A*) Fairholm Creek, (*B*) Lapoel Creek, (*C*) Smith Creek, (*D*) Barnes Creek, (*E*) Piedmont Creek, and (*F*) Lyle River, near Lake Crescent, Washington, April 2006 to September 2007.

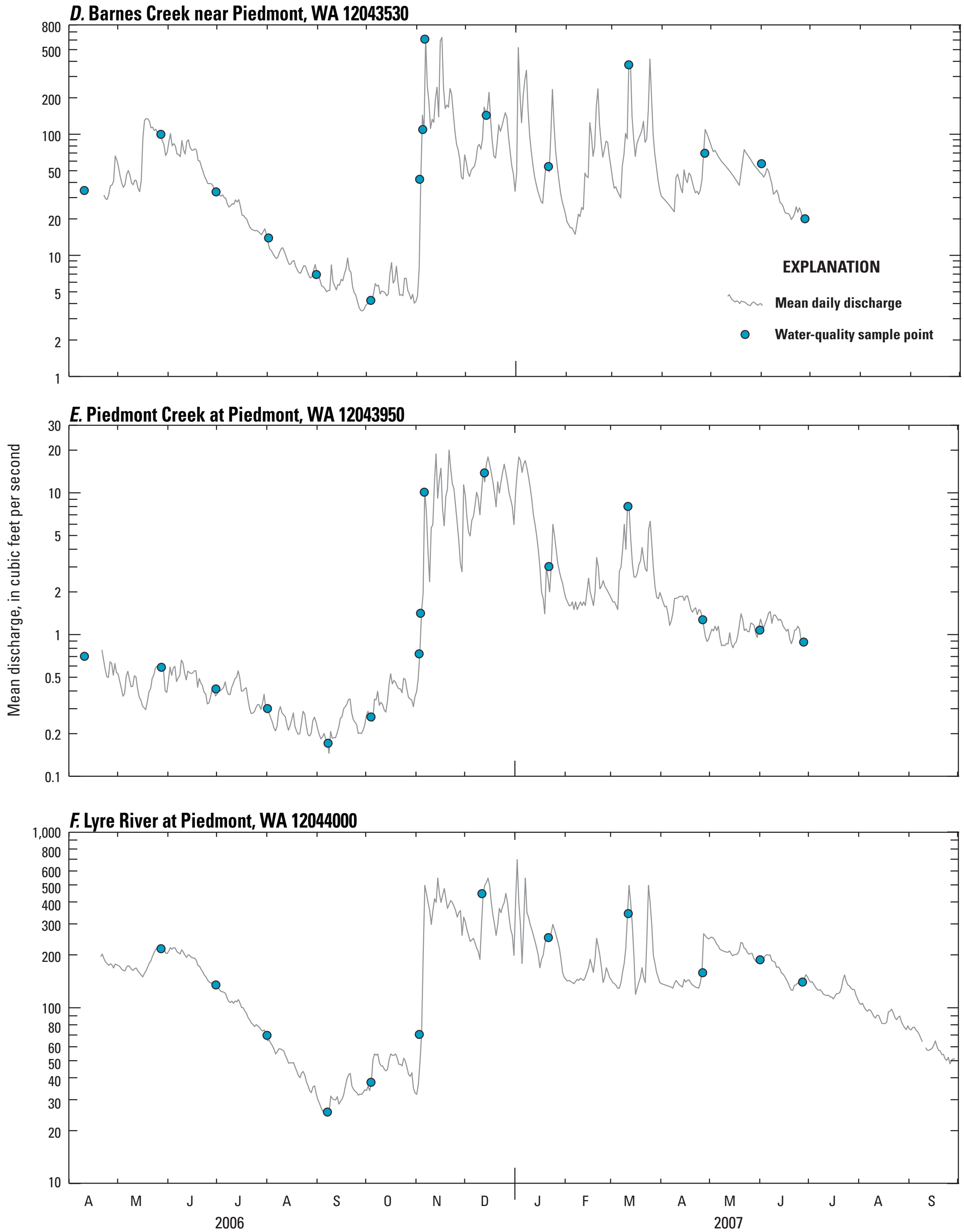


Figure 7.—Continued.

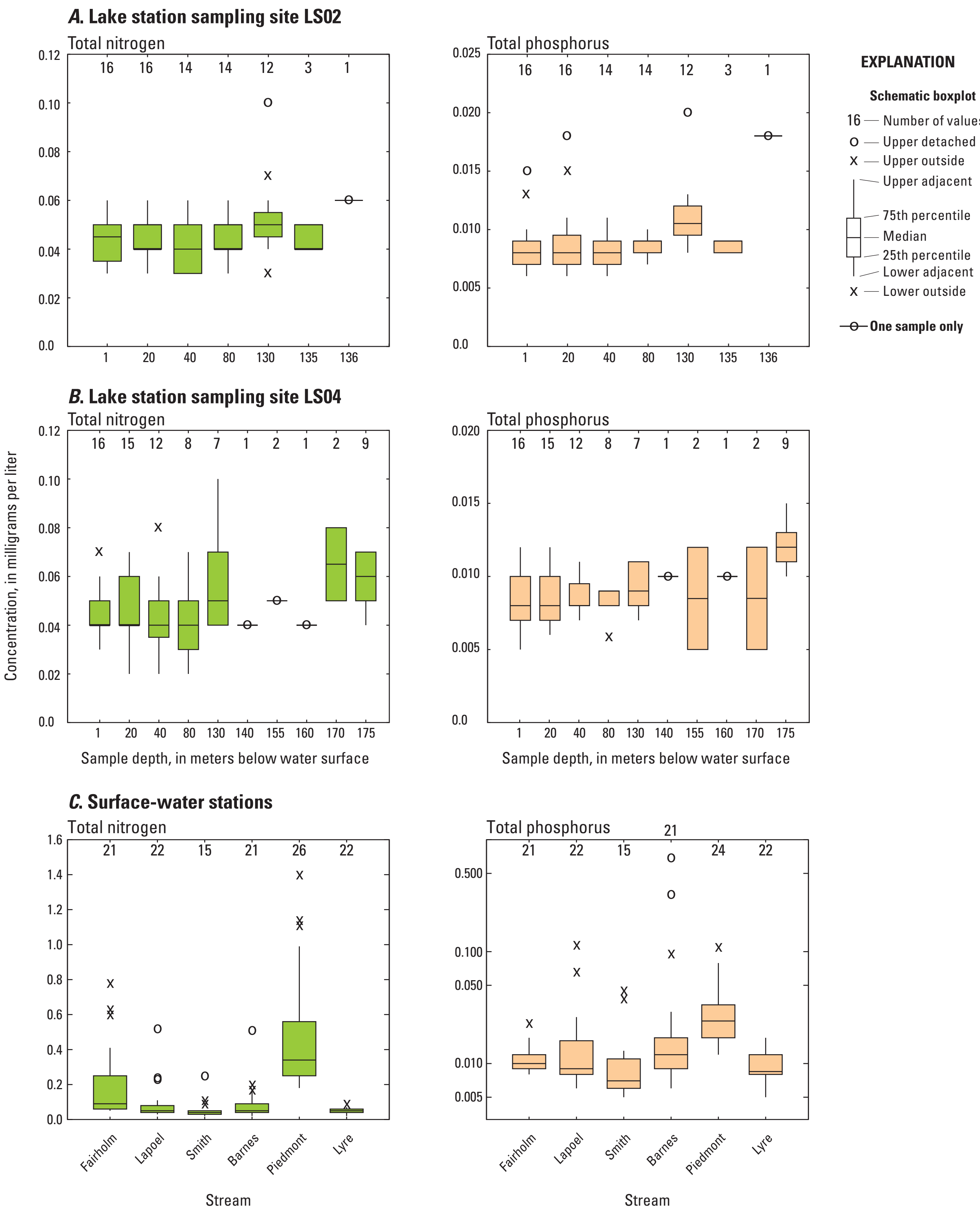


Figure 8. Total nitrogen and total phosphorus concentrations at sites (*A*) LS02, (*B*), LS04, and (*C*) stream sites, Lake Crescent, Washington, 2006–07.

Table 4. Summary of water-quality and nutrient concentrations in water samples collected from streams near Lake Crescent, Washington, April 10, 2006, to February 13, 2008.

[Additional information is available in appendix C. Total values reported on a nitrogen or phosphorous equivalent basis. Water temperature and specific conductance are single measurements. **Abbreviations**: °C, degrees Celsius; µS/cm, microseimens per centimeter; mg/L, milligram per liter; <, less than]

Stream site	Water temperature (°C)			Specific conductance (µS/cm)			Total nitrogen (mg/L)			Nitrite-plus-nitrate nitrogen (mg/L)			Total phosphorus (mg/L)		
	Range	Median	Number of observations	Range	Median	Number of observations	Range	Median	Number of observations	Range	Median	Number of observations	Range	Median	Number of observations
Fairholm Creek at Fairholm	7.0–9.4	8.35	10	89–120	114	7	0.05–0.78	0.09	21	0.03–0.679	0.071	21	0.008–0.023	0.01	21
Lapoel Creek near Fairholm	4.6–11.1	7.8	9	96–138	119	7	0.03–0.52	0.05	22	0.014–0.109	0.028	22	0.006–0.115	0.009	22
Smith Creek near Fairholm	6.0–14.2	8.2	6	86–123	95	4	0.02–0.25	0.02	15	0.005–0.044	0.012	15	0.005–0.045	0.009	15
Barnes Creek near Piedmon	3.9–21.6	9.5	9	98–116	112.5	6	0.02–0.51	0.055	21	0.002–0.078	0.014	21	0.006–0.69	0.013	21
Piedmont Creek at Piedmont	6.8–11.1	8.8	7	79–176	120	7	0.18–1.4	0.34	26	0.148–0.991	0.249	24	0.011–0.11	0.024	24
Lyre River at Piedmont	5.3–21.7	10.15	10	115–123	116	6	0.02–0.09	0.05	22	<0.002–0.024	0.002	22	0.005–0.017	0.008	22

Nutrient concentrations in the water column at sites LS02 and LS04 in Lake Crescent were low, with median concentrations less than 0.08 mg/L for total nitrogen and less than about 0.015 mg/L for total phosphorus (fig. 8; table 5).

The low nutrient concentrations in the Lyre River closely resembled the magnitude and ranges of concentrations in samples collected from the upper 40 m of the water column at sites LS02 and LS04. Median concentrations of total nitrogen and nitrate nitrogen for the Lyre River were 0.05 and 0.002 mg/L, respectively (fig. 8). In samples collected from the lake site nearest the Lyre River (LS02), median total nitrogen concentrations ranged from 0.04 mg/L at 40 m depth to 0.05 mg/L at 20 m depth and median nitrate concentrations were less than the reporting limit of 0.004 mg/L. At both lake sites (LS02 and LS04) nutrient concentrations appeared to shift in magnitude below about 80 m depth. Total nitrogen and total phosphorus concentrations generally were lower in the shallow sampled depths of 1, 20, 40, and 80 m than in the sampled depths of 130 m and more (fig. 8; table 5). These results would be consistent with ONP's 2002 Summary Report that describes the hypolimnion functioning as a limited nitrogen pool during stratification (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002).

The ratio of nitrogen to phosphorus concentration in lake water samples collected in this study was consistently less than 10, averaging about 5.3. Based on the Redfield ratio (Wetzel 2001), these data suggest that nitrogen is more limiting relative to phosphorus, and therefore that nitrogen is the limiting, or co-limiting, nutrient throughout the measured areas of Lake Crescent, a finding which is consistent with the findings of previous researchers (Boyle and Beeson 1991, John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002). Nutrient and physical-chemical data indicated stratification within the water column of Lake Crescent throughout much of the year. Nutrient concentrations were consistently, but slightly larger in water near the lake bottom than in water near the surface, with a more uniform concentration profile measured throughout the water column during winter months (appendix C7 and C8).

Table 5. Summary of nutrient concentrations in water samples collected from Lake Crescent, Washington, June 2006 to November 2007.

[Additional information is available in appendix C. Concentrations are in milligrams per liter. **Abbreviations**: m, meter; mg/L, milligram per liter; <, less than]

Site	Sample depth (m)	Number of samples	Total nitrogen		Nitrate nitrogen		Total phosphorus	
			Range	Median	Range	Median	Range	Median
LS02	1	16	0.03–0.06	0.04	<0.002–0.014	<0.002	0.006–0.015	0.008
	20	16	0.03–0.06	0.05	<0.002–0.01	<0.002	0.006–0.018	0.008
	40	14	0.03–0.06	0.04	<0.002–0.013	<0.002	0.006–0.011	0.008
	80	14	0.03–0.06	0.05	0.002–0.02	0.014	0.007–0.01	0.009
	130	12	0.03–0.10	0.05	<0.002–0.03	0.02	0.008–0.02	0.010
	135–136	4	0.04–0.06	0.05	0.012–0.033	0.02	0.008–0.018	0.009
LS04	1	16	0.03–0.07	0.04	<0.002–0.017	<0.002	0.005–0.012	0.008
	20	15	0.02–0.07	0.04	<0.002–0.016	<0.002	0.006–0.012	0.008
	40	12	0.02–0.06	0.04	<0.002–0.014	<0.002	0.007–0.011	0.008
	80	8	0.02–0.07	0.04	0.004–0.014	0.011	0.006–0.009	0.009
	130	7	0.04–0.10	0.05	0.003–0.024	0.019	0.005–0.011	0.009
	140	1	[1]0.04	NA	[1]0.009	NA	[1]0.01	NA
	155	2	0.05–0.05	0.05	0.02–0.023	0.022	0.005–0.012	0.009
	160	1	[1]0.04	NA	[1]0.021	NA	[1]0.01	NA
	170	2	0.05–0.08	0.06	0.012–0.019	0.016	0.005–0.012	0.009
	175	9	0.04–0.07	0.06	0.006–0.028	0.025	0.01–0.015	0.012

[1] Single-sample concentration.

Groundwater Chemistry

Chemical analysis of 50 water samples collected from the temporary wells indicate that concentrations of dissolved constituents in groundwater discharging to Lake Crescent are generally dilute, containing near background levels of nitrogen and phosphorus (see appendix E for data). Overall, constituent concentrations in groundwater are similar to those measured in tributary streams and Lake Crescent, although they are often larger and showed a greater range of variability. Specific conductance, which is a general measure of the total amount of dissolved constituents, typically ranged from 85to160 µs/cm in samples of groundwater and often was less than the specific conductance of lake water, which ranged from 110 to 120 µs/cm. The concentration of dissolved oxygen in groundwater was often low, typically less than 1.0 mg/L in most water samples collected from the temporary wells.

Groundwater samples were collected from temporary drive-point wells installed in unconsolidated sediments located in 13 areas from around Lake Crescent (fig. 9*A*). At some sampling sites multiple temporary wells, spaced from 100 to 200 ft (30 to 61 m) apart, were installed to increase the representative sampling area and to provide some assessment of spatial variability. Groundwater in many shoreline areas surrounding Lake Crescent could not be sampled because the lake shoreline was either composed of bedrock or the slope of the shoreline area was too steep for installation of temporary drive-point wells. The physical setting where temporary wells could be installed was often associated with developed or previously developed shoreline areas. Only 2 of the 13 groundwater sampling areas were in areas that could be described as undeveloped. Additionally, the areas downgradient from the drain-field areas associated with multi-unit septic disposal systems located at the Lake Crescent Lodge-Barnes Point area and Log Cabin Resort area where selected as sampling sites as septic tank effluent was considered to potentially influence groundwater in these areas.

The nitrogen content of groundwater discharging to Lake Crescent is generally small, less than 0.5 mg/L nitrogen. The concentration of TN, in the groundwater samples, ranged from below detection limit (0.05 mg/L) to a maximum of 2.93 mg/L; with the median TN concentration was 0.2 mg/L. The concentration of TN in samples obtained from two locations that were undeveloped and lacked nearby road access, (West La Poel and Spruce Railroad terminus) ranged from 0.07 to 0.23 mg/L. Samples from these areas provide data from areas with limit potential for septic influence associated with developed areas, including day use areas. Samples from the East Beach Drive location ranged from 0.27 to 0.43 mg/L; this area lacks development other than the roadway that is immediately adjacent to the shoreline. The concentration of TN in samples collected downgradient of the multi-unit septic system drain fields located near Lake Crescent Lodge and Log Cabin Resort ranged from 0.13 to 2.93 mg/L nitrogen. Typically, only one of the four or more temporary wells sampled in these areas produced groundwater with largely elevated TN concentrations. At the Lake Crescent Lodge site, a second set of groundwater samples were collected 3 months later (mid-winter) from temporary wells installed near the same location. The concentration of TN measured in the groundwater samples collected mid-winter ranged from 0.04 to 0.28 mg/L which is similar to the range measured in samples from undeveloped areas. Samples collected downgradient from single family buildings (Lake Crescent Laboratory and Lady of the Lake) provided a similar pattern of TN concentrations.

When the concentrations data for TN measured in groundwater discharging to Lake Crescent are plotted to show the cumulative frequency distribution (fig. 9*B*), an apparent discontinuity in the distribution of TN concentrations at about 0.5 mg/L. This pattern suggests that about 90 percent of the groundwater samples represent the range of concentrations observed in background levels of TN in groundwater (less than 0.5 mg/L); whereas about 10 percent of the groundwater sampled contained concentrations of TN that were elevated above background levels from an additional source of nitrogen, which likely include effects from on-site septic systems. The two largest concentrations were obtained from beach locations in the downgradient vicinity of the main drainfields used for the two large sewage package systems at Barnes Point and near Log Cabin Resort. High nutrient concentrations also were measured in groundwater from near the La Poel day-use area and may be related to ongoing day-use activity as evidence by toilet tissue observed at the site or historical use of the area as a campground.

The concentration of TP ranged from less than detection limits to 0.906 mg/L with a median concentration of 0.04 mg/L. The frequency distribution of TP shows a pattern similar to TN with a discontinuity at about 0.15 mg/L. However, the locations of elevated concentrations of TP wereall obtained in the eastern basin of Lake Crescent (fig. 9). The underlying geology of the Aldwell formation, a marine siltstone present along the shoreline of much of the eastern basin, may yield more phosphorus than basaltic volcanic rocks that make up much of the western basin shoreline of Lake Crescent (fig. 5; Schasse 2003).

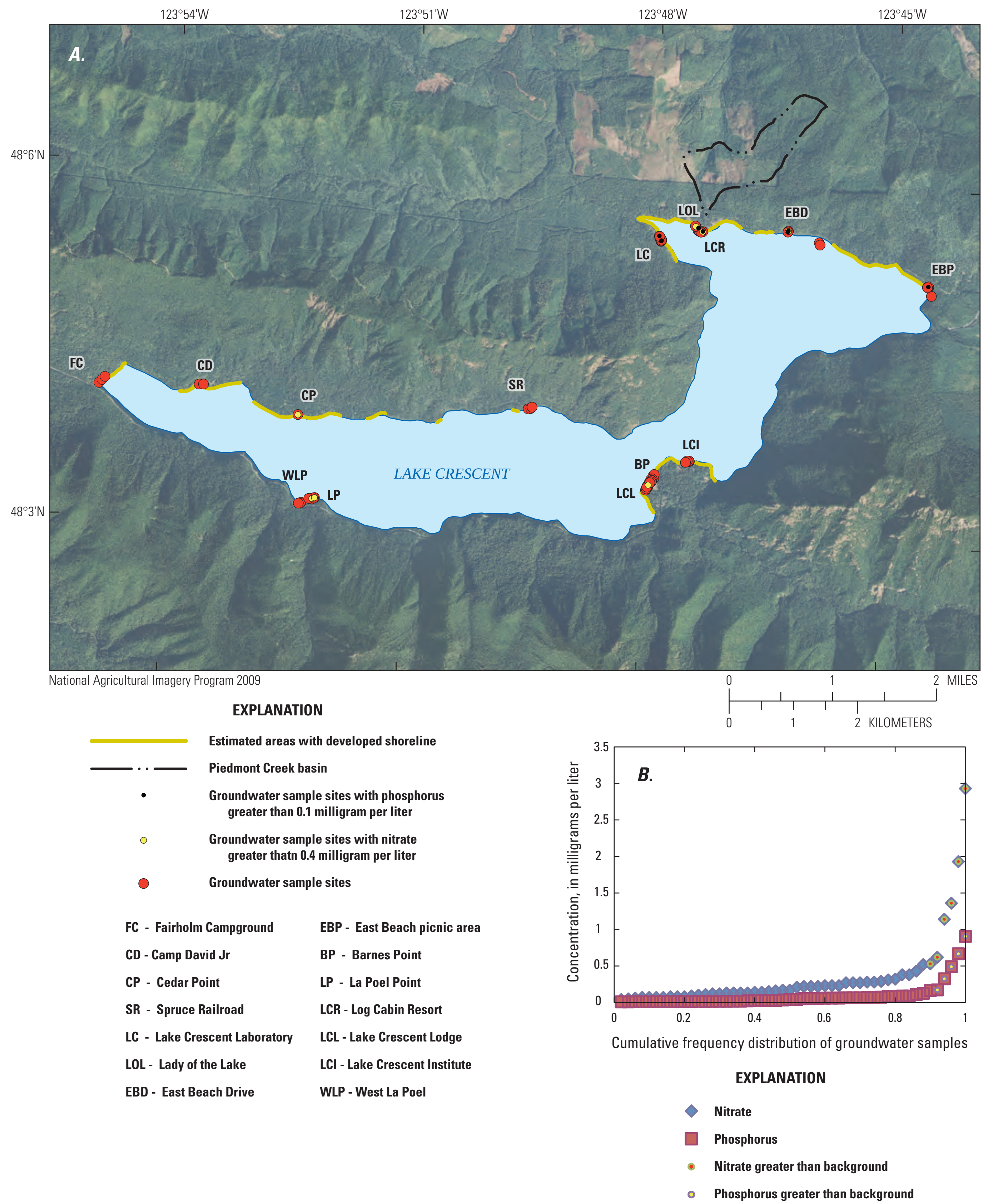


Figure 9. Groundwater (*A*) sampling locations, areas of shoreline development, and (*B*) corresponding distribution of nutrient concentrations, Lake Crescent, Washington, April 2006–June 2008.

Lake Sedimentation

Sediment chemistry data obtained from two sediment cores were used to estimate of the annual mass of nitrogen and phosphorus sequestered in sediment accumulated at the bottom of Lake Crescent. The sediment accumulated at both coring sites were composed of predominantly silts and clays sized particles that often contained interspersed very-fine sand and organic material. Sediment from site LS04 contained more occurrences of interspersed very-fine sand and organic material possibly reflecting episodic influx of sediment from Barnes Creek and other drainages which are more prominent in the main basin as compared to the eastern basin.

Nitrogen content measured in lake sediment at sites LS02 and LS04 ranged from 0.02 to 0.32 percent with an average of 0.18 percent. Carbon content averaged 2.18 percent and ranged from 0.96 to 3.35 percent. Standard deviation of triplicate analysis of nitrogen and carbon content ($n=13$) was 0.014 percent and 0.10 percent, respectively. Profiles of nitrogen and carbon content of sediments from deep lake sediment cores are shown in figure 10. Both profiles show a trend of generally decreasing concentrations of nitrogen and carbon with depth in the cores. In core LS02, nitrogen content of sediment core in the depth range used to estimate nitrogen sequestration (10–50 cm) was 0.26 percent ($n=12$) and in the bottom 40 cm of core depth the concentration of nitrogen was roughly 40 percent less or about 0.16 percent nitrogen ($n=15$). Likewise, in core LS04, nitrogen content of sediment core in the depth range used to estimate nitrogen sequestration (10–50 cm) was 0.24 percent ($n=12$), whereas in the bottom 40 cm of core depth concentration of nitrogen was 0.16 percent ($n=9$). The ratios of carbon and nitrogen were generally constant with each core but varied between cores; the average of carbon-nitrogen ratio at core LS02 was 9.4, whereas the average at LS04 was 13.6.

Measurements of sediment phosphorus were limited to the samples collected near the sediment surface that were analyzed for trace elements and radionuclides. The average phosphorus concentration in the 11 samples collected from the upper 50 cm of sediment was 1,260 mg/kg.

The estimate of annual sequestration of nitrogen in lake sediments was calculated from the average nitrogen content of sediment determined in sediment core sections between 10 and 50 cm below the sediment water interface. Biological activity can transfer nitrogen from shallow lake sediments into the overlying water; therefore, the nitrogen content in sediment within the zone from 0 to 10 cm were not included in estimates of sequestered nitrogen.

The rate of sedimentation was determined by dividing the length of accumulated sediments above the measured time horizon. Carbon-14 measurements of discrete plant fragments provided the best estimate for sediment accumulation rates. A nearly intact conifer cone was embedded in the sediment collected 254 cm below the sediment water interface in the core obtained at site LS04. Additional plant fragments including partial leaf material and small twigs were obtained at depths of 178 cm in the same core and at 148 cm depth in the core extracted from site LS02. Carbon-14 analysis of these plant fragments yield uncorrected age estimates of 2,740, 2,114, and 2,460 years before present. The corresponding estimates of the rate of linear sediment accumulation were 0.93 and 0.84 mm/yr for sediment accumulation at the LS04 location, and 0.60 mm/yr for sediment at LS02. The weighted average rate of sediment accumulation for estimating sequestration of nitrogen and phosphorus in sediment accumulating on the lake bed was 0.79 mm/yr. The sediment accumulation rate based on carbon-14 analysis is consistent with the anthropogenic signals present in the lake sediments from atmospheric thermonuclear testing (cesium-137) and leaded gasoline which showed concentration increased greater than background levels in sediment from the upper 6 cm of sediments analyzed to trace-elements and radionuclides (appendix D).

The mass of nitrogen and phosphorus sequestered in lake sediment was calculated as the mass fraction of nitrogen or phosphorus of the total mass of sediment accumulating. Sediment was assumed to accumulate uniformly over 99 percent of the lake area (2,010 ha) and the sediment bulk density of lake sediment was assumed to be 450 kg/m^3 that resulted in an average mass of accumulated sediment of 7,146,000 kg of which 17,900 kg was nitrogen and 8,980 kg was phosphorus.

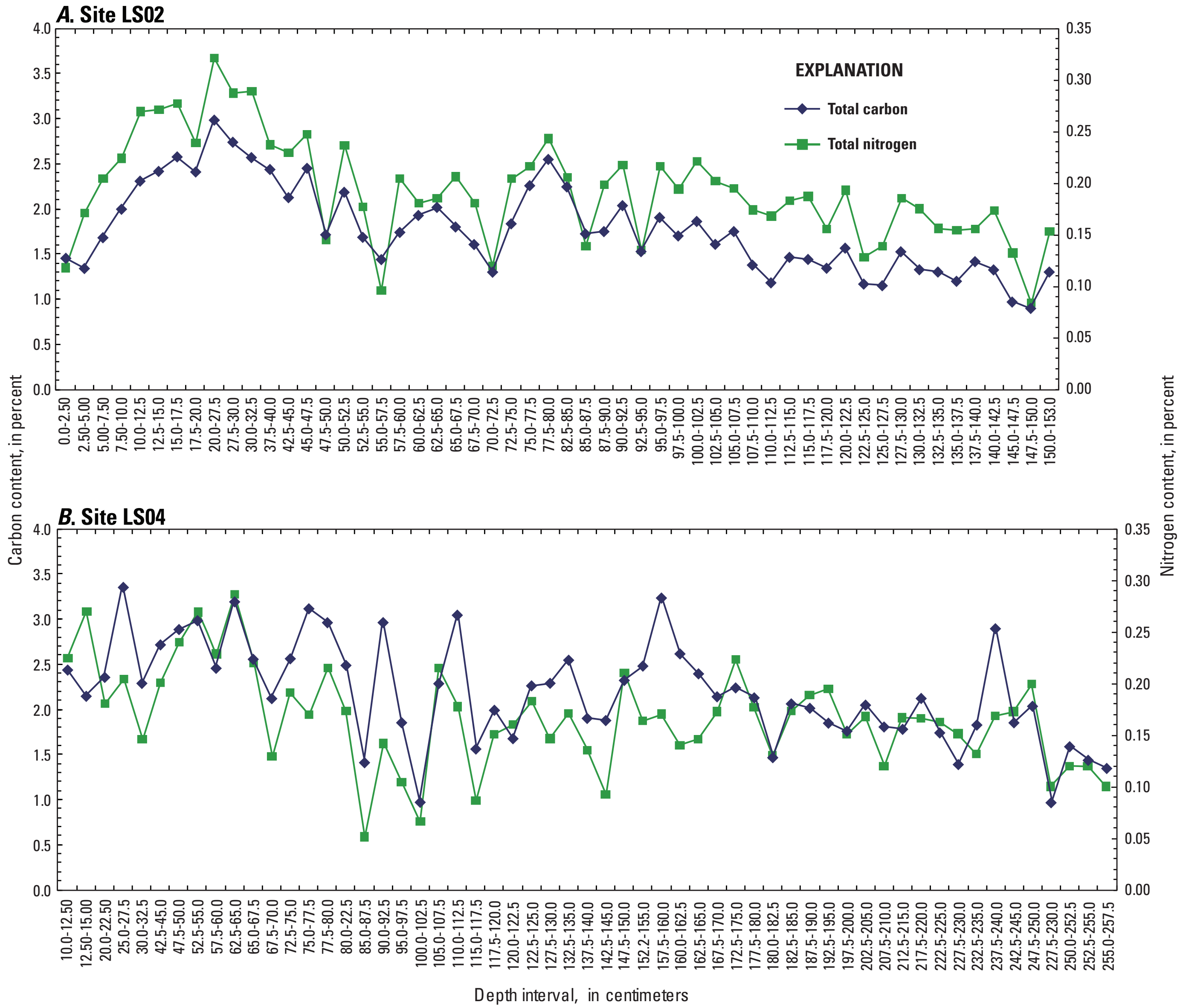


Figure 10. Percentages of carbon and nitrogen content in lake core sections (*A*) site LS02, and (*B*) site LS04, Lake Crescent Washington, September 2006.

Mass Balances

A mass balance approach was taken to estimate the annual nutrient budget for the Lake Crescent watershed. Two components are needed to construct a nutrient budget for the lake; a water budget and a description of a representative nutrient concentration for each water source or sink. The product of water volume and the characteristic nutrient concentration is the load from that source, and these sources can be summed to create a mass balance for the particular nutrient. Similarly, the discussion below presents a description of the water budget and is followed by a description of the nutrient load associated with the water budget.

Water Balance

Components to construct the water balance for the lake included measured inflows (five gaged tributary streams and measured precipitation), as well as measured outflows (evaporation and runoff; the Lyre River) and any input or losses from ungaged parts of the watershed. The residual in the balance from the difference between gains (tributary and ungaged inflows, precipitation) and losses (Lyre River outflow, evaporation) was assigned to groundwater to close the water balance. These measured and estimated components of the water balance assisted in developing a mass balance for the nutrients.

Precipitation

Precipitation amounts and other climatic data were obtained from four weather stations near Lake Crescent. Three of these weather stations are on the lake shore: at the ONP laboratory near Crescent, along the southeastern shoreline (wind only) and on the north shoreline at the constriction point between the west and east lake basins (fig. 4). A fourth weather station was the ONP Elwha Ranger Station, about 12 km east of the lake and not immediately in the Lake Crescent watershed, was used to “fill in” dates that were missing record at more than one station. Daily precipitation data were available from October 2005 through May 2007. Average daily precipitation over the lake was 0.2 in. and daily precipitation ranged from 0 to 3.9 in. Precipitation tended to be greatest during November through January (fig. 11). The general relations between precipitation and water levels of Lake Crescent and between precipitation and discharge in the Lyre River are shown in figure 11. Total average precipitation from across these three stations, using all available data, was 83 in. from May 2006 through April 2007.

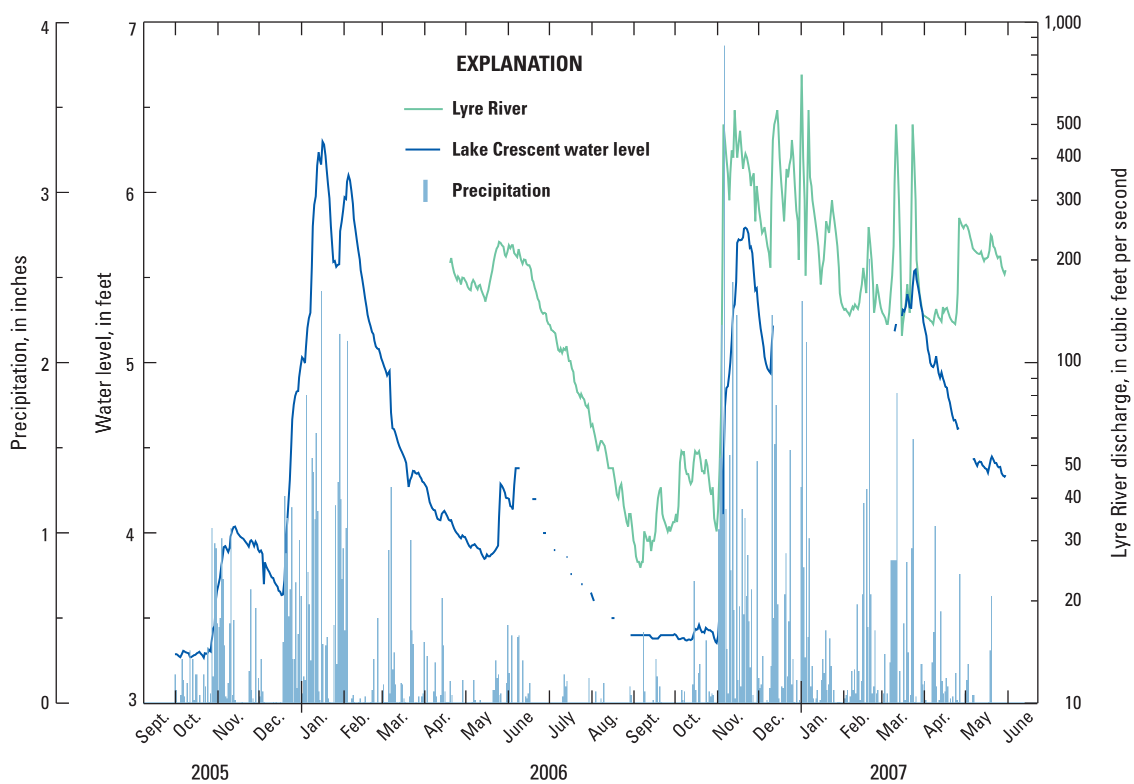


Figure 11. Daily precipitation and water level of Lake Crescent, and discharge in the Lyre River, Washington, October 2005 to May 2007.

Evaporation

Climatic data recorded at 15-minute intervals from the three weather stations were averaged for each parameter and used in calculating evaporation for that time step. Due to mechanical failures, recording complications, or both, not all stations recorded data at all times, so an average of the available data at a given time-point was used to calculate the overall lake average.

Evaporation was calculated using the mass-transfer equation from Harbeck (1962),

as:

$$E = N\,u\,(e_0 - e_a), \qquad (1)$$

where

- E is evaporation in inches per hour,
- N is 0.0025 and is the mass transfer coefficient proportional to lake surface area,
- u is wind speed in miles per hour,
- e_0 is saturation vapor pressure, in millibars (see eq. 2),
- e_a is vapor pressure in the air, in millibars, at 2 meters.

Saturation vapor pressure in millibars was calculated from surface water temperature using Murray's (1967) equation for water surfaces:

$$e_s = 6.1078 \exp\{a(T\text{-}T^*)/(T\text{-}b)\}, \qquad (2)$$

where

- a is 17.27,
- T^* is 273.16 Kelvin,
- b is 35.86,
- T is measured air temperature at 2 meters in Kelvin.

The evaporation method of Harbeck (1962) used here is heavily dependent upon wind speed. Upon review of the data collected and from observations of the lake, the recorded wind speeds on the shore likely underestimate the maximum wind speeds from the middle of the lake and therefore, would underestimate the calculated evaporation. Conversely, the effect of averaging the wind speed from the three weather stations likely overestimates low wind speeds to parts of the lake when there is no measurable wind. However, the effect of under-representing maximum wind speeds, and therefore overall evaporation, is expected to have a more pronounced effect than overestimating low or zero wind speeds. Thus, the expected evaporation estimates here likely are lower than actual evaporation, but it is not certain by how much.

Gaged Basins

Total annual discharge for input creeks and outflow through the Lyre River was calculated by summing the average daily estimates of streamflow by the number of seconds in a day, and then summed for the total days in the budget period. This calculation was done for each gaging station, (the Lyre River gaging station was assigned a negative value) for the budget period of May 2006 through May 2007 (fig. 7 and appendixes B and C). When incorporating this estimate with the evaporation and precipitation estimates, the water balance shows a net amount of -33,300 megaliters (ML); equivalent to 1 million liters) or -41,100 acre-ft of water, which indicates more water leaving the watershed than entering (table 6).

The -41,100 acre-ft (sum of May 2006–April 2007 monthly net balance in table 6) indicates that an unmeasured volume of water is entering the system. This is not surprising as several small ephemeral streams, springs and (or) seeps contributing surface water were observed that were not practical to measure in this study. Similarly, there is not a direct measure of the groundwater contribution (see section "Groundwater"). Although estimating water produced from the ungaged basin areas and groundwater was attempted, in this system with steep topography and relatively coarse substrate where underflow is common, the distinction between groundwater and surface water is somewhat arbitrary. Nevertheless, the median surface water concentrations of nutrients are slightly lower than the median groundwater concentrations and therefore, for nutrient budgeting purposes, groundwater and ungaged surface water were estimated separately.

Ungaged Basins

The ungaged drainage basins, totaling 5,160 ha of the watershed, were generally small, less than 250 ha (about 1 mi^2), basins that flowed directly to the lake. Many of these basins were observed during monthly sampling visits and were documented as dry during the summer months (after the first week of July until the last week of October 2006). Runoff from the ungaged area was estimated using three approaches: an average approach which assumes that summertime base flow is indicative of groundwater flow, and low and high scenarios where different assumptions about the runoff /area relations were made and then applied to the ungaged areas. A different method was used for each approach to arrive at an overall average annual runoff per drainage area value (table 1). This average runoff/ungaged basin area was multiplied by the extent of ungaged drainage area, or 5,160 ha to estimate an ungaged runoff value. In the average scenario, the approach attempts to estimate groundwater contribution, and then assumes the difference is attributable to ungaged surface water. In the two scenarios, referred to as the high and low ungaged runoff scenarios, the approach estimates ungaged surface water, includes it in the water balance, and solves for groundwater by difference (table 7).

Average Ungaged Area Runoff Scenario

The hydrographs for Lapoel, Barnes, and Piedmont Creeks (fig. 7) and monthly volumes (table 6), indicate that during April 2006 to May 2007, there was low, stable flow in the creeks during August, September, and October. If these low, stable summertime flows are assumed to be groundwater driven, it is possible to use this period to generate a 'groundwater only' runoff/area relation. Using only the low flows from August to October from Lapoel, Barnes, and Piedmont Creeks (Smith and Fairholm were not included because significant underflow and/or dry streambed conditions were observed there during this period), scaled to 12 months, an average estimate of 1.15 (acre-ft/ha)/yr as groundwater discharge was calculated. This value is about one-half that calculated for the entire basin based on only the Lyre River summertime base flow/area relation for the same months, or 2.4 acre-ft/ha. This is a reasonable confirmation of the groundwater production assumption. Using this average value of 1.15 (acre-ft/ ha)/yr and the ungaged area, 5,160 ha, an estimated 5,900 acre-ft was contributed to groundwater annually. This leaves 35,300 acre-ft (or 41,200 – 5,900 acre-ft) assumed to be produced from the ungaged area as surface runoff. Monthly runoff estimates are shown in table 6 and comparison of the average, high and low runoff scenarios are shown in table 7.

Table 6. Measured water-balance components including monthly runoff from streams, precipitation, lake evaporation, and net balances near Lake Crescent, Washington, May 2006 to May 2007.

[All values in acre-feet per year. Shaded cells indicate loss of water from the watershed. Negative net value indicates more water leaving the system than entering, and is assumed to be groundwater. May 2007 not used in 12-month annual budget; 12-month totals are from May 1, 2006, through April 30, 2007; some totals are rounded. Totals for the 13-month period of record are from May 1, 2006, through May 31, 2007. Net balance is the difference between measured total water inputs and measured total water lost. **Abbreviations**: A.O., in budget as annual value only; ET, lake evapotranspiration; n, number]

Month	Fairholm Creek	Lapoel Creek	Smith Creek	Barnes Creek	Piedmont Creek	Rainfall	Ungaged basins	Lyre River	ET	Net balance (assigned as groundwater)
May 2006	25	357	327	4,580	28	482	A.O.	–11,226	[1]–147	[1]–5,427
June	37	272	197	3,882	29	971	A.O.	–10,945	–722	–6,279
July	30	98	0.10	1,404	24	244	[2]0	–6,109	–587	–4,896
August	4.7	25	0	553	15	156	[2]0	–2,985	–734	–2,965
September	8.8	18	0.10	340	14	447	[2]0	–1,888	–1,718	–2,779
October	154	13	0.30	327	23	876	[2]0	–2,856	–874	–2,337
November	314	830	70	10,660	467	11,138	A.O.	–20,348	–284	2,846
December	233	591	241	5,766	649	5,020	A.O.	–20,390	–66	–7,955
January 2007	263	512	267	6,462	441	4,424	A.O.	–17,098	–99	–4,827
February	185	333	177	3,501	108	3,841	A.O.	–8,991	–17	–862
March	254	435	176	6,756	210	4,407	A.O.	–12,958	–333	–1,053
April	203	238	218	2,692	91	1,699	A.O.	–9,130	–537	–4,526
12-month totals	1,712	3,722	1,674	46,923	2,099	33,705	[3]**35,300**	–124,924	–6,118	
Net balance							[4]125,100		[5]–131,000	**–5,900**
May 2007[6]	54	334	316	3,529	[2]	[2]	[2]	–13,174	–1,214	
Total	1,766	4,056	1,990	50,452	2,162	34,328	[2,3]**39,700**	–138,098	–7,332	**–50,600**
13-month balance							[4]134,500		[5]–145,400	**–10,900**

[1] Values for May 2006 are underestimated for ET and overestimated for the net balance due to an incomplete climate-data record.

[2] Scaling factor of one-eighth used based on observations at several small, unnamed channels and Smith Creek (a basin of similar size).

[3] Value estimated from average of area-runoff relations, n = 3.

[4] Total surface water in, values rounded according to significant digit considerations of budget entries. Totals may not sum exactly.

[5] Total surface water out, values rounded according to significant digit considerations of budget entries. Totals may not sum exactly.

[6] May 2007 values provided for informational purposes; values not used in 12-month budget scenario.

Table 7. Comparison of average, low, and high runoff scenarios on water balance of the Lake Crescent watershed, Washington, May 2006–April 2007.

[Negative values indicate more water leaving the system than accounted for by inputs. Values in columns might sum differently than values in report due to significant digits and rounding. Shaded cells indicate values used in estimating low, average, and high ungaged nutrient delivery. **Residual:** Assumed to be groundwater. **Abbreviations**: E, estimated; NA, not applicable]

Scenario	Annual runoff from gaged streams (acre-feet per hectare)	Annual net water balance, without ungaged areas (acre-feet)	Estimated annual runoff from ungaged basin area (acre-feet)	Residual (acre-feet per year)
Average	NA	–41,100	35,300	[1]E–5,900
Low runoff	3.66 (summer only)	NA	18,900	–22,300
High runoff	10.1 (eight winter months)	NA	[2]34,700	–6,500

[1] Estimate based on average annual runoff during summer base flow of the perennial streams only, Barnes, Lapoel, Piedmont (1.15 acre-feet per hectare) and applied to ungaged area (5,160 hectare) for annual groundwater input.

[2] Estimated annual runoff for ungaged part of the basin was adjusted by assuming no flow from July to October 2006.

High Ungaged Area Runoff Scenario

Statistical regression tools have been developed within the National Hydrologic Dataset-Plus (NHDPlus) software, a GIS data tool, intended to estimate mean annual runoff for ungaged basins. The datasets and tools provide application-ready geospatial data sets that incorporate many features of other GIS based datasets (Horizon Systems Corporation, 2006). Selected ungaged and gaged basins within the Lake Crescent watershed were delineated within the NHDPlus dataset that included estimates of mean annual runoff from the regression tools provided (table 1). These runoff estimates are higher than the annual runoff/area estimates generated from the gaged basins. That is, the steep topography and large amount of precipitation-dominated ephemeral streams were infrequently observed to carry large amounts of water during storm events (for example, see Smith Creek hydrograph in figure 7). Including the mean annual runoff estimates from NHDPlus for those ungaged basins where there is no gaging data, (for example, Cross Creek, Unnamed tributary near Lapoel, and Aurora Creek) along with the five gaged runoff/area estimates (total NHD sample size n = 8; table 1), the average runoff/area value is 10.1 acre-ft/ ha annually. This results in an annual ungaged basin production of 52,100 acre-ft of additional runoff. However, most ungaged streams were dry from the second week in July through October; therefore, the estimate of ungaged surface water is reduced by four-twelfths, resulting in 34,700 acre-ft. Including this runoff assumption into the annual water budget, where -41,200 acre-ft were unaccounted for, there is a residual of -6,100 acre-ft. This ‘High’ runoff scenario estimate, based on five gaged and three estimated runoff-area relations, of 41,200 acre-ft, is similar to the ungaged runoff value of 35,300 acre-ft, when groundwater was accounted for and ungaged runoff was assumed to be the difference.

Low Ungaged Runoff Area Scenario

A scenario for a low ungaged runoff might be arrived at by assuming the ephemeral gaged basins, Smith and Fairholm Creeks, are indeed more indicative of the ungaged basins, which are of similar size and were likewise observed to be ephemeral. Under these assumptions, only the average annual water yield per area for those two basins is used, or 5.57 and 1.74 (acre-ft/ha)/yr. Using the average of those, 3.66, and the ungaged area, 5,160 ha, an estimate of 18,900 acre-ft might be attributed to the ungaged areas. The result of these various scenarios on the overall water budget is compared and contrasted in table 7.

Groundwater

The groundwater system of the Lake Crescent watershed is difficult to assess because few wells or other access points are available to use or observe the regional groundwater-flow system. The flux of groundwater in and out of Lake Crescent is controlled by seepage through the geologic material at the lakebed surface, hydraulic permeability, and gradient of the surrounding geologic material. Groundwater flux to Lake Crescent likely is spatially and temporally variable because of the nature of surrounding geology and physical setting. The most likely areas for groundwater occurrence are in the fluvial deposits in the Barnes Point and Fairholm areas (fig. 4). These areas may yield some quantities of groundwater (Walters, 1970). Bedrock exposures of marine sediments and basalts are along much of the shoreline and little groundwater flux is expected from these locations. The steep terrain of the valley would suggest that if groundwater were present, the hydraulic gradient would be large and facilitate movement of groundwater. However, the geologic properties of the lakebed and adjacent bedrock are not conducive to transmit large quantities of groundwater. The thick accumulation of silt and clay sediments (fig. 6) can significantly restrict the movement of groundwater through much of the lake bed. Groundwater flux likely is much greater in the nearshore areas where wave action reduces the accumulation of fine grain sediment. Measurement of shallow groundwater flux in the nearshore of the lakebed was attempted at a few locations using seepage meters, but the sampling was problematic and the data are not reported here. Instead, groundwater flux was estimated indirectly by evaluating summertime base flow in gaged streams, and groundwater contribution was estimated by difference, after accounting for all other inputs and outputs.

Under the “average ungaged area” runoff scenario, an estimate of -5,900 acre-ft is attributed to groundwater (table 7). This approach assumes that summer base flow of perennial streams is representative of the groundwater available per area in other parts of the basin. If accurate, this volume of water attributed to groundwater is less than 5 percent of the annual measured outflow at the Lyre River. This relatively small contribution fits well with observations and the local geology, discussed previously. Interestingly, the value of 5,900 is similar to the 6,500 acre-ft/ha value arrived at under the ‘high ungaged area runoff ’ scenario, where a separate estimate of runoff per area from three ungaged basins, as reported in NHDPlus, is used along with the five measured runoff values, (n=8) to get an estimate of average annual runoff per area. Lastly, under the ”low ungaged area runoff” scenario (table 7), groundwater contribution is assumed to be much higher in order to balance the budget. In this approach, the groundwater contribution is about –22,300 acre-ft, or the equivalent of 30 ft^3/s for the year. Under this low ungaged area runoff scenario, which results in a high groundwater attribution, groundwater yield is 18 percent of the annual Lyre River outflow. Although higher than in other scenarios presented here and a sizable contribution, this ‘low runoff’ (high groundwater) scenario estimate is still reasonable for this location and geology.

Water Balance Summary

During the period of record of available streamflow, precipitation, and calculated evaporation, (not including the estimates of ungaged contribution), monthly net balances assigned as groundwater ranged from –9,500 acre-ft for May 2007 to 2,846 acre-ft in November 2006 (table 6). (A negative net balance indicates more measured water leaving the system than entering for the month.) A review of the monthly water balances for 2006–07 appears consistent with an Olympic Peninsula watershed that included higher elevations with substantial snowpack and the particular weather patterns of that year. That is, maximum negative values, presumed to be from ungaged runoff or groundwater contribution, are measured in May and June 2006 and again in April and May 2007. The only positive value, in November 2006, indicates a month when more water entered the system than exited (fig. 7). This is consistent with the quick increase in rainfall in November 2006 and a period of soil water absorption and water retention following a long period of low rainfall in summer and early autumn 2006 (table 6).

The inclusion of an estimate for the three small ungaged basins that were observed to be flowing occasionally, an estimated volume of 35,300 acre-ft, balances the budget within 5 percent of the total measured annual outflow. Additionally, if the surface water contribution from ungaged basins is applied over the 13 month period of record, by ‘scaling up’ the 12 month 35,300 acre-ft estimate, by an additional month (one-eighth was used for the additional month as opposed to one-twelfth as no flow was observed in many of the ephemeral streams and in Smith Creek, from July to October) the water budget balances to less than 8 percent. The similar estimated average value of –5,900 acre-ft/yr compared with –6,500 acre-ft/yr, from two scenarios of estimating groundwater (table 7), suggests that more confidence might be associated with values in this range. However, this difference is on the order of +10 percent, and is less than the measurement error and underlying variability that should be associated with the discharge measurement in this limited study.

In this study, the groundwater component was derived by difference (that is, attributing groundwater to the net balance after measuring or estimating other likely sources). Regardless of whether the 12 month annual budget or the 13 month period of record balance was used, it seems that after a contribution from ungaged areas is included, relatively little volume can be attributed to groundwater; less than 5 and 8 percent, respectively. These estimates are predicated on the assumption that there is no other loss of water from the system, except evaporation from Lake Crescent and the outflow to the Lyre River. However, some groundwater loss to Lake Sutherland (fig. 4) is possible and evaporation estimates likely underestimate total evaporation due to the location of the wind sensors. Overall, however, the water budget is useful for developing perspective on sources and sinks of water in the entire watershed, and provides a useful framework to assign measured nutrient concentrations (fig. 12). The lake level of the end of the budget period (May 31, 2007) was about 15 cm higher than it was at the beginning of the budget period. Given the lake surface area, this equates to 2,508 acre-ft of water storage that is not explicitly accounted for in the water budget. However, this value is less than 2 percent of the total annual export from the system (table 6), and is within the measurement error of the stream-gaging and evaporation measurements.

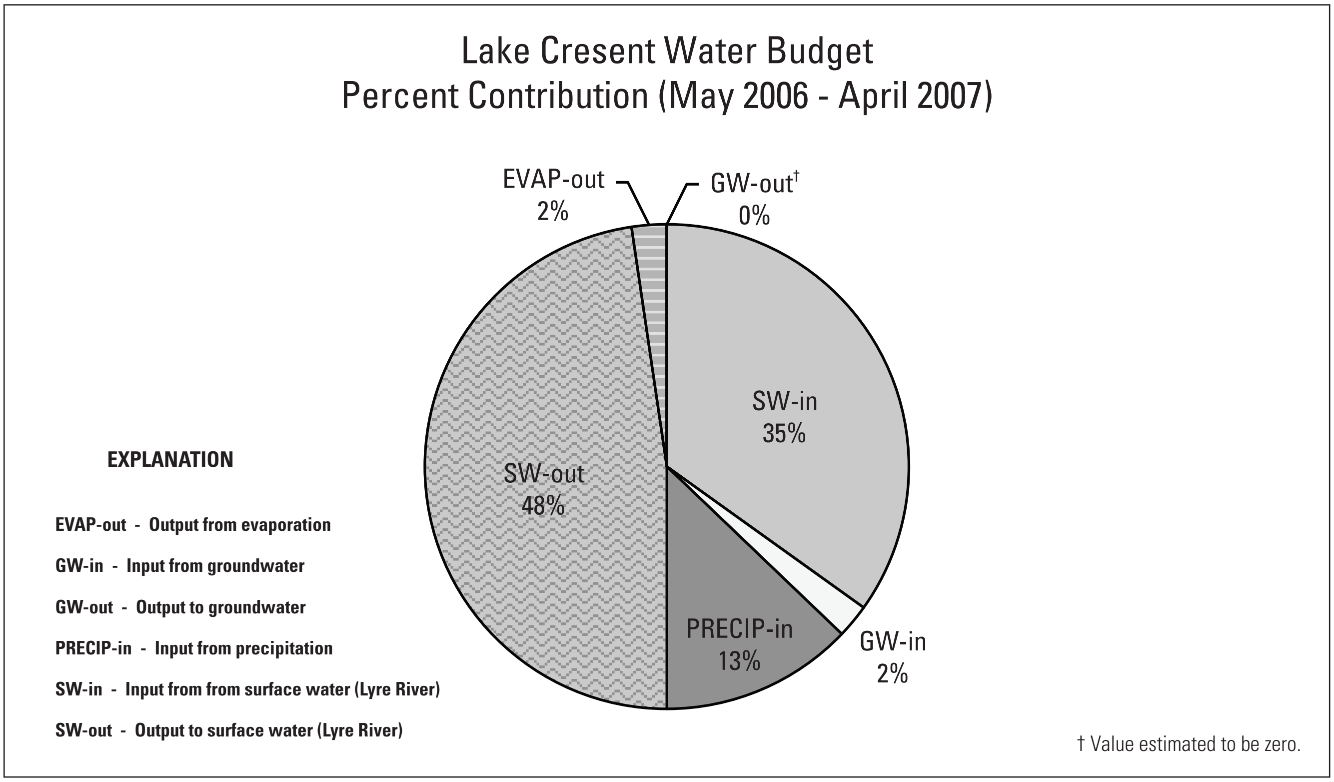


Figure 12. Water sources and sinks to Lake Crescent watershed, Washington, May 2006–April 2007, under 'average' scenario estimates.

The lake level of the end of the budget period (May 31, 2007) was about 15 cm higher than it was at the beginning of the budget period. Given the lake surface area, this equates to 2,508 acre-ft of water storage that is not explicitly accounted for in the water budget. However, this value is less than 2 percent of the total annual export from the system (table 6), and is within the measurement error of the stream-gaging and evaporation measurements.

Nutrient Balance

The primary component of the nutrient balance is the load transported into Lake Crescent by the tributary streams and the load transported out of the lake by the Lyre River. Estimated loads transported by streams are based on measured nutrient concentrations in streams and stream discharge. Other balance components are based on values applied to the Lake Crescent landscape and watershed.

Nutrient Transport in Streams

Total nitrogen and phosphorus loads transported by the gaged tributary streams and Lyre River were estimated with the program LOADEST (LOAD ESTimation) developed and documented by Runkel and others (2004), which is based on previous work by Cohn (1988), Cohn and others (1989), and Crawford (1991, 1996). LOADEST uses a calibration dataset consisting of instantaneous sample concentrations and a dataset composed of daily streamflows for the period of interest. The primary load estimation method used within LOADEST is Adjusted Maximum Likelihood Estimation (AMLE), which has been shown to have negligible bias when the calibration data set is censored (Cohn and others, 1992). LOADEST, which is included as an add-on in the TIBCO® Spotfire S+® statistical software package, 2008 ver., (TIBCO Software Inc., 2012) was used for estimating annual, monthly, and daily total nitrogen and phosphorus loads for this study.

Uncertainty associated with each estimate of mean load is expressed in terms of the standard error (SE) and the standard error of prediction (SEP). The SE for each mean load estimate represents the variability that can be attributed to the model calibration (parameter uncertainty). As explained in Runkel and others (2004), calculation of the SEP begins with an estimate of parameter uncertainty (the SE) and adds the unexplained variability about the model (random error). Because SEP incorporates parameter uncertainty and random error, it is larger than SE and provides a better description of how closely estimated loads correspond to actual loads.

The SEP is used within LOADEST to develop 95 percent confidence intervals for each estimate of mean load (Runkel and others, 2004).

For the annual estimates of TN, the ratio of the SEP to the load was largest for Smith Creek (32 percent) and smallest for the Lyre River (12 percent). For the estimates of TP, ratios of SEP to loads ranged from 0.06 for Fairholm Creek to 0.64 for Barnes Creek. This amount of error from model simulation results for the Barnes Creek TP estimate resulted in a relatively wide confidence interval with the lower limit of 1,540 kg/yr to the upper limit of 15,300 kg/yr. For all other estimates of TN or TP the SEP was less than about 33 percent of the load (table 8).

Model simulation results of daily loads from LOADEST also were compared with calculations of measured daily loads. For all five streams, estimates of daily loads appear reasonable (appendix F), when plotted alongside (plot not shown) the calculated monthly loads (fig. 13). Actual loads may vary depending on nutrient concentrations and stable or unstable discharge during sample collection. The load estimates for total nitrogen and total phosphorus by month, and their associated error bars, for the six gaged streams are shown in figure 13.

Table 8. Estimates of annual loads for total nitrogen and total phosphorus in streams and annual yields from tributary basins near Lake Crescent, Washington, May 2006–April 2007.

[Totals are rounded. **Abbreviations**: kg, kilograms; kg/ha, kilograms per hectare; (kg/ha)/yr, kilograms per hectare per year; kg/yr, kilograms per year; –, no data]

Stream	Total nitrogen					
	Total nitrogen load (kg/yr)	Standard error of prediction (kg/yr)	Percent error	Upper 95 percent confidence limit (kg/yr)	Lower 95 percent confidence limit (kg/yr)	Total nitrogen yield ([kg/ha]/yr)
Fairholm Creek at Fairholm	222	59	27	354	131	0.22
Lapoel Creek near Fairholm	544	154	28	906	299	1.81
Smith Creek near Fairholm	109	34	32	190	54	0.30
Barnes Creek near Piedmont	7,700	1,450	29	11,000	5,260	1.90
Piedmont Creek at Piedmont	997	154	15	1,360	770	7.36
Total input to Lake Crescent	9,570	–	–	13,800	6,510	–
Lyre River at Piedmont (annual loss from the lake)	5,580	680	12	7,030	4,350	–

Stream	Total phosphorous					
	Total phosphorus load (kg)	Standard error of prediction (kg)	Percent error	Upper 95 percent confidence limit (kg)	Lower 95 percent confidence limit (kg)	Total phosphorus yield ([kg/ha]/yr)
Fairholm Creek at Fairholm	22	2.7	6	25	20	0.02
Lapoel Creek near Fairholm	118	81	31	204	59	0.39
Smith Creek near Fairholm	25	16	29	42	14	0.07
Barnes Creek near Piedmont	5,750	8,100	64	15,300	1,540	1.42
Piedmont Creek at Piedmont	63	28	20	91	43	0.47
Total input to Lake Crescent	6,000	–	–	15,700	1,680	–
Lyre River at Piedmont (annual loss from the lake)	1,310	220	8	1,500	1,130	–

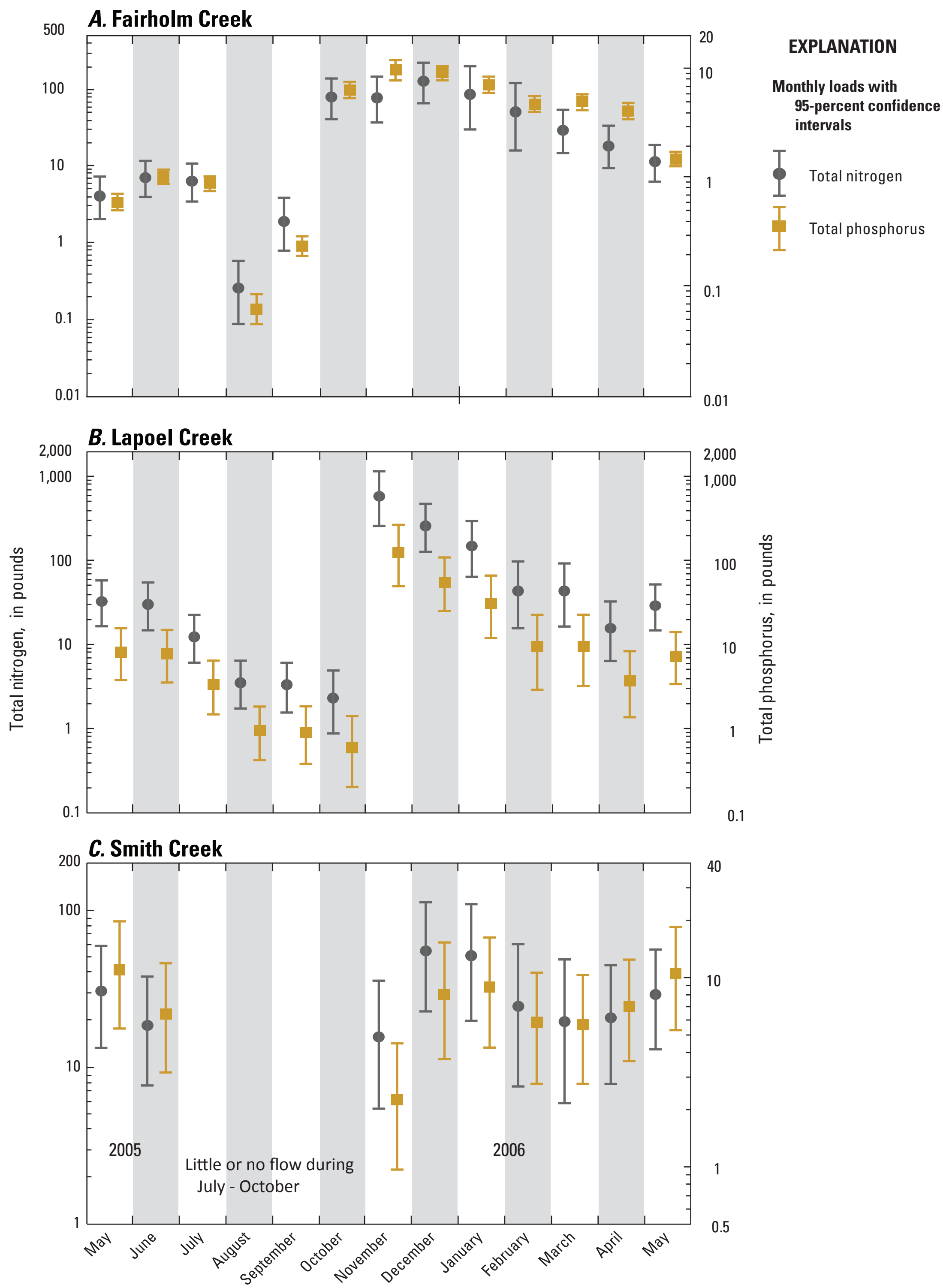


Figure 13. Estimated monthly nutrient loads in (*A*) Fairholm Creek, (*B*) Lapoel Creek, (*C*) Smith Creek, (*D*) Barnes Creek, (*E*) Piedmont Creek, and (*F*) Lyre River, near Lake Crescent, Washington, May 2006–April 2007.

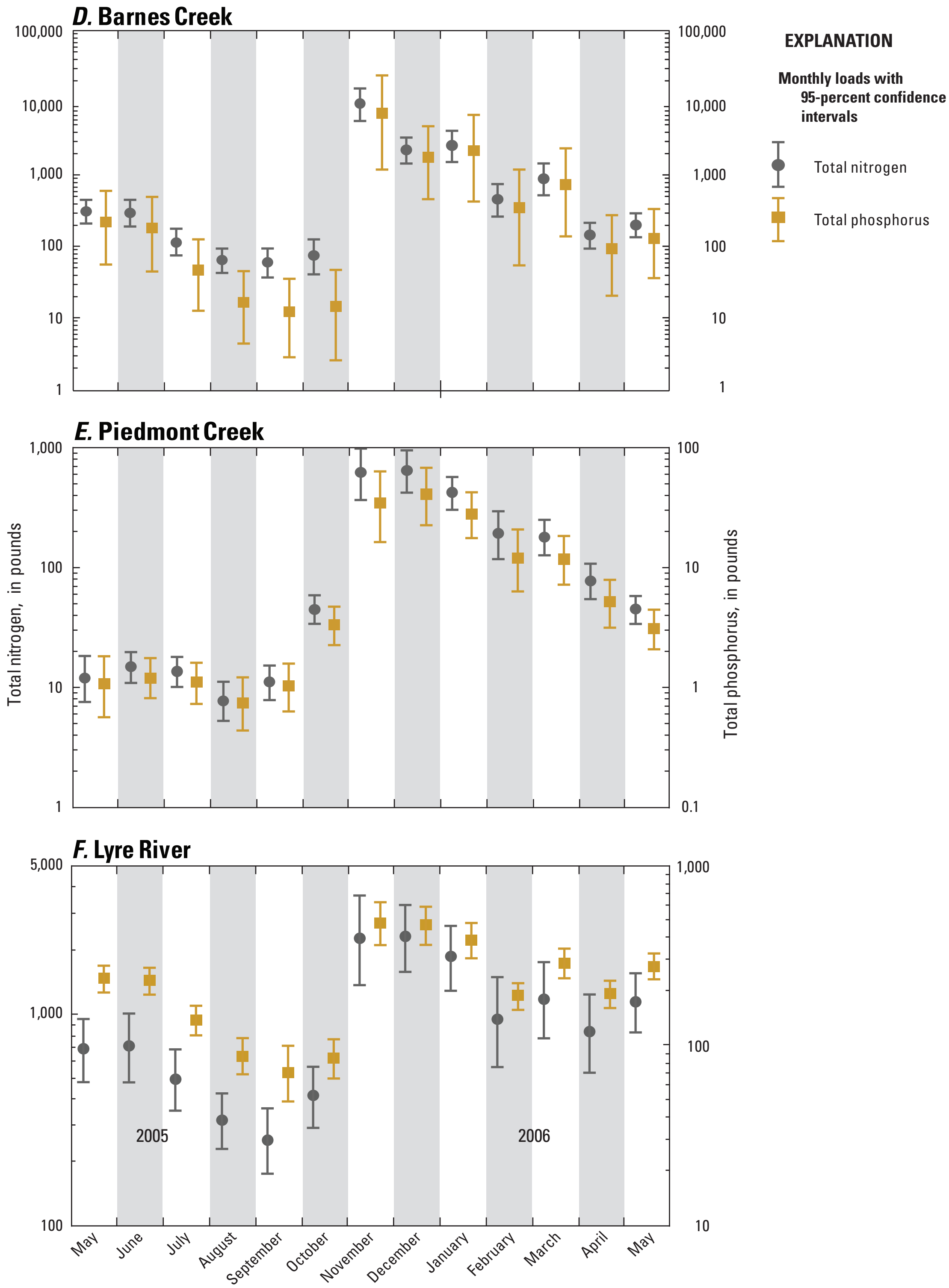


Figure 13.—Continued.

Average relative percent differences between model estimated and measured/calculated daily loads of TN ranged from 23 percent for Barnes Creek to 53 and 58 percent for Smith and Piedmont Creeks, respectively. The average relative percent differences for TP between estimated and calculated observed daily loads ranged from 9 percent for Fairholm Creek to 65 percent for Smith Creek and Lyre River. Some of the large differences for Smith Creek might be partly due to the small load amounts, which can contribute to large relative percent differences, and partly to collection of samples during rapidly changing discharge conditions (table 8; appendix F).

Nutrients from Ungaged Basins

Using the same rationale as for the water budget, nutrient loads through streamflow from the ungaged basins also can be estimated. Using the "average" scenario, 35,300 acre-ft of water is assumed to be produced from the ungaged areas. Nutrient delivery for this area (ungaged basin yield) from the ungaged basins was determined by assuming total ungaged yield is similar to the basin yield in the five measured basins. A nutrient in kilograms per basin area (square kilometers) value was calculated by dividing the total nutrients delivered for a given stream for the year (table 8), by the area of that basin (table 1).

The five measured kilogram per area estimates of nutrient yield (table 8), for TN and TP, were assumed to represent the range of likely values; upper and lower confidence intervals were used for estimating variability, or uncertainty in the ungaged basins estimate. These annual TN yield estimates applied to the ungaged basins, are variable and range from 0.22 to 7.36 (kg/ha)/yr (table 8). The highest yield of TN was from Piedmont Creek (7.36 [kg/ha]/yr), consistent with the observed high turbidity and sediment loads in this stream. The Piedmont Creek basin was the only basin with anthropogenic activity such as active logging, besides the cluster of established development in the Barnes Point area during the period of this study. However, as all ungaged basin stream channels were observed to be dry from July to October, those yield estimates (based on all streams annually) should be reduced by four-twelfths. This suggests that as little as 0 (1.7 average + 1.9 as the 95 percent confidence interval) and as much as 3.6 kg of nitrogen is produced per hectare from the ungaged basins. This TN yield estimate translates to a mean value of 8,770 kg produced from the 5,160 ha of ungaged basin area. Given the wide confidence intervals, this value could range from 0 to 20,000 kg TN annually (see low and high ungaged runoff scenarios, respectively; table 9). These values are presented in the overall nitrogen budget (table 9) as the ungaged area load entry.

Similarly, estimated TP yield from the ungaged basins ranged from 0.02 to 1.42 (kg/ha)/yr (table 8) with a mean of 0.47 and a standard deviation of 0.56. Reducing these also by four-twelfths to account for dry conditions during the summer months, the mean and 95th percent confidence interval for total phosphorus yield becomes 0.36 and 0.37 (kg/ha)/yr. Given the ungaged area, this results in average, high, and low estimates of ungaged area surface water production of 1,860, 3,770, and 0 kg, respectively (table 10).

Precipitation

Atmospheric precipitation can be a substantial source of nutrients to many terrestrial and aquatic ecosystems. The most consistent and highest quality measure of nutrients in precipitation is routinely collected through the National Atmospheric Deposition Program (NADP; National Atmospheric Deposition Program, 2012). NADP collects, reviews, and disseminates information of known quality regarding precipitation chemistry from numerous sites around the United States, including four active sites in western Washington. The site at the Hoh Ranger Station, Olympic National Park, approximately 25 km south-southwest of Lake Crescent, was actively collecting information during 2006 and 2007. Assuming the nitrogen concentration in precipitation falling to the lake is equivalent to the measured nitrogen from the Hoh NADP site (as nitrate plus ammonia) the total nitrogen load from precipitation can be calculated. For that location, the NADP program reports 56 measurements of ammonia and nitrate in precipitation from 2006 and 2007 (National Atmospheric Deposition Program, 2012). The average concentration of ammonia plus nitrate from those years was 0.180 mg/L, with a standard deviation of +0.145. Using this estimate, the concentration of nitrogen in precipitation, the measured volume from the budget period (203 cm), and the lake area of 2,030 ha, an average 7,420 kg of nitrogen was calculated, with an upper and lower estimates, based on the standard deviation, of 8,970 and 5,830 kg, respectively (table 9).

The NADP program does not collect phosphorous deposition information, and none was available for the Hoh site. However, Edmonds and others (1998) report phosphate concentration from 1987 to 1993 in rainwater from a West Twin Creek subbasin (farther up the valley from the Ho Ranger Station and closer in proximity to Lake Crescent). Edmonds and others (1998) report a 7-year mean value of 0.07 (+0.07) microequivalents per liter (µeq/L) phosphate in rainwater. Using this value and the average measured precipitation at Lake Crescent from May 2006 to April 2007, there is a calculated 91 kg of phosphorous deposition to the lake from precipitation. (This calculation assumes 0.03165 µeq/L PO_4 per milligram PO_4; 4.12E 10 L of precipitation to the lake surface from the May 2006 to April 2007 budget period). Using the standard deviation reported by Edmonds and others (1998), the 95 percent confidence interval is 23–159 kg total phosphate annually from precipitation.

Table 9. Annual total nitrogen balance for the Lake Crescent watershed, Washington, May 2006–April 2007.

[Values are in kilograms. Totals are rounded. **Symbol:** –, no data]

Average nitrogen deposition estimate			
Balance component	**Annual input**	**Annual loss**	**Balance**
Gaged stream load	9,600	–	–
Ungaged area load	8,770	–	–
Precipitation	7,420	–	–
Septic and waste-water	[1]623	–	–
Litterfall	1,820	–	–
Pollen	1,160	–	–
Alders	6,900	–	–
Vehicles	4,220	–	–
Dry deposition	674	–	–
Groundwater	1,470	–	–
Lyre River	–	–5,580	–
Sedimentation	–	–17,500	–
Total	42,670	–23,500	19,570

Nitrogen deposition estimates based on ungaged and groundwater scenarios						
Balance component	**High input scenario**			**Low input scenario**		
	Annual input	**Annual loss**	**Balance**	**Annual input**	**Annual loss**	**Balance**
Gaged stream load	13,800	–	–	6,510	–	–
Ungaged area load	20,000	–	–	0	–	–
Precipitation	8,970	–	–	5,830	–	–
Septic and waste water	[1]925	–	–	[1]325	–	–
Litterfall	2,070	–	–	1,570	–	–
Pollen	1,940	–	–	400	–	–
Alders	8,840	–	–	4,990	–	–
Vehicles	4,560	–	–	3,880	–	–
Dry deposition	810	–	–	540	–	–
Groundwater	1,090	–	–	2,680	–	–
Lyre River	–	–7,030	–	–	–4,350	–
Sedimentation	–	–19,100	–	–	–16,700	–
Total	63,010	–26,100	36,910	26,740	–21,000	5,740

[1] Value not used separately in total, but included in groundwater component.

[2] Totals adjusted for significant digits.

Table 10. Annual total phosphorus balance for the Lake Crescent watershed, Washington, May 2006–April 2007.

[Values are in kilograms. Totals are rounded. **Abbreviations:** NA, not applicable; –, no data]

Average phosphorous deposition estimate			
Balance component	**Annual input**	**Annual loss**	**Balance**
Gaged streams	6,000	–	–
Ungaged drainage area	1,860	–	–
Precipitation	91	–	–
Septic and waste-water	[1]81	–	–
Litterfall	224	–	–
Pollen	198	–	–
Alders	NA	–	–
Vehicles	NA	–	–
Groundwater	538	–	–
Lyre River	–	–1,310	–
Sedimentation	–	–8,980	–
Total [2]	8,990	–10,300	–1,310

High and low phosphorous deposition estimates based on ungaged and groundwater scenarios						
Balance Component	**High input scenario**			**Low input scenario**		
	Annual input	**Annual loss**	**Balance**	**Annual input**	**Annual loss**	**Balance**
Gaged streams	15,700	–	–	1,680	–	–
Ungaged drainage area	3,770	–	–	0	–	–
Precipitation	159	–	–	23	–	–
Septic and waste-water	[1]108	–	–	[1]54	–	–
Litterfall	255	–	–	193	–	–
Pollen	330	–	–	7.5	–	–
Alders	NA	–	–	NA	–	–
Vehicles	NA	–	–	NA	–	–
Groundwater	980	–	–	398	–	–
Lyre River	–	–1,500	–	–	–1,130	–
Sedimentation	–	–10,200	–	–	–7,790	–
Total [2]	21,300	–11,700	9,600	2,400	–8,920	–6,520

[1] Value not used separately in total, but included in groundwater component.

[2] Totals adjusted for significant digits.

Groundwater and Septic Systems

Samples from shallow groundwater were collected at undeveloped and developed sites, and specifically targeted downgradient locations from known and active onsite septic systems. Therefore, the septic contribution should be captured in the range of nitrogen and phosphorus concentrations in water samples that were collected for this study. As an additional informational exercise, estimates of potential onsite septic input from literature reported septic “escapement,” beyond the designed drainfields, is provided here for comparative purposes. However, although these septic input estimates are provided in tables 9 and 10, the line item is not included in the total input because they should be captured by the shallow groundwater sampling.

Onsite septic systems and the two sewage treatment plants were investigated to assess their potential contribution. During interviews with ONP staff and conversations with local residents, no indication of direct sewage or effluent discharge to the lake was reported. All homeowners and treatment facilities reported using drain fields, and (or) direct pumping out of septic tanks for offsite removal. In addition to interviews, samples of shallow groundwater were collected from the temporary drive point wells downslope of the apparent location of several active drain fields.

Elevated TN and TP concentrations measured in shallow groundwater (greater than that observed in undeveloped areas) collected immediately down slope of known onsite septic fields were not consistently observed during sample collection. A few high concentrations were measured, but they were in both developed and undeveloped shoreline areas (appendix F). However, several of the drain fields examined were close (less than10 m) to the lakeshore. Retention of nutrients in drain fields has been extensively studied and typically ranges from 50 to 90 percent (U.S. Environmental Protection Agency 2000, 2002). Given that, it is expected that some, but currently unknown, amount of nutrients likely is leaving septic drain fields and entering Lake Crescent. That amount is estimated here and provided in the nutrient budgets of tables 9 and 10 for informational and comparative purposes only.

Using estimates of annual visitor days (John Meyer and Steve Fradkin, Olympic National Park, written commun., January 2002), it was established that there were 79,676 person days of septic system use around Lake Crescent in 2000. This equates to an average of 219 users per day. Given that, and per person nutrient loading and drain field retention efficiencies provided by the U.S. Environmental Protection Agency (2000, 2002), an estimated contribution from septic systems was calculated (table 11). Given the extensive review by U.S. Environmental Protection Agency (2002, table 3–7), average, high, and low estimations for per person septic contribution were used in the average, high and low scenarios for Lake Crescent presented in tables 9 and 10. Using the U.S. Environmental Protection Agency (2002) average, high, and low loading values for nitrogen of 11.5, 17, and 6 g/d per person, and the day use estimates, results in an estimated nitrogen load of 623, and 921, 325 kg/yr, respectively, that may be entering Lake Crescent from septic sources. Similarly, average, high, and low loading values for phosphorus of 1.5, 2, and 1, g/d per person, resulted in average, high, and low estimated phosphorus concentrations of 81, 108, and 54 kg/yr, respectively, entering Lake Crescent from septic sources (table 11).

Table 11. Estimates of nitrogen and phosphorus loading from septic systems to groundwater based on 2002 shoreline population estimates, Lake Crescent, Washington.

[Estimates include visitors and staff. **Person days:** From 2000 (Meyer and Fradkin, 2002). **Loading to Lake Crescent:** From Environmental Protection Agency (2002, table 3-7). **Abbreviations**: g/d per person, gram per day per person; kg/yr, kilogram per year]

Location	Person days
Fairholm campground	12,730
Staff (2 people, 120 days per year)	240
Lake Crescent Lodge	15,017
Staff (10 people, 160 days per year, plus 4 people, 365 days)	3,056
Log Cabin Resort	13,247
Staff (10 people, 160 days per year plus 4 people, 365 days)	3,056
Olympic Park Institute/Rosemary Inn	5,730
Staff (10 people, 365 days)	3,650
Year-round residents	10,950
Seasonal residents	12,000
Total	79,676

Scenario	Loading to Lake Crescent (g/d per person)	Loading to unsaturated zone (kg/yr)	Loading to groundwater (kg/yr)
Total nitrogen			
Average	11.5	916	623
High	17	1,354	921
Low	6	478	325
Total phosphorous			
Average	1.5	120	81
High	2	159	108
Low	1	80	54

Groundwater budget entries in nutrient budgets of tables 9 and 10 for nitrogen and phosphorus reflect the median measured concentration, as discussed in the section "Groundwater" and presented in appendix E multiplied by the estimated volumes from the water budget. The locations shallow wells around Lake Crescent where water samples were collected and a plot of the cumulative distribution function for the nitrogen and phosphorus concentrations in those samples are shown in figure 9.

The cumulative frequency distribution (fig. 8) indicates that there are two populations within the data set, with a few samples indicative of an elevated nutrient source. Some of those samples were collected from developed shorelines and are assumed to represent a nutrient source. In estimating groundwater concentration for the entire watershed, the outlier adjusted concentrations (that is, outlier values not included) of TN and median TP, with the associated 95 percent confidence intervals are 0.16 and 0.05 mg/L, respectively (see appendix E for raw data).

In the water budget scenarios (table 7), the average and high ungaged annual runoff scenarios resulted in an estimate of –5,900 and –6,500 acre-ft of groundwater, respectively. Given the median groundwater concentrations, those ungaged scenarios result in groundwater loads of 1,470 and 1,090 kg of TN, and 538 and 398 kilograms of TP, respectively. (Groundwater loads are lower in the high ungaged-runoff scenario because more water is assumed to enter the lake as surface water, and at a higher concentration, than entering the lake as groundwater, which had lower concentrations of TN and TP; 0.16 and 0.05 mg/L median, respectively.) In the low ungaged runoff scenario, considerably more water is attributed to groundwater production. Assuming the value of –22,300 acre-ft/yr (table 7) might be groundwater, and the median concentrations from groundwater sample concentrations, 2,680 and 980 kg of TN and TP, respectively, is estimated as an "upper limit" of the estimated groundwater contribution to the lake (also see tables 9 and 10).

Other Sources

Researchers in forested ecosystems of the Pacific Northwest have determined that numerous terrestrial and anthropogenic sources contribute nutrients freshwater lakes. The sources relevant to this study include litterfall, pollen, vehicle emissions, and nitrogen fixation. Quantification of these other sources is presented for comparison purposes and should not be considered comprehensive or exact. The relative magnitude of some of the larger 'other' sources are summarized or estimated here for comparative purposes with the expectation that some inputs may be manageable from institutional or engineering controls and some may not. Some uncertainty remains regarding unaccounted for sources or sinks that are infrequent, difficult to quantify, or both, such as woody debris, landslides to the lake, fish escapement or harvest, water fowl, and motor boat operation. These sources are not discussed here but can be considered when managing the lake in the future.

Litterfall

Given the steep, forested, surrounding hillsides, various leaves, needles, branches, even whole trees can fall into Lake Crescent and can act as a nutrient source. Measurement of direct litterfall input was not done in this study; however, numerous studies of litterfall from Pacific Northwest forests, some in the Olympic forests, have been reported. Edmonds and Murray (2002) report a summary of litterfall estimates from the West Twin Creek drainage in the adjacent Hoh River drainage. They report a mean annual litterfall deposition, across two years and three forest habitat types at a similar elevation, of 2,938 + 408 kg litterfall per ha. Further, this rate of litterfall deposition resulted in 30.8 kg of nitrogen and 3.8 kg of phosphorus (Edmonds and Murray, 2002, table 3b) per year, per hectare to the soil. Using this estimate and a lakeshore acreage that is within one mature-tree width (local coniferous and alder species native are assumed to be 25 m), one-half of the annual literfall from the undeveloped shoreline is assumed to enter the lake. Given this assumption, the total acreage of litterfall within 20 m of the lakeshore was calculated, minus the areas of impervious surface in the 20 m buffer as determined from National Land Cover Dataset 2001 (Homer and others, 2007) Urban Land Uses classes 21 and 22 , was 59 ha. Given the nutrient composition in Olympic forest litterfall from Edmonds and Murray (2002) of 30.8 kg/ha for TN and 3.8 kg/ha for TP, an estimated average mass of 1,820 kg of nitrogen and 224 kilograms of phosphorus was contributed to the annual nutrient budget from litterfall. Using the confidence interval reported by Edmonds and Murray (2002) of 13.9 percent, the range in litterfall contribution in nitrogen may range from 1,570 to 2,070 kg (table 9), and in phosphorus from 193 to 255 kg (table 10).

Pollen

Several studies in forested ecosystems have demonstrated the significant role that pollen grains, primarily from coniferous tress, but other plants as well, can play in contributing to the nitrogen budgets of adjacent terrestrial (Solomon and Silkworth 1986; Lee and others, 1996a, 1996b; Perez-Moreno and Read, 2001) and aquatic (Richerson and others, 1970; McLennan and Mathewes, 1984; Doskey and Ugoagwu, 1989; Graham and others, 2006) ecosystems. Indeed, spatially large, conspicuous, yet thin layers of yellow-green pollen grains commonly are observed on Lake Crescent during spring days with low wind, and have been reported for other forested lakes (Richerson and others, 1970; Graham and others, 2006). For pine forest ecosystems, the annual deposition of pollen was reported in the 10–80 kg/ha range, and one study reported as much as 1–3 metric tons per hectare per year (Perez-Moreno and Read, 2001). Direct measurements of pollen deposition to the lake surface were not conducted during this study; however, previous research addressing pollen deposition to lakes was reviewed and is summarized in table 12. The total deposition of pollen per area (usually reported as grains per square centimeter) was remarkably similar within and across studies. Further, several of these forest-lake studies comment on sources of "regional pollen," pollen "rain," or both, that is not significantly affected by proximity to their shoreline pollen sources until after several kilometers (Allen, 1999; McLennan and Mathews, 1984; Lee and others, 1996b; Graham and others, 2006). Given these findings and the mountainous slopes around Lake Crescent, the deposition rate is assumed to be uniform across the lake surface.

Many pollen researchers in aquatic and terrestrial habitats have reported pollen grain deposition as numbers of grains per square centimeter (table 12). For the purposes of this nutrient budget, those values had to be translated to mass per area per year to determine a total deposition to the lake surface. This required an estimation of the weight per pollen grain. Weights of pollen grains have been measured by Erdtman (1943), Richerson and others (1970), and Lee and others (1996b) and also are summarized in table 12. Given those deposition rates and mass per pollen grain (as 1.5–263 grains per microgram), the estimated total pollen deposition to the lake was 53,500 kg, annually. Further, several other researchers have reported consistent ratios (as percent) of TN, as 2 percent, and TP, as 0.4 percent, to total pollen (table 12; McLennan and others, 1984; Solomon and Silkworth, 1986; Lee, 1996a).

The values summarized in table 12 were used to estimate 1,160 and 198 kg of nitrogen and phosphorus, respectively, from pollen deposited annually to Lake Crescent. Assuming the lower and upper 95 percent confidence interval around this average deposition rate, as 9 and 44 kg/ha, respectively, the estimated annual deposition rates range from 396 to 1,940 kg of TN and 7.5 to 330 kg of TP from pollen.

Table 12. Pollen deposition studies reviewed and applied to Lake Crescent, Washington.

[All deposition values are in kilograms per hectare, unless indicated otherwise. Because of the surface area of the lake, 2,030 hectares, and the average values shown here, an estimated 53,500 kilograms of pollen was deposited annually (1,160 kilograms as nitrogen and 198 kilograms as phosphorous). **Abbreviations**: grains/cm^2, grain per square centimeter; kg/ha, kilogram per hectare; µg, microgram; NA, not reported]

Author	Year	Average deposition	Units (annual)	Pollen (grains per microgram)	Total mass deposition	Average nitrogen (percent)	Average phosphorus (percent)
Lee and others	1996b	6,850	Grains/cm^2	NA	[1]9.79	NA	NA
McLennan and Mathews	1984	5,048	Grains/cm^2	NA	[1]7.21	NA	NA
McLennan and Mathews	1984	5,147	Grains/cm^2	NA	[1]7.35	NA	NA
Solomon and Silkworth[2]	1986	3,304	Grains/cm^2	NA	[1]4.72	NA	NA
Solomon and Silkworth[2]	1986	5,077	Grains/cm^2	NA	[1]7.25	NA	NA
Solomon and Silkworth[2]	1986	3,025	Grains/cm^2	NA	[1]4.32	NA	NA
Solomon and Silkworth[2]	1986	3,770	Grains/cm^2	NA	[1]5.39	NA	NA
Solomon and Silkworth[2]	1986	3,254	Grains/cm^2	NA	NA	NA	NA
Noll and Khalili	1988	NA		NA	94	NA	NA
Doskey and Ugoagwu	1989	NA		NA	65	2	0.29
Graham and others	2006	NA		NA	70	NA	0.5
Lee and others (P. mariana)	1996a	NA		26	16	NA	NA
Lee and others (all others)	1996a	NA		79	NA	2	0.29
Richerson and others (Abies)	1970	NA		1.5	NA	NA	NA
Richerson and others (Pinus)	1970	NA		2.4	NA	NA	NA
Lee and others (P. banksiana)	1996a	NA		51	25	NA	NA
Erdtman (13 species reported)	1943	NA		13–263; 123 median	NA	NA	NA
Perez-Moreno and Read	2001	NA			NA	2.5	0.4
Average		4,434	Grand average	102	26.34	2.17	0.37

[1] Indicates a value calculated from data presented in this report.

[2] Only values from sites with drainage areas greater than 5 kilometers were used (Solomon, 1986, table 1).

Vehicle Emissions

U.S. Highway 101 runs immediately along the southern shore of Lake Crescent (fig. 14). Using GIS information from 1:24,000 digital-ortho quadrangles, it was determined that 14.6 km of the highway is within 100 m of the lakeshore. Traffic volume along this section of highway was measured by the Washington State Department of Transportation (WSDOT; Washington State Department of Transportation, 2007). Measuring locations at mileposts 216, 227, and 232 of U.S. Highway 101 reported in Washington State Department of Transportation (2007) reflect traffic volumes adjacent to the lakeshore, and indicates an average traffic volume of 2,275 vehicles per day between 2004 and 2007, with 2006 having a near average value for those years at 2,200 vehicles a day. The report also indicates that in 2005, 18 percent of the traffic volume in that section of U.S. Highway 101 was trucks (defined as two or three axel trucks or buses).

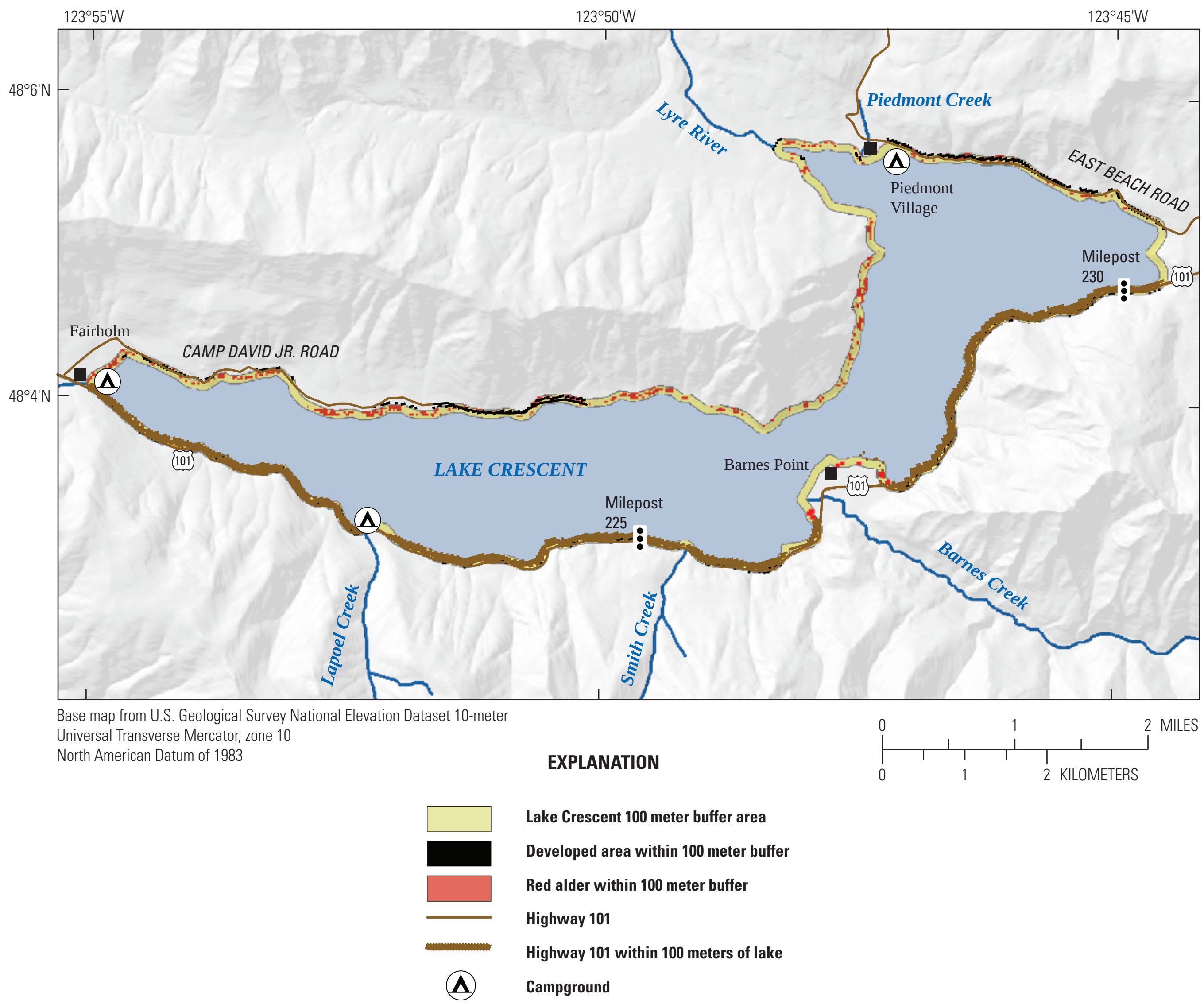


Figure 14. Summary of shoreline nitrogen sources to Lake Crescent, Washington.

NOx compounds from 37 privately owned and operated vehicles were measured, with an average mileage of 59,500 km per vehicle, in more than 36 weight-driving condition scenarios (Alvarez and others, 2008). A median value from those 36 scenarios, including both diesel and gasoline vehicles, was 0.38 g NOx/km driven. That median value was used for estimating nitrogen inputs from cars. For trucks or "heavy-duty" commercial diesel vehicles, Yankowitz and others (2000) reviewed numerous diesel emission studies and reported a mean fleet value of 16.9 (±0.6) grams of nitrogen per mile from chassis dynamometer studies and a mean of 11.8 (+1.16) grams of N per km from tunnel studies. These values were used for car and truck emission estimates in equation 3.

$$\text{Emissions} = (r) * (n) * (D) * (t), \quad (3)$$

where

- r is emissions rate in grams NOx /kilometers,
- n is number of vehicles per day,
- D is distance (kilometers), and
- t is time (days).

For the budget year of May 1, 2006, to May 31, 2007, 82 percent of the 2,200 daily traffic was assumed to be cars and 18 percent was assumed to be diesel trucks The relevant emission rates for cars and trucks were 0.38 and 14.3 g NOx/km (mean of 16.9 and 11.8 km), respectively. Given the 14.6 km of highway and 365 days per year, an estimated 3,650 and 30,200 kg of NOx compounds were emitted per year from cars and trucks, respectively, from U.S. Highway 101 traffic. The upper and lower confidence intervals around the mean (n=11) in the study by Alvarez and others (2008), indicate that the total emission rate by cars could range from 4,400 to 2,800 kg. Likewise, the review by Yankowitz and others (2000) reports 95 percent confidence intervals for 'heavy-duty emissions"; therefore, the total emission was estimated to range from 32,300 to 28,500 total NOx emissions from trucks annually.

Due to the close proximity of the highway to the lakeshore, often less than 30 m, the amount of precipitation in this region (65 in. per year lake average), the abundance of roadside streams and seeps, and the prevalence of tall and typically wet roadside rock surfaces, or "road-cuts." that all drain to the lake, some of the of the emitted NOx compounds adjacent to the lake are expected to enter the lake. Furthermore, air studies on NOx compounds have shown significantly elevated concentrations adjacent to highways, near ground level, in the first few hundred meters, and returning to background concentrations thereafter (Carslaw, 2005, Karner and others, 2010). Given that the lake width is wider than several hundred meters for all 14.6 km considered here, 12.5 percent of the emitted NOx compounds were assumed to enter the lake (The 12.5 percent NOx was determined from the assumptions that 75 percent of the NOx vehicle emission either undergoes moderate transport out of the watershed, is transformed in the atmosphere, or deposited into an immobile site. Of the remainder, 12.5 percent falls onto the south side of the highway where it is retained or consumed by forest vegetation, and 12.5 percent falls on the north side where it enters the lake). The dominant wind pattern is west to east, parallel to the direction of the highway. This is likely an underestimation on rainy days (67 of the 396 budget days had precipitation levels greater than 10 mm), and an overestimation on dry days (only 149 of the 396 days in period or record reported no measureable precipitation). Given a deposition rate of 12.5 percent, we estimate 4,220 kg of vehicle emitted NOx compounds end up in the lake for our 12-month budget period. Estimates for the high and low source scenarios were made using the confidence interval around the mean with the 11 emission estimates for cars, but not for trucks (n=2). The same 8 percent coefficient of variation from the cars study was assumed to represent the upper and lower estimates for the trucks (table 9). Studies of phosphorus emissions from vehicles were rare and not included in the budget estimates here.

Nitrogen Fixation

Due to the consistently measured saturated oxygen concentrations for the entire profile of the lake and its N-limited oligotrophic nature, nitrogen fixation in the lake was assumed to be negligible (Lewis and Wurtsbaugh, 2008). However, alder trees are known to have nodules with a nitrogen-fixing bacterial symbiote of a streptomycete family, *Frankia*, and the ability to fix N_2 gas (Brock and others, 1994). This has led several researchers in the Pacific Northwest to investigate the potential of reduced nitrogen production from stands of red alder (*Alnus rubra*) common to this region (Goldman, 1961; Van Miergroet and Cole, 1984; Cole and others, 1990; Compton and others, 2003). In particular, Compton and others (2003) examined 26 watersheds in the coast range of Oregon for alder, broadleaf, and conifer percent cover, and developed regression models for export of total nitrogen, nitrate, and dissolved organic nitrogen in stream water based on percent cover. Using equation 1 from Compton and others (2003), annual N export (kg N ha /yr) = -4.8 + 39.0 (broadleaf) + 29.0 (mixed) and the estimates of broadleaf cover (10.6 percent) and mixed forested cover (67.4 percent) in the 368.2 ha that compose a 100 m buffer around Lake Crescent, 6,900 kg of N was exported annually from the near shore area around the lakeshore. This buffer width cutoff is somewhat arbitrary, but it was selected to balance the competing needs of estimating input from the clearly abundant alder that dominate many of the rocky shorelines around the lake, while preventing double counting in the contribution from groundwater, which likewise was sampled in shallow drive points wells along the shoreline, including many types of tree cover and land use. Further, for their equation 1, Compton and others (2003) report a standard error of +5 and +7 (kg/ha)/yr for watersheds with 100 percent broadleaf and mixed cover, respectively. Given these error rates and assuming a normal distribution, we estimate an upper and lower 95 percent confidence interval of our 6,900 kg estimate as 8,840 and 4,990 kg per year, respectively. Dry deposition data, as opposed to wet deposition discussed above, is available from a National Park Service sponsored Clean Air Status and Trends Network (CASTNET) managed by EPA measurement site in Port Angeles, Washington, from 1999 to 2004. Dry deposition is defined as the product of chemical concentration and deposition velocity as measured by 3-layer filter packs and measured and modeled atmospheric conditions at the site. Wet plus dry deposition commonly is used to approximate total deposition, as was calculated for this study. However, the estimates from pollen and vehicle emissions, in the "Other sources" section, are each components that also may be measured by the filter packs and reported within the dry deposition value. This potential 'double counting' is noted, but reported separately for two reasons: (1) for comparative purposes, the estimates from various unique sources within the general "Dry Deposition" category is provided for specificity and to place each sub-component in perspective; and (2) given the uniquely confined, steep and forested nature of the Lake Crescent watershed and numerous springtime observations of large, floating pollen mats on the lake surface, pollen production in the watershed appears large and is expected to exceed that recorded by the Port Angeles site. Regardless of whether the dry deposition estimate is included from the CASTNET site or not, it is a relatively small value and constitutes less than 2 percent of the total annual nitrogen budget. Estimates of dry deposition due to phosphorus were not available from CASTNET program and are not included in the phosphorus budget herein.

Dry deposition was measured weekly by filter packs in Port Angeles, about 35 km to the east, between 1999 and 2004 within the CASTNET network. The average of the six annual average deposition values reported by the network (U.S. Environmental Protection Agency, 2012) for the Port Angeles site is 0.332 kg N/ha. Including this deposition rate and the total lake surface (2,030 hectares), an annual estimate of 673 kg is calculated for dry deposition. The upper and lower 95 percent confidence interval around this value, 540 and 810 kg, respectively, were used in the high and low scenarios.

Dry Deposition

Dry deposition data, as opposed to wet deposition discussed above, is available from a National Park Service sponsored Clean Air Status and Trends Network (CASTNET) managed by EPA measurement site in Port Angeles, Washington, from 1999 to 2004. Dry deposition is defined as the product of chemical concentration and deposition velocity as measured by 3-layer filter packs and measured and modeled atmospheric conditions at the site. Wet plus dry deposition commonly is used to approximate total deposition, as was calculated for this study. However, the estimates from pollen and vehicle emissions, in the "Other sources" section, are each components that also may be measured by the filter packs and reported within the dry deposition value. This potential 'double counting' is noted, but reported separately for two reasons: (1) for comparative purposes, the estimates from various unique sources within the general "Dry Deposition" category is provided for specificity and to place each sub-component in perspective; and (2) given the uniquely confined, steep and forested nature of the Lake Crescent watershed and numerous springtime observations of large, floating pollen mats on the lake surface, pollen production in the watershed appears large and is expected to exceed that recorded by the Port Angeles site. Regardless of whether the dry deposition estimate is included from the CASTNET site or not, it is a relatively small value and constitutes less than 2 percent of the total annual nitrogen budget. Estimates of dry deposition due to phosphorus were not available from CASTNET program and are not included in the phosphorus budget herein.

Dry deposition was measured weekly by filter packs in Port Angeles, about 35 km to the east, between 1999 and 2004 within the CASTNET network. The average of the six annual average deposition values reported by the network (U.S. Environmental Protection Agency, 2012) for the Port Angeles site is 0.332 kg N/ha. Including this deposition rate and the total lake surface (2,030 ha), an annual estimate of 673 kg is calculated for dry deposition. The upper and lower 95 percent confidence interval around this value, 540 and 810 kg, respectively, were used in the high and low scenarios.

Nutrient Budget

The largest nutrient budget entries for nitrogen and phosphorus to Lake Crescent were from the various components of the hydrologic cycle, including the in-lake sedimentation. Because of the large amount of precipitation in this region (203 cm measured during this budget period of record) and the steep terrain, there is a large contribution of nutrients from surface water (tables 9 and 10; figs. 15 and 16). Similarly, the estimated input from ungaged basins is of a similar magnitude as that from precipitation input (see tables 9 and 10). Although measurements of nitrogen and phosphorus were made with unfiltered samples, the role of suspended sediment in delivering nutrients is still not clear. Given the precipitation pattern, terrain, and hydrologic measurements, storm events clearly play a significant role in nutrient delivery. Characterization of the sediment load and sediment concentrations during storm events, although attempted, was beyond the scope of this project; however, future research is needed to address this known data gap. Such information would may show an increase the estimated contribution of nutrients from gaged and ungaged basins alike.

Although nitrogen input from alder trees was roughly the same magnitude as precipitation, and at times, the same as the contribution from the gaged basins (both previously reported in studies of Pacific Northwest watersheds), the estimated TN input from vehicles was less than expected. Relative estimates of nitrogen sources from partially developed watersheds of the Olympic peninsula region were also evaluated by Steinberg and others (2011). They concluded the relative role of alder is substantially larger than that of onsite septic systems.

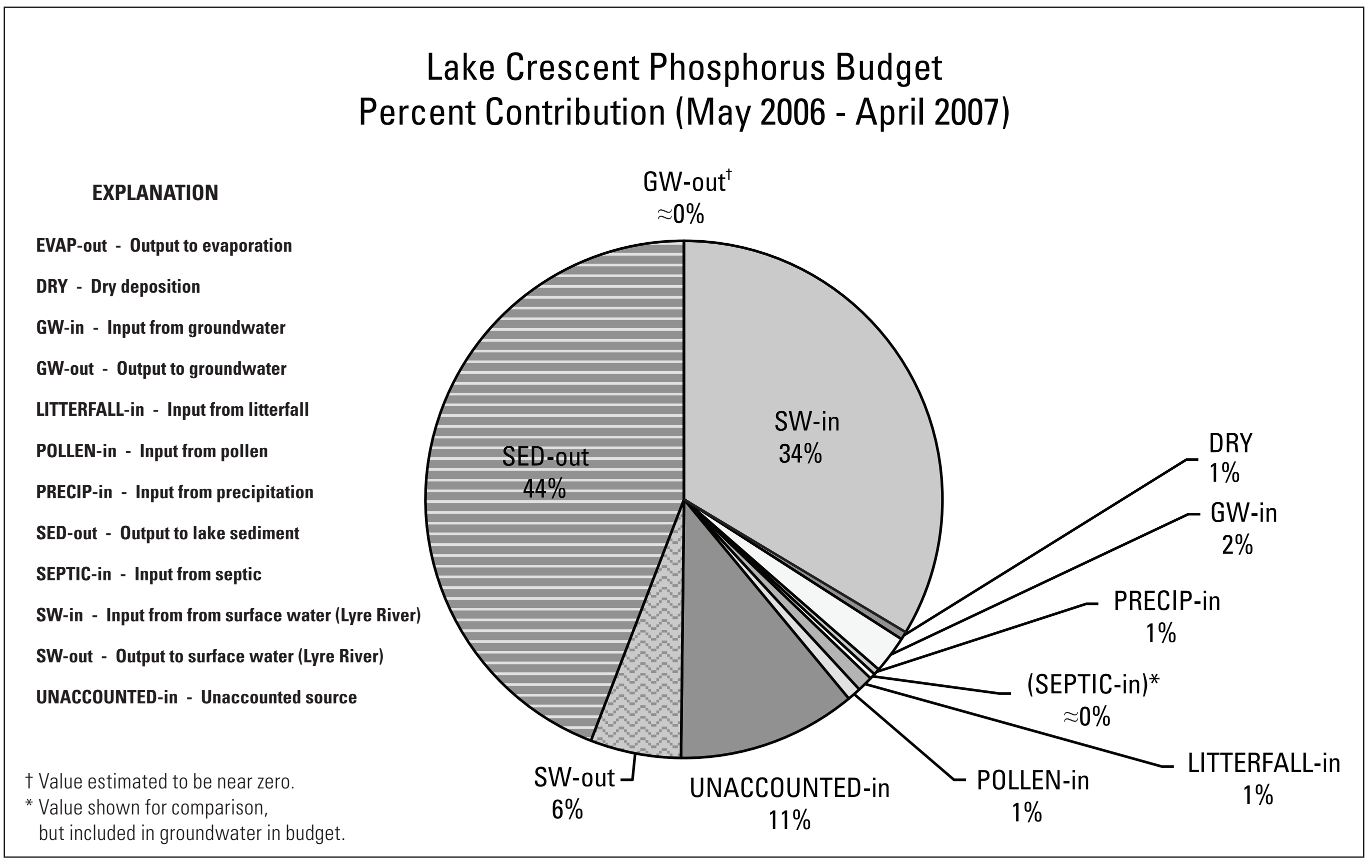


Figure 15. Total phosphorus sources and sinks to Lake Crescent watershed, Washington, May 2006–April 2007, under 'average' scenario estimates.

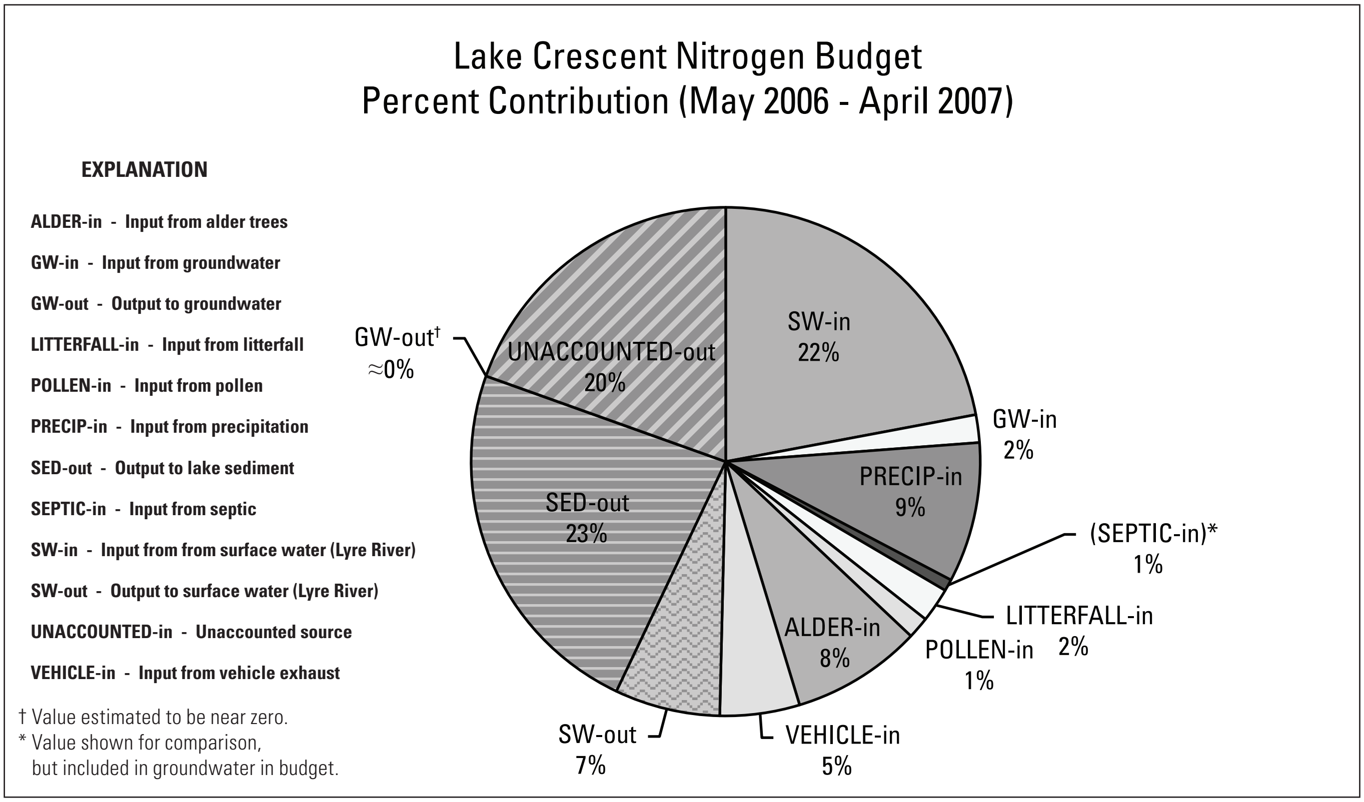


Figure 16. Total nitrogen sources and sinks to Lake Crescent watershed, May 2006–April 2007, Washington, under 'average' scenario estimates.

Uncertainties

Despite the measurement of more than 500 samples for nutrient concentrations and thousands of environmental observations logged during the budget year, there is still significant uncertainty in reporting the sources and sinks of nutrients in a watershed of this scale. This challenge is not unique, and the inherit uncertainties in estimating a watershed or lacustrine nutrient budget have been previously noted by Nelson and Larson (1996), Wetzel (2001), LeBaugh and others (2009), and Winter and Rosenberry (2009). Much of this uncertainty has to do with the scale and heterogeneity of this and other basins of its size and the difficulty of sufficiently characterizing the variable geology and biology across such a scale. Secondly, several components, such as sedimentation and groundwater movement, are difficult to sample or observe. Additionally, there is uncertainty in the procedures and formulas used in the calculation and error estimation process. Nevertheless, these whole watershed approaches have been insightful to help understand the various sources and processes that control ecosystem function (Likens and Bormann, 1999).

For calculated values in the report, the confidence values provided do not reflect a multiplication of the upper or lower confidence values for each of the subvariables, (for instance, if variable A, variable B, and variable C were multiplied). Doing so usually resulted in upper and lower estimates that appeared nonsensical and ultimately were not helpful. Rather, the variance in each subvariable was examined for a given budget entry, such as pollen, and the upper and lower confidence intervals around the single subvariable with the greatest overall magnitude of variation on the outcome was then used to report the variance in the final value. The average value for the other variables were then used when more than one variable was considered in a given budget entry.

Denitrification (when nitrogen compounds are converted through the bacterially mediated reduction of nitrogen to nitrogen gas or nitrous oxide and released) was not measured in this study. Several literature reviews on this topic for lake ecosystems (Seitzinger, 1988; Wetzel, 2001) determined that for oxygenated, oligotrophic systems, this value is likely to be small and (or) difficult to measure. Reported denitrification values from sediments of cold, oligotrophic, oxygenated lakes are either not reported, or when occasionally reported, rates are very slow. If those slow rates of denitification are applied over the area of Lake Crescent, a denitrification "estimate" results in a nitrogen sink orders of magnitude greater than the entire nitrogen budget presented here. Although this topic is ripe for more investigation, (see review by Burgin and Hamilton [2007]), these pathways in an oxygenated, oligotrophic systems are considered to be minimal (Wetzel, 2001; Pina-Ochoa and Alvarez-Cobelas, 2006; Lewis and Wurtsbaugh, 2008). Hence, dentrification is assumed to be negligible in this lake setting. However, because all three current nitrogen budget scenarios show an annual excess of nitrogen delivered to a particular lake, an accurate and representative estimate of denitrification in lake sediments might help balance the nitrogen budget.

However, several budget entries, such as nitrogen from pollen, vehicles, and phosphorus in precipitation, required a number of assumptions, and the conversion and scaling-up to an area appropriate for Lake Crescent. This scaling up process undoubtedly resulted in the magnification of errors from each of the individual studies. Effort was made to be as transparent as possible in the calculation and presentation of data so that future readers or managers might be able to update and recalculate particular budget entries as new or more appropriate information becomes available.

Lake Crescent is situated in a steep basin and is expected to obtain groundwater inflow along all of its margin; however, the upland areas on the east end of the lake are limited to a massive, historical landslide blockage that separated Lake Crescent from Lake Sutherland. The landslide resulted in lake Crescent being about 25–26 m higher in elevation, which would support a substantial hydraulic gradient over the horizontal distance of roughly 1,500 m through the blockage between the lakes. Groundwater flow through the landslide blockage is likely to occur at some depth, although that depth is not currently documented. The existence of such a lake bed 'leak' would indicate an increased role of groundwater, ungaged runoff, or both, than indicated in this report. However, as summarized in figure 12, the role of groundwater in the system is estimated to be low, or about 2 percent of overall budget.

Further, the values from numerous literature-sources are estimates. The values used, although sometimes from studies in ONP, were not developed specifically for the Lake Crescent watershed. Application of values of study results from other environments or ecological settings to Lake Crescent includes an unknown level of uncertainty. As more research and basin specific studies become available, these estimated budget entries could be revised (see fig. 12).

Summary

Although a number of assumptions were made in closing the water budget, and three scenarios are presented, the water mass balance appears surprisingly balanced. Under the average runoff scenario, which assumes summer base flow in the smaller gaged basins is indicative of the year-round groundwater flow in ungaged basins of that size or smaller, about 4.5 percent more water is leaving the system than entering. (This assumes that subsurface or shallow groundwater flow produced in the ungaged areas is equivalent to this summer low-flow rate.) If the difference in the lake level is considered between May 2006 and May 2007, this value is 2.7 percent. This relative balance in the water budget is further confirmed by a second estimation approach used in the high runoff scenario. Here, no assumptions about summer base flow are made, rather the runoff per area relation from the five gaged basins and three NHD Plus values are averaged to obtain a common runoff/area relation for the ungaged basins. In this approach, 5 percent more water is estimated to be entering the system than leaving the system. Conversely, if one assumes that all the ungaged, small basins (which were ephemeral) are characterized best by just the ephemeral, similar sized gaged streamflow rates, (that is, Smith and Fairholm Creeks in particular), then there is a net unaccounted for flow equal to 17 percent of the total outflow. This flow is assumed to come from groundwater in the low runoff scenario.

The review of overall budgets for total nitrogen indicates the relative size and complexity of the numerous nutrient sources in this study. In the three budget scenarios developed, more nitrogen is entering the Lake Crescent system than is leaving with a nutrient balance in the range of 5,700 to almost 37,000 kilograms per year. This surplus is assumed to be present annually as a storage term in the primary and secondary production in the lake and in littoral zones; however, secondary production was not quantified in this study. Although the sedimentation rates should account for production in the central basins of the lake, the ability of the sediment cores to reflect sedimentation in the littoral zones is questionable. The most likely nutrient sinks not quantified are denitrification and other chemical and microbial nitrate removal processes, which were not measured in this study. As anticipated, sources of nutrients from surface water, such as the gaged and ungaged basins and precipitation were the dominate source of nitrogen to Lake Crescent. However, the role of litterfall, pollen, and vehicles, even when their inputs are applied over small percentages of the adjacent shorelines, were considerable. Alder trees also seem to play a dominant role in contributing nitrogen to the lake, as demonstrated in other Pacific Northwest watersheds.

Differences in water and nutrient yield were noticeable across the gaged sub-basins. Barnes Creek contributes the largest input to the system, accounting for 31 percent of the watershed area, 84 percent of the measured streamflow to the lake, and 80 and 96 percent of the nitrogen and phosphorus streamflow inputs. Also noticeable from a comparison from these sub-basins is the elevated role that Piedmont Creek plays, relative to the other basins. The largest water yield (runoff per area) of all the measured basins and the highest and second highest nitrogen and phosphorus yields, respectively, was from Piedmont Creek. The nitrogen yield from Piedmont Creek is significantly higher than that from the other four basins (one-sided T-test, p-value 0.018). This was the only subbasin with markedly different overall land use. A predominate amount of the basin is owned as private timberland and an active logging operation was ongoing during the study.

Water was sampled from approximately 50 shallow wells along developed and undeveloped shorelines. Elevated nitrogen concentrations were measured in 8 of approximately 50 sampling locations. Similarly, although a few elevated concentrations were measured in drive point wells along developed shorelines, approaching 2 and 3 milligrams per liter, all other samples were not elevated, and there was no consistent indicator from developed shorelines. The literature-based estimates of potential nutrient delivery from onsite septic storage, based on a review and recommendation by the U.S. Environmental Protection Agency, suggests that relatively little total nutrient is expected to leave the drainfield systems. However, it has been demonstrated that this 'retention' in the drain field is really a storage term, that maybe available under different conditions, (for example, disturbance), and little nitrogen or phosphate may be actually removed. Although a few high concentrations were measured during this study, adjacent to the Log Cabin Resort and Lake Crescent Lodge, those concentrations were considerably lower than other sites in Washington with known septic nutrient issues. Similarly, many of the lowest concentrations in groundwater came from shallow wells in developed areas. Because of the lack of a clearly measureable indicator downgradient of septic drain fields, a literature-based estimate based on the number of shoreline residents and users also was included. This accounting suggests a relatively small potential contribution to Lake Crescent from septic tanks and drainfields. Furthermore, estimates from the septic and groundwater combined would need to be increased by a factor of 5–10 before they would begin to approximate the estimates for alder trees or vehicles.

There is significant uncertainty in the estimate of nitrogen contribution from alder trees. Specifically, the estimate of alder abundance and density, and the somewhat arbitrary designation of what buffer width (100 meters in this case) to consider as contributing to the lake, are areas of considerable uncertainty in the alder estimate. Although alder beyond the buffer width is also assumed to be a nitrogen source, it is expected that this upslope production would be consumed locally or reflected in the shallow groundwater concentrations. It could be argued that alder not be included separately, as their total contributions should be reflected in the groundwater sampling. However, because of the great abundance and density of alder immediately along the rocky shoreline it was decided that this 'alder proximity' needed special consideration. The role of alder at a nitrogen source of Pacific Northwest watershed is an area of active and ongoing research.

The budget for phosphorus is considerably different than for nitrogen. In two of the three scenarios, more phosphorus is estimated as leaving the system than entering. This is not unexpected, because soils and lakebed sediments generally serve as a significant 'onsite' source of phosphorus in lakes. Suspended sediments are known to be the predominant transport mechanism for phosphorus in streams. Characterization and quantification of nutrients specifically in the suspended sediment load, as opposed to the dissolved or whole water fractions, of the gaged streams was attempted (data not reported here). However, such an effort involves storm sampling and requires equipment that was ultimately determined to be beyond the scope and budget of this study. Estimation methods of suspended-sediment load and the associated nutrient load of those sediments are generally not recommended.

Nitrogen and phosphorus are reported as total values, not filtered, and reflect the degree of suspended sediments that were present at the time of sampling. Likewise, close examination of the phosphorus load plots confirms the well-described exponential relation between streamflow and suspended-sediment load (and therefore phosphorus). Furthermore, infrequent or episodic storm events cause streamflow to deliver large volumes of suspended sediments, as evidenced by the large, shallow submerged alluvial fan at the mouth of Barnes Creek, would bring large volumes of nutrients, phosphorus in particular, to the lake. The characterization and quantification of those storm events, when they occur, and the character of the materials they mobilize, could prove to be significant sources of nutrients and should be considered in future studies.

The nutrient budget for Lake Crescent shows that the watershed acts essentially as a closed basin, with the exception of streamflow out through the Lyre River. Any nutrients brought into the system by vehicles, people, consumable products, or waste will remain in one form or another unless physically removed from the basin or denitrified to nitrogen gas. Although change in chemical form or retention in soils or as plant material, for example, is possible, from a mass balance perspective, the nutrient will remain within the watershed until it is removed. The various forms of nitrogen are particularly mobile in wet soils and aquatic systems; they would be transported along flow paths and have the potential to affect the oligotrophic nature of the lake. With the tendency of phosphorous species to sorb strongly to particles, large buffering, storage, and burial processes in the soil and sediments are expected.

Recommendations

The following list of recommendations regarding nutrient inputs to Lake Crescent are provided to more effectively communicate to managers, scientists, and interested parties where opportunities lie to improve the understanding and the science of nutrient dynamics and nutrient mass balance in the watershed. In addition, some management considerations regarding nutrient management are provided.

- *Suspended Sediment Delivery*. A study of suspended and bed load delivery from the major input streams, first from Barnes Creek and second, from Piedmont, Smith, and Lapoel Creeks is recommended to quantify the episodic nature of sediment-bound nutrient delivery. As discussed in the "Uncertainties" and "Summary" sections, a large pulse of nutrients seems to be delivered during episodic storm events where suspended and bed sediments are mobilized. (A large delta is visible in the lake downstream of the mouth of Barnes Point and local residents report landslides and road or culvert washouts.) Sediment nutrient loads are a function of streamflow, the concentration of suspended material, and the associated nutrient concentration on the suspended material. Large storm events appear to play significant role in this watershed. A multi-year stream-gaging and storm-related sediment sampling regime at Barnes Creek would be the best way to address this data gap. Quantifying these events was considered for this study, and some initial efforts were made toward the end of the study, but these efforts were determined to be beyond the scope of this study and warrant a separate investigation.

- *Phosphate deposition data*. Phosphate is not regularly reported by either the wet (NADP) or dry (CASTNET) deposition programs. Available wet deposition data were used from a smaller study in the adjacent Hoh River Basin, but the degree to which that data is representative and (or) is subject to through fall at the sampling site is unknown. It is recommended that aerial phosphate deposition to the lake surface and the phosphate load associated with suspended sediments in the tributary streams be explicitly quantified to fully refine the overall phosphate budget for the lake.

- *Traffic volumes along East Beach and Camp David Junior*. Due to additional entry and exit points between the WSDOT reporting milepost, (that is, driveways, residential streets) the volume of vehicle traffic that may be traveling along East and Camp David Junior Roads (each road has sections adjacent to the lake) was not clear. A better traffic estimate for these areas would help refine overall input assigned to vehicles by including these areas. This is especially important for East Beach Road where some 'commuter' traffic may occur along the Joyce-Piedmont Road that connects State Highway 112 and U.S. Highway 101.

- *Roads*. Estimates from a review of the literature and the accounting provided in the "Vehicle Emissions" section, indicate that input from vehicle traffic along U.S. Highway 101 is disproportionate for diesel trucks as a nutrient source. From the 2005 WDOT traffic data, multi-axle diesel trucks account for 18 percent of the traffic on Highway 101 along Lake Crescent, but account for about 89 percent of the nutrient emissions (see section "Vehicle Emissions"). Controlling or limiting diesel traffic or improving diesel emissions in this section of Highway 101 should decrease nutrient input from road runoff.

- *Vegetated ditches (Bioswales), constructed wetlands, and retention ponds*. Many published studies indicate that vegetated areas that receive and slow the runoff from impervious surfaces and increase contact time with plants and soils, can eventually improve water quality. These vegetated ditches, constructed wetlands, or ponds could be considered, but with the understanding that for nutrients the uptake and conversion of nutrients delivered by runoff into plant material is a permanent solution only if the plant material is harvested and removed and the wetland or retention ponds are maintained. Studies have shown that nutrients are released upon the death and breakdown of plant materials and improperly maintained retention ponds (Reed and Brown, 1992).

- *Nitrate removal process*. Perhaps the most intensive and challenging scientific unknown would be testing for the presence of and quantifying one of several chemical or microbial nitrate removal pathways possible in various habitat types present within the lake. Given the sizeable lake area, any quantified rate, scaled to the lakebed, is likely to be a sizable number. However, such approaches are not straightforward and would be difficult to conduct in the deeper sections of the lake.

- *Refinement of sedimentation rate*. As discussed in "Lake Sediment Coring" and "Uncertainties" sections, the ability of the sediment cores from the deepest basins of the lake to reflect the sedimentation rates in the littoral zones adequately, as minimal as they may be, is questionable. Additional measures of sedimentation rates in littoral zones could be accomplished with submerged sediment traps, as opposed to more coring and dating. These traps could be installed to capture sediment settling from the water column over various time scales. In lacustrine applications, sediment traps do not require the constant maintenance and storm chasing efforts as needed for streams.

- *Denitrifying Permeable Reactive Barriers*. Nitrate removal has been shown to be accelerated in soils where various mineral or organic materials are added to the unsaturated zone to promote the removal of nitrate by a variety of pathways, including precipitation, sorption, and denitrification. These removal methods would be most effective when placed downgradient of large drain fields adjacent to the lake (Beal and others, 2005b; Robertson and others, 2008).

- *Proper inspection and maintenance of existing septic systems*. A number of authors and agencies have pointed to the need for and benefits of increased accountability and maintenance of septic systems as an important step in preventing surface or groundwater pollution (U.S. Environmental Protection Agency, 2002; Beal and others, 2005a and 2005b; Washington State Department of Ecology, 2012).

Acknowledgments

The authors would like acknowledge and thank the contributions from numerous individuals who made this study possible. First and foremost was the assistance provided by Olympic National Park, William Baccus and Hazel Levine in particular, in collecting meteorological, stream, and lake data in all types of weather. Michael Kalahar, also with Olympic National Park, provided insightful background regarding the infrastructure and facilities in the Lake Crescent watershed. From the U.S. Geological Survey, Joseph Gilbert conducted much to stream gaging and water quality sampling reported here and, along with Robert Drzymkowski, provided insightful approaches to generating streamflow estimates from limited datasets.

References Cited

Allen, G.B., Brown, K.J., and Hebia, R.J. 1999, Surface pollen spectra from southern Vancouver Island, British Columbia, Canada: Canadian Journal of Botany, v. 77, p. 786–799.

Alvarez, R., Weilenmann, M., and Favez, J. 2008, Evidence of increased mass fraction of NOx emissions of modern light vehicles—Derived from a reliable online measuring method: Atmospheric Environment, v. 42, p. 4,699–4,707.

Beal, C., Gardner, E., Christiansen, C., and Beavers, P., 2005a, A review of on-site wastewater practices in south-east Queensland: Water, v. 32, no. 4, p. 69–74.

Beal, C.D., Gardner, E.A., and Menzies, N.W., 2005b, Process, performance and pollution potential—A review of septic tank-soil adsorption systems: Soil Research, v. 43, no. 7, p. 781–802.

Bergstrom, A.K., Blomqvist, P., and Jansson, M., 2005, Effects of atmospheric nitrogen deposition on nutrient limitation and phytoplankton biomass in unproductive Swedish lakes: Limnology and Oceanography, v. 50, no. 3, p. 987–994.

Boyle, T.P., and Beeson, D.R., 1991, Trophic status and assessment of non-point nutrient enrichment of Lake Crescent, Olympic National Park: National Park Service, Pacific Northwest Region Technical Report NPS/PNRWR/NRTR-91/01, 51 p.

Brock, T.D., Madigan, M.T., Martinko, J.M., and Parker, J., 1994, Biology of microorganisms, (7th ed.): Englewood Cliffs, N.J., Prentice-Hall, 903 p.

Carlson, R.E., 1977, Atrophic state index for lakes: Limnology and Oceanography, v. 22, no. 2, p. 361–369.

Carpenter, S., Caraco, N.F., Correll, D.L., Howarth, R.W., Sharpley, A.N., and Smith, V.H., 1998, Nonpoint pollution of surface waters with phosphorous and nitrogen: Washington, D.C., Ecological Society of America, Issues in Ecology, v. 3, 12 p.

Carslaw, D.C., 2005, Evidence of an increasing NO2/NOX emissions ratio from road traffic emissions: Atmospheric Science, v. 37, p. 4,793–4,802.

Childress, C.J.O., Foreman, W.T., Connor, B.F., and Maloney, T. J., 1999, New reporting procedures based on long-term method detection levels and some considerations for interpretations of water-quality data provided by the U.S. Geological Survey National Water Quality Laboratory: U.S. Geological Survey Open-File Report 99-019, 19 p., accessed March 27, 2012, at http://water.usgs.gov/owq/OFR_99-193/.

Cohn, T.A., 1988, Adjusted maximum likelihood estimation of the moments of lognormal populations from type I censored samples: U.S. Geological Survey Open-File Report 88-350, 34 p. (Also available at http://pubs.er.usgs.gov/publication/ofr88350.)

Cohn, T.A., Delong, L.L., Gilroy, E.J., Hirsch, R.M., and Wells, D.K., 1989, Estimating constituent loads: Water Resources Research, v. 25, no. 5, p. 937–942.

Cohn, T.A., Gilroy, E.J., and Baier, W.G., 1992, Estimating fluvial transport of trace constituents using a regression model with data subject to censoring, *in* Joint Statistical Meeting: Boston, 1992, Proceedings: American Statistical Association, p. 142–151.

Cole, D.W., Compton, J., Van Miegroet, H., and Homann, P., 1990, Changes in soil properties and site productivity caused by Red Alder: Water, Air, and Soil Pollution, v. 54, p. 231–246.

Compton, J.E., Church, M.R., Larned, S.T., and Hogsett, W.E., 2003, Nitrogen export from forested watersheds in the Oregon Coast Range—The role of N_2-fixing red alder: Ecosystems, v. 6: p. 773–785.

Cooperative Chemical Analytical Laboratory, 2012, Methodology: Oregon State University web site, accessed March 21, 2012, at http://www.ccal.oregonstate.edu/methodology.htm.

Crawford, C.G., 1991, Estimation of suspended-sediment rating curves and mean suspended-sediment loads: Journal of Hydrology, v. 129, p. 331–348.

Crawford, C.G., 1996, Estimating mean constituent loads in rivers by the rating-curve and flow-duration, rating-curve methods: Bloomington, Ind., Indiana University, Ph.D. dissertation, 245 p.

Department of Ecology, 2012, Septic systems: State of Washington Department of Ecology, accessed November 2, 2012 at http://www.ecy.wa.gov/programs/wq/wqguide/septic.html.

Doskey, P.V., and Ugoagwu, B.J., 1989, Atmospheric deposition of macronutrients by pollen at a semi-remote site in Northern Wisconsin: Atmospheric Environment, v. 23, no. 12, p. 2,761–2,766.

Eaton, A.D., Clesceri, L.S., Rice, E.W., Greenberg, A.E., and Franson, M.A.H., eds., 2005, Standard methods for the examination of water and wastewater, 21st edition: Washington, D.C., American Public Health Association, American Water Works Association, and Water Environment Federation, variously paged.

Edmonds, R.L., Blew, R.D., Marra, J.L., Blew, J., Barg, A.K., Murray, G., and Thomas, T.B., 1998, Vegetation patterns, hydrology and water chemistry in small watersheds in the Hoh River valley, Olympic National Park: U.S. Department of the Interior, National Park Service, Scientific Monograph, NPS/NRUSGS/NRSM-98/02.

Edmonds, R.L., and Murray, G.L.D., 2002, Overstory litter inputs and nutrient returns in an old-growth temperate forest ecosystem, Olympic National Park, Washington: Canadian Journal of Forest Research, v. 32, p. 742–750.

Erdtman, G., 1943, An introduction to pollen analysis: Waltham, Mass., Chronica Botanica Company, 239 p.

Fenn, M.E., Lambert, K.F., Blett, T.F., Burns, D.A., Pardo, L.H., Lovett, G.M., Haeuber, R.A., Evers, D.C., Driscoll, C.T., and Jeffries, D.S., 2011, Setting limits—Using air pollution thresholds to protect and restore U.S. ecosystems: Ecological Society of America, Issues in Ecology, v. 14, 21 p.

Goldman, C.R., 1961, Contribution of alder trees (*Alnus tenuifolia*) to the primary productivity of Castle Lake, California: Ecology, v. 42, no. 2, p. 282–288.

Goldman, C.R., 1988, Primary productivity, nutrients, and transparency during the early onset of eutrophication in ultra-oligotrophic Lake Tahoe, California-Nevada: Limnology and Oceanography, v. 33, no. 6, pt. 1, p. 1231–1333.

Graham, M.D., Vinebrooke, R.D., and Turner, M., 2006, Coupling of boreal forests and lakes—Effects of conifer pollen on littoral communities: Limnology and Oceanography, v. 51, no. 3, p. 1,524–1,529.

Harbeck, G.E., Jr., 1962, A practical field technique for measuring reservoir evaporation utilizing mass-transfer theory—Studies of evaporation: U.S. Geological Survey Professional Paper 272-E, 5 p. (Also available at http://pubs.er.usgs.gov/publication/pp272E.)

Homer, C., Dewitz, J., Fry, J., Coan, M., Houssain, N., Larson, C., Herold, N., McKerrow, A., VanDriel, J.N., and Wickham, J., 2007, Completion of the 2001 National Land Cover Database for the conterminous United States: Photogrammetric Engineering and Remote Sensing, v. 73, no. 4, p. 337–341, accessed March 28, 2012, at http://www.mrlc.gov/nlcd2001.php.

Horizon Systems Corporation, 2006, National Hydrology Dataset: Horizon Systems Corporation, accessed March 22, 2012, at http://www.horizon-systems.com/nhdplus/index.php.

Horvath, A., and Hendrickson, C., 1998, Comparison of environmental implications of asphalt and steel-reinforced concrete pavements: Washington, D.C., National Research Council, Transportation Research Record, Transportation Research Board.

Jenkins, Kurt, Woodward, Andrea, and Schreiner, Ed, 2003, A framework for long-term ecological monitoring in Olympic National Park—Prototype for the coniferous forest biome: U.S. Geological Survey Information and Technology Report 2003-0006, 150 p. (Also available at http://pubs.er.usgs.gov/publication/itr030006.)

Karner, A.A., Sisinger, D.S., and Niemeier, D.A., 2010, Near-roadway air quality—Synthesizing the findings from real world data: Environmental Science Technology, v. 44, p. 5,334–5,344.

Kemmerer, G., 1923, Northwestern lakes of the United States—Biological and chemical studies with reference to possibilities in production of fish: Bulletin of Bureau of Fisheries, v. 39, p. 51–140.

Kemmerer, G., Bouard, J.F., and Boorman, W.R., 1924, Northwestern lakes of the United States—Biological and chemical studies with reference to possibilities in production of fish: Bulletin of the Bureau of Fisheries, v. 39, p. 51–140.

Kirk, Ruth, and Alexander, Carmela, 1995, Exploring Washington's past, a road guide to history—Revised edition: Seattle, Washington, University of Washington Press, 540 p.

LeBaugh, J.W., Buso, D.C., and Likens, G.E., 2009, Evaluation of methods and uncertainties in the chemical budget, *in* Winter, T.C., and Likens, G.E., eds., Mirror Lake—Interactions among air, land, and water: Berkeley, University of California Press, p. 225–297.

Lee, E.J., Kenekl, N.C., and Booth, T., 1996a, Atmospheric deposition of macronutrients by pollen in the boreal forest: Ecoscience, v. 3, no. 3, p. 304–309.

Lee, E.J., Kenkel, N.C., and Booth, T., 1996b, Pollen deposition in the boreal forest of west-central Canada: Canadian Journal of Botany, v. 74, p. 1,265–1,272.

Leopold, L.B., Wolman, W.G., and Miller, J.P., 1992, Fluvial processes in geomorphology: New York, Dover Publications, Inc., 522 p.

Lewis, W.M., and Wurtsbaugh, W.A., 2008, Control of lacustrine phytoplankton by nutrients—Erosion of the phosphorus paradigm: International Review of Hydrobiology, v. 93, p. 446–465.

Likens, G.E., and Bormann, F.H., 1999, Biogeochemistry of a forested ecosystem: New York, Springer-Verlag.

Logan, R.L., and Schuster, R.L., 1991, Lakes divided—The origin of Lake Crescent and Lake Sutherland, Clallam County, Washington: Washington Geology, v. 19, no. 1, p. 38–42.

McLennan, D.S., and Mathewes, R.W., 1984, Pollen transport and representation in the Coast Mountains of British Columbia, I—Flowering phenology and aerial deposition: Canadian Journal of Botany, v. 62, no. 10, p. 2154–2164.

Motter, K., and Jones, C., 2008, Quality assurance plan—CCAL Water Analysis Laboratory (rev. 0): Department of Forest Science, Oregon State University, 51 p., accessed August 4, 2009, at http://ccal.oregonstate.edu/qaqc.htm.

Murray, F.W., 1967, On the computation of saturation vapor pressure: Journal of Applied Meteorology and Climatology, v. 6, p. 203–204.

National Atlas of the United States, 2011, Average annual precipitation, *in* National Atlas of the United States: U.S. Department of the Interior, accessed March 13, 2012, at http://nationalatlas.gov/.

National Atmospheric Deposition Program, 2012, National Trends Network Monitoring Location WA14: National Atmospheric Deposition Program, accessed March 22, 2012, at http://nadp.sws.uiuc.edu/sites/siteinfo.asp?net=NTN&id=WA14.

National Park Service, 2011, Visiting Lake Crescent: National Park Service web site, accessed March 12, 2012, at http://www.nps.gov/olym/planyourvisit/visiting-lake-crescent.htm.

National Park Service, 2012, Olympic National Park, Washington: National Park Service web site, accessed March 12, 2012, at http://www.nps.gov/olym/index.htm.

Nelson, P.O., Reilly, J.F., and Larson, G.L., 1996, Chemical solute mass balance of Crater Lake, Oregon: Journal of Lake and Reservoir Management, v. 12, p. 248–258.

Noll, K.E., and Khalili, E., 1988, Dry deposition of sulfate associated with pollen: Atmospheric Environment, v. 22, no. 3, p. 601–604.

Passeport, E., Hunt, W., Line, D., Smith, R., and Brown, R., 2009, Field study of the ability of two grassed bioretention cells to reduce storm-water runoff pollution: Journal of Irrigation and Drainage Engineering, v. 135, no. 4, p. 505–510.

Perez-Moreno, J.P., and Read, D.J., 2001, Exploitation of pollen by mycorrhizal mycelia systems with special reference to nutrient recycling in boreal forests: Proceedings of Biological Sciences., v. 268, p. 1,329–1,335

Pierce, B.E., 1984, The trouts of Lake Crescent, Washington: Fort Collins, Colo., Colorado State University, Master's Thesis, 252 p.

Pina-Ochoa, E., and Alvarez-Cobelas, M., 2006, Denitrification in aquatic environments—A cross-system analysis: Biogeochemistry, v. 81, no. 1, p. 111–130.

Porterfield, George, 1972, Computation of fluvial-sediment discharge: U.S. Geological Survey Techniques of Water Resource Investigations, book 3, chap. C3, 66 p. (Also available at http://pubs.usgs.gov/twri/.)

Rector, Julie, and Hallock, Dave, 1991, Lake water quality assessment project, 1989: Olympia, Washington State Department of Ecology, Environmental Investigations and Laboratory Services Program, no. 91–60, 230 p.

Reed, S.C., and Brown, D.S., 1992, Constructed wetland design—The first generation: Water Environment Federation, v. 64, no. 6, p. 776–781.

Richerson, P.J., Moshiri, G.A., and Godshalk, G.L., 1970, Certain aspects of pollen dispersion in Lake Tahoe (California-Nevada): Limnology and Oceanography, v. 15, no. 1, p. 149–153.

Richardson, Donald, 1962, Drainage-area data for Western Washington: U.S. Geological Survey Open-File Report, 244 p.

Robertson, W.D., Vogan, J.L., and Lombardo, P.S., 2008, Nitrate removal rates in a 15-year-old permeable reactive barrier treating septic system nitrate: Groundwater Monitoring and Remediation, v. 28, no. 3, p. 65–72.

Rosenberger, E.E., Hampton, S.E., Fradkin, S.C., and Kennedy, B.P., 2008, Effects of shoreline development on the nearshore environment in deep oligotrophic lakes: Freshwater Biology, v. 53, p. 1,637–1,691.

Runkel, R.L., Crawford, C.G., and Cohn, T.A., 2004, Load estimator (LOADEST)—A FORTRAN program for estimating constituent loads in streams and rivers: U.S. Geological Survey Techniques and Methods, 4-A5, 75 p. (Also available at http://pubs.er.usgs.gov/publication/tm4A5.)

Schasse, H.W., 2003, Geologic map of the Washington portion of the Port Angeles 1:100,000 quadrangle: Washington State Department of Natural Resources, Division of Geology and Earth Resources Open-File Report 2003–6, 1 p.

Seitzinger, S., 1988, Denitrification in freshwater and coastal marine ecosystems: Ecological and geochemical significance: Limnology and Oceanography, v. 33, no. 4, pt. 2, p. 702–724.

Smith, Kirk, Hallock, Dave, and O’Neal, Sarah, 2000, Water quality assessments of selected lakes within Washington State, 1998: Olympia, Washington State Department of Ecology Environmental Assessment Program, no. 00-03-039, 251 p.

Solomon, A.M., and Sikworth, A.B., 1986, Spatial patterns of atmospheric pollen transport in a Montane Region: Quaternary Research, v. 25, p. 150–162.

Steinberg, P.D., Brett, M.T., Bechtold, J.S., Richey, J.E., Porensky, L.M., and Smith, S.N., 2011, The influence of watershed characteristics on nitrogen export to and marine fate in Hood Canal, Washington, USA: Biogeochemistry, v. 106, no. 3, p. 415–433.

Triska, F.J., Sedell, J.R., Cromack J., Jr., Gregory, S.V., and McCorson, F.M., 1984, Nitrogen budget from a small coniferous forest stream: Ecological Monographs, v. 54, p. 119–140.

U.S. Environmental Protection Agency, 2000, Criteria development guidance—Lakes and reservoirs: Washington, D.C., U.S. Environmental Protection Agency, Office of Water , Office of Science and Technology, EPA-822/B00/001, variously paged, accessed December 27, 2010, http://water.epa.gov/scitech/swguidance/standards/criteria/nutrients/lakes/index.cfm.

U.S. Environmental Protection Agency, 2002, Onsite wastewater treatment system manual: Washington, D.C., U.S. Environmental Protection Agency, Office of Water, Office of Research and Development, EPA-625/R-00/008 variously paged, accessed December 27, 2010, at http://www.epa.gov/ORD/NRMRL/pubs0402.html.

U.S. Environmental Protection Agency, 2012, Clean Air Status and Trends Network: U.S. Environmental Protection Agency Web site, accessed October 24, 2012, at http://epa.gov/castnet/javaweb/index.html.

U.S. Geological Survey, 2006, Collection of water samples (ver. 2.0): U.S. Geological Survey Techniques of Water Resources Investigations, book 9, chap. A4, accessed March 30, 2012, at http://pubs.water.usgs.gov/twri9A4/.

U.S. Geological Survey, 2009, Long term-method detection levels (LT-MDL) for the U.S. Geological Survey, National Water Quality Laboratory: U.S. Geological Survey database, accessed August 11, 2009, at http://bqs.usgs.gov/ltmdl/.

U.S. Geological Survey, 2010a, StreamStats: U.S. Geological Survey database, accessed March 28, 2012, at http://water.usgs.gov/osw/streamstats/Washington.html.

U.S. Geological Survey, 2010b, Seamless data warehouse—What is elevation?: U.S. Geological Survey database, accessed March 28, 2012, at http://seamless.usgs.gov/about_elevation.php.

U.S. Geological Survey, variously dated, National field manual for the collection of water-quality data: U.S. Geological Survey Techniques of Water-Resources Investigations, book 9, chaps. A1–A9. (Also available at http://pubs.water.usgs.gov/twri9A.)

Van Miegroet, H., and Cole, D.W., 1984, Impact of nitrification on soil acidification and cation leaching in a red alder ecosystem: Journal of Environmental Quality, v. 13, p. 586–590.

Walters, K.L., 1970, Water supplies for selected sites in Olympic National Park, Washington: U.S. Geological Survey Open-File Report 70-358, 72 p.

Washington State Department of Ecology, 2012, Septic systems: Washington State Department of Ecology Web site, accessed November 2, 2012, at http://www.ecy.wa.gov/programs/wq/wqguide/septic.html.

Washington State Department of Transportation, 2007, 2007 annual traffic report: Washington State Department of Transportation, U.S. Department of Transportation Federal Highway Administration, accessed March 12, 2012, at http://www.wsdot.wa.gov/mapsdata/travel/annualtrafficreport.htm.

Wetzel, R.G., 2001, Limnology—Lake and river ecosystems, (3d ed.): San Diego, Academic Press, 1,006 p.

Winter, T.C., and Rosenberry, D.O., 2009, Evaluation of methods and uncertainties in the water budget, *in* Winter, T.C., and Likens, G.E., eds., Mirror Lake—Interactions among air, land, and water: Berkeley, University of California Press, p. 205–223.

Wolcott, E.E., 1973, Lakes of Washington: Olympia, Wash., Washington Department of Ecology State Water Program, 3d ed.: Water Supply Bulletin, v. 1, no. 14, western Washington, 619 p.

Yanowitz, J., McCormick, R.L., and Graboski, M.S., 2000, In-use emissions from heavy-duty diesel vehicles—Critical review: Environmental Science and Technology, v. 34, no. 5, p. 729–740.

Appendixes

Appendixes A–F are included as PDFs and can be downloaded from http://pubs.usgs.gov/sir/2012/5107/.

Appendix A. Results of Chemical Analyses on Field Blank-Water, Field-Replicate, and Aqueous Standard-Reference Quality-Control Samples

Table A1. Control blank-water samples prepared during sample collection from Lake Crescent.

Table A2. Field blank-water samples prepared during sample collection from Lake Crescent stations LS02 480508123455710 and LS04 480333123503210.

Table A3. Field blank-water samples prepared during sample collection at selected stream sites.

Table A4. Field-replicate samples prepared during sample collection from Lake Crescent station LS02 480508123455710.

Table A5. Field-replicate samples prepared during sample collection from Lake Crescent station LS04 480333123503210.

Table A6. Field-replicate samples prepared during sample collection at stream sites.

Table A7. Aqueous standard-reference samples submitted to Cooperative Chemical Analytical Laboratory (CCAL), Corvallis, Oregon, and U.S. Geological Survey (USGS) National Water Quality Laboratory, Denver, Colorado.

Appendix B. Daily Mean Streamflows for Fairholm Creek, Lapoel Creek, Smith Creek, Barnes Creek, Piedmont Creek, and Lyre River, Washington, Water Years 2006–07

Appendix C. Results of Chemical Analyses on Water Samples from Lake Crescent and Streams

Table C1. Fairholm Creek at Fairholm, Washington, 480307123545710, nutrients and suspended sediment.

Table C2. Lapoel Creek near Fairholm, Washington, 480310123521410, nutrients and suspended sediment.

Table C3. Smith Creek near Fairholm, Washington, 480305123490410, nutrients and suspended sediment.

Table C4. Barnes Creek near Piedmont, Washington, 12043530, nutrients and suspended sediment.

Table C5. Piedmont Creek at Piedmont, Washington, 480544123472610, nutrients and suspended sediment.

Table C6. Lyre River at Piedmont, Washington, 12044000, nutrients.

Table C7. Lake Crescent station LS02 480508123455710, nutrients.

Table C8. Lake Crescent station LS04 480333123503210, nutrients.

Table C9. Lake Crescent station 480508123455710 LS02, July 26, 2006, major-ion and trace-element analyses from U.S. Geological Survey National Water Quality Laboratory, Denver, Colorado.

Table C10. Lake Crescent station 480333123503210 LS04, July 26, 2006, major-ion and trace-element analyses from U.S. Geological Survey National Water Quality Laboratory, Denver Colorado.

Appendix D. Results of Chemical Analyses on Bottom-Sediment Core Samples Collected from Lake Crescent, Washington, September 2008

Table D1. Lake Crescent station LS02 480508123455710, September 13, 2006.

Table D2. Lake Crescent station LS04 480333123503210, September 12, 2006.

Appendix E. Results of Chemical Analyses and Field Measurements on Water Samples from Piezometers, October 2007

Appendix F. Estimated and Observed Daily Total Nitrogen and Total Phosphorus Loads and Loadest Model Parameters

Figure F1. Fairholm Creek time series of estimated and observed total nitrogen and total phosphorus loads and LOADEST model parameters.

Figure F2. Lapoel Creek time series of estimated and observed total nitrogen and total phosphorus loads and LOADEST model parameters.

Figure F3. Smith Creek time series of estimated and observed total nitrogen and total phosphorus loads and LOADEST model parameters.

Figure F4. Barnes Creek time series of estimated and observed total nitrogen and total phosphorus loads and LOADEST model parameters.

Figure F5. Piedmont Creek time series of estimated and observed total nitrogen and total phosphorus loads and LOADEST model parameters.

Figure F6. Lyre River time series of estimated and observed total nitrogen and total phosphorus loads and LOADEST model parameters.

Publishing support provided by the U.S. Geological Survey
Publishing Network, Tacoma Publishing Service Center

For more information concerning the research in this report, contact the
Director, Washington Water Science Center
U.S. Geological Survey
934 Broadway, Suite 300
Tacoma, Washington 98402
http://wa.water.usgs.gov

Moran and others—**Sources and Sinks of Nitrogen and Phosphorus, Lake Crescent, Olympic National Park, Washington**—Scientific Investigations Report 2012–5107