Prepared in cooperation with the Vancouver Lake Watershed Partnership and Clark County Environmental Services Division

Water and Nutrient Budgets for Vancouver Lake, Vancouver, Washington, October 2010–October 2012

Scientific Investigations Report 2014–5201

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

Front Cover: Photograph showing U.S. Geological Survey (USGS) hydrologist collecting a width and depth-integrated water quality sample across the mouth of Burnt Bridge Creek, Washington. (Photograph taken by James Foreman, USGS, November 2010.)

Back Cover: Satellite image of Vancouver Lake, Washington. Imagery from U.S. Department of Agriculture, 2011 National Agriculture Imagery Program.

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By Rich W. Sheibley, James R. Foreman, Cameron A. Marshall, and
Wendy B. Welch

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SALLY JEWELL, Secretary

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

U.S. Geological Survey, Reston, Virginia: 2014

Suggested citation:
Sheibley, R.W., Foreman, J.R., Marshall, C.A., and Welch, W.B., 2014, Water and nutrient budgets for Vancouver Lake, Vancouver, Washington, October 2010–October 2012: U.S. Geological Survey Scientific Investigations Report 2014–5201, 72 p., plus appendixes, *http://dx.doi.org/10.3133/sir20145201.*

ISSN 2328-0328 (online)

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Conversion Factors, Datums, and Abbreviations and Acronyms

Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.4047	hectare (ha)
acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
ounce, fluid (fl. oz)	0.02957	liter (L)
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic inch (in^3)	0.01639	liter (L)
cubic foot (ft^3)	28.32	cubic decimeter (dm^3)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
acre-foot (acre-ft)	1,233	cubic meter (m^3)
	Flow rate	
acre-foot per year (acre-ft/yr)	1,233	cubic meter per year (m^3/yr)
foot per second (ft/s)	0.3048	meter per second (m/s)
foot per minute (ft/min)	0.3048	meter per minute (m/min)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)
inch per day (in/d)	0.0254	meter per day (m/d)
	Mass	
pound, avoirdupois (lb)	0.4536	kilogram (kg)
pounds per month (lb/month)	0.4536	kilogram per month (kg/month)
	Pressure	
atmosphere, standard (atm)	101.3	kilopascal (kPa)
bar	100	kilopascal (kPa)

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Conversion Factors—Continued

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
	Area	
square centimeter (cm^2)	0.001076	square foot (ft^2)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

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

$$°F = (1.8 \times °C) + 32$$

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)

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

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

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

Conversion Factors, Datums, and Abbreviations and Acronyms—Continued

Abbreviations and Acronyms

Chl-*a*	Chlorophyll-*a*
LOADEST	LOAD ESTimation
NADP	National Atmospheric Deposition Program
NFM	National Field Manual
NWIS	National Water Information System
NWQL	National Water Quality Lab
RO	Reverse Osmosis
SE	Standard Error
SEP	Standard Error of Prediction
TAL	TestAmerica Laboratory
TN	Total Nitrogen
TSI	Trophic State Index
TP	Total Phosphorus
UMDCBL	University of Maryland Chesapeake Biological Laboratory
USACE	US Army Corps of Engineers
USGS	US Geological Survey
VLSC	Vancouver Lake Sailing Club
VLWP	Vancouver Lake Watershed Partnership
WSUV	Washington State University, Vancouver

Water and Nutrient Budgets for Vancouver Lake, Vancouver, Washington, October 2010–October 2012

By Rich W. Sheibley, James R. Foreman, Cameron A. Marshall, and Wendy B. Welch

Abstract

Vancouver Lake, a large shallow lake in Clark County, near Vancouver, Washington, has been undergoing water-quality problems for decades. Recently, the biggest concern for the lake are the almost annual harmful cyanobacteria blooms that cause the lake to close for recreation for several weeks each summer. Despite decades of interest in improving the water quality of the lake, fundamental information on the timing and amount of water and nutrients entering and exiting the lake is lacking. In 2010, the U.S. Geological Survey conducted a 2-year field study to quantify water flows and nutrient loads in order to develop water and nutrient budgets for the lake. This report presents monthly and annual water and nutrient budgets from October 2010–October 2012 to identify major sources and sinks of nutrients. Lake River, a tidally influenced tributary to the lake, flows into and out of the lake almost daily and composed the greatest proportion of both the water and nutrient budgets for the lake, often at orders of magnitude greater than any other source. From the water budget, we identified precipitation, evaporation and groundwater inflow as minor components of the lake hydrologic cycle, each contributing 1 percent or less to the total water budget. Nutrient budgets were compiled monthly and annually for total nitrogen, total phosphorus, and orthophosphate; and, nitrogen loads were generally an order of magnitude greater than phosphorus loads across all sources. For total nitrogen, flow from Lake River at Felida, Washington, made up 88 percent of all inputs into the lake. For total phosphorus and orthophosphate, Lake River at Felida flowing into the lake was 91 and 76 percent of total inputs, respectively. Nutrient loads from precipitation and groundwater inflow were 1 percent or less of the total budgets. Nutrient inputs from Burnt Bridge Creek and Flushing Channel composed 12 percent of the total nitrogen budget, 8 percent of the total phosphorus budget, and 21 percent of the orthophosphate budget. We identified several data gaps and areas for future research, which include the need for better understanding nutrient inputs to the lake from sediment resuspension and better quantification of indirect nutrient inputs to the lake from Salmon Creek.

Introduction

Vancouver Lake, located in Clark County, near Vancouver, Washington, is a relatively large (approximately 2,300 acres) and shallow (mean depth 3–5 ft) lake that has recreational, environmental, and aesthetic value to the local community (fig. 1). It is the largest lake of the historical Columbia River floodplain lakes, and it is the largest lake in the Portland/Vancouver metropolitan area. In the late 1800s, the lake was much deeper (20 ft in some places) with clear waters (Bhagat and Orsborn, 1971). Historically, the lake was connected to the Columbia River and degradation of water quality began shortly after flood control structures for the Columbia River were constructed, which severed the connection to 'flushing' water. Nutrient and sediment loading has increased over time, and hypoxia (low dissolved oxygen concentrations) and cyanobacterial blooms in the lake led to poor water quality as early as the 1960s. The first detailed water-quality study of the lake took place in 1967–68 by scientists at Washington State University (Bhagat and Orsborn, 1971). This early work was undertaken to assess how water quality would change if the hydrological characteristics of the lake were altered by the addition of a 'flushing channel' that would reconnect the lake directly to the Columbia River. The hope was that restoring this connection would decrease residence times in the lake and promote better flushing that would address water-quality issues. In the early 1980s, the flushing channel was completed. The project included a large dredging operation, which formed a small island in the lake (fig. 1). Vancouver Lake is now hydrologically connected to the Columbia River by Lake River to the north, and by the Flushing Channel in the southwest. Compared to previous work, nutrient concentrations in the lake have declined, but high sediment loads are still a problem and the lake still experiences water-quality problems.

Recent community concern regarding reoccurring cyanobacterial blooms, which can be toxic to wildlife and humans, brought renewed attention to the lake and prompted the formation of the Vancouver Lake Watershed Partnership (Partnership) in October 2004.

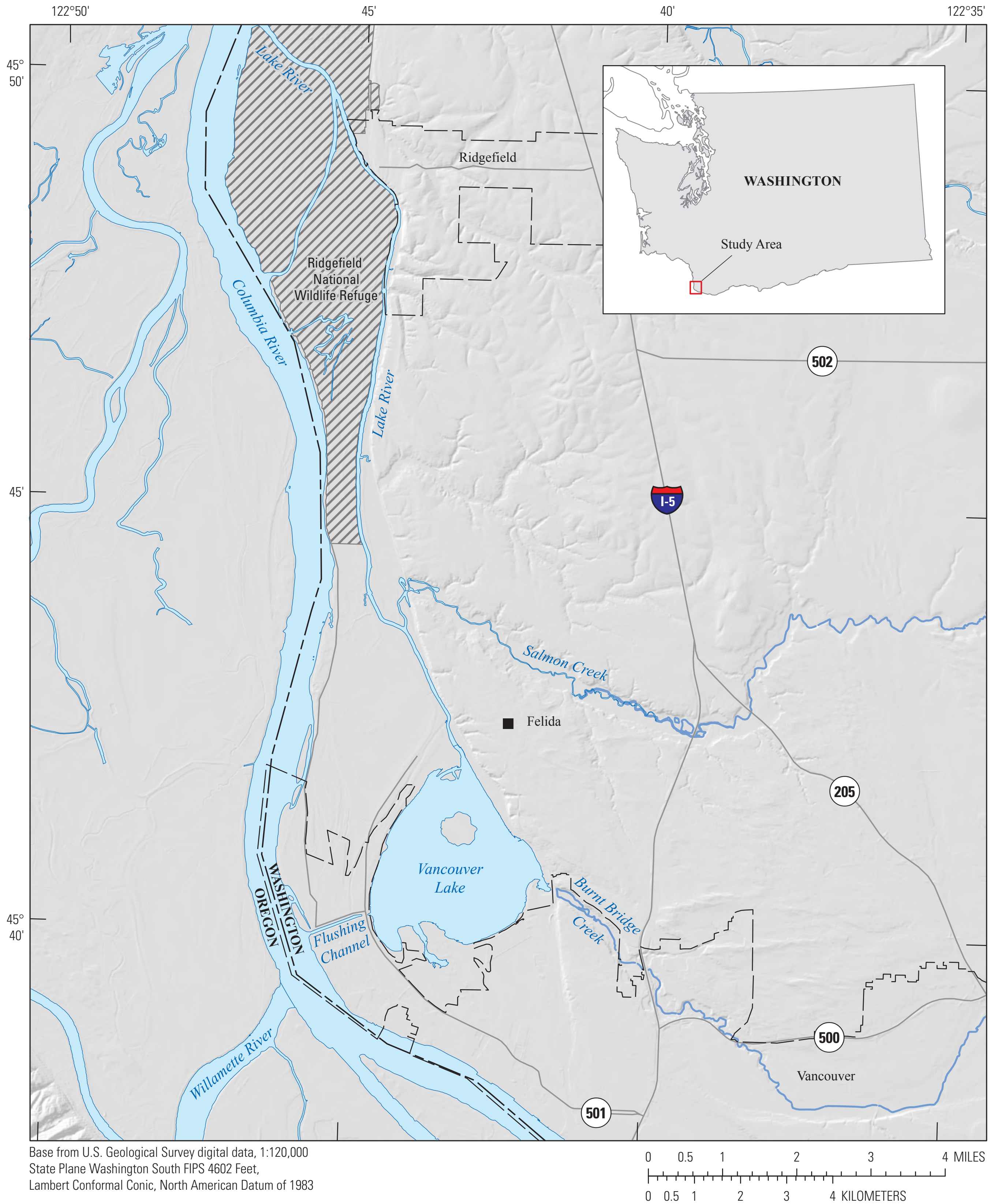


Figure 1. Location of Vancouver Lake near Vancouver, Washington.

This Partnership is made up of 22 members representing citizens and interest groups, as well as Federal, State, and local agencies, and is trying to understand how the lake functions in order to address water-quality problems in the lake. As part of this effort, the Partnership has joined with Washington State University–Vancouver (WSUV) to study the controls on cyanobacterial algal blooms and the U.S. Army Corps of Engineers (USACE) to study lake hydraulics. From 2004 to 2013, the lake has been closed to recreational activity for 1–4 weeks in summer months because of cyanobacterial blooms, except for 2008, 2001, and 2012 (Vancouver Lake Watershed Partnership, 2013). In addition to the cyanobacteria blooms, Vancouver Lake is included in the Washington State 303(d) list of impaired water bodies for total phosphorus and bacteria (Washington State Department of Ecology, 2013). These problems impair the lake by reducing water contact activities for the public and can have detrimental effects on the local ecosystem, including plants, animal, and fish species. While these algal blooms are a central concern, the community is concerned about other issues including the presence of toxins and pathogens, high temperatures, excessive nutrients, and high turbidity levels.

In a recent technical report outlining significant data gaps and priorities of study for the lake, the need for water and nutrient budgets were identified as top priorities (Vancouver Lake Watershed Partnership, 2008). In 2008, the U.S. Geological Survey (USGS) was contacted by the Partnership to provide technical assistance in developing a water and nutrient budget for the lake. An understanding of the timing and flow of water and the nutrients entering and exiting Vancouver Lake is a fundamental and important first step to understanding the biological and ecological functions of the lake. A previous water budget for the lake was compiled before the addition of Flushing Channel (Bhagat and Orsborn, 1971). Although flow at Flushing Channel and Burnt Bridge Creek (fig. 1) has been periodically measured in the past (Port of Vancouver, 2009; Myers, 2010), generally, there is a lack of understanding of the hydrological characteristics of the lake. Lake algal food web interactions contribute to cyanobacterial blooms in Vancouver Lake (Boyer and others, 2011; Rollwagen-Bollens and others, 2013), and it is also suspected that nutrients, in particular phosphorus, play an important role regarding algal blooms.

Purpose and Scope

The purpose of this study was to develop water and nutrient budgets for Vancouver Lake in order to better understand the biological and ecological functioning of the lake. From October 2010 to October 2012, the USGS conducted water-quality and flow monitoring to identify the important sources of water and nutrients (nitrogen and phosphorus) to the lake. These data will help resource managers address water-quality problems in the lake, and provide additional information to ongoing work by WSUV to help identify controls on cyanobacterial blooms.

Study Area

Vancouver Lake, located just west of downtown Vancouver, Washington, is a large (approximately 2,300 acres), shallow lake. Surface water inlets to the lake consist of Flushing Channel in the southwest, Burnt Bridge Creek in the southeast, and Lake River to the north (fig. 1). The hydrological characteristics of the lake are complex, with only Burnt Bridge Creek acting like a true surface water tributary to the lake. Burnt Bridge Creek watershed is approximately 28 mi^2 and is highly urbanized. Since the 1990s, flows in the reach have been artificially maintained by industrial cooling water entering the upper watershed (Sinclair and Kardouni, 2012). Flushing Channel was constructed in the 1980s to connect the Columbia River with the lake to increase water inputs. Water flows through two 7-ft diameter culverts equipped with tide gates that only allow water to flow into the lake. If the lake level rises higher than the stage of the Columbia River, the tide gates close and water flow from the channel is stopped. Lake River connects to the Columbia River approximately 14 mi downstream of the lake, and the flow here is bidirectional and the flow direction changes almost every day. The direction of flow in Lake River is determined by the Columbia River stage, which is controlled by the tides and hydropower operations upstream of the Portland/Vancouver area. Because of the influence of the Columbia River, Vancouver Lake shows a large change in lake stage over the year, with the deepest depths in winter months and shallowest conditions in summer, resulting in a 10–15 ft difference in lake depth during a given water year (fig. 2).

In addition to the direct inputs, Salmon Creek, a tributary to Lake River and located about 2 mi north of Vancouver Lake, is an important indirect source of water to the lake. The Salmon Creek watershed is important because it covers a large area (approximately 90 mi^2) and it includes a high proportion of agriculture and urban/suburban land uses (Wierenga, 2005). When Lake River flows into the lake, water (and nutrients) that originate from Salmon Creek also can enter the lake.

Bathymetry of the lake was measured in February 2008 by the USACE and showed some deeper channels along the eastern and western sides of the lake, but relatively flat elsewhere (fig. 3). Surficial geological material in the area primarily consists of recent alluvial deposits and the lake bottom consists mainly of unconsolidated fine sediment and virtually no macrophytes are present (Caromile and others, 2000). Detailed geological and hydrogeological information for the Vancouver Lake region is provided elsewhere (Mundorff, 1964; McFarland and Morgan, 1996; Morgan and McFarland, 1996; Parametrix, 2008; Sinclair and Kardouni, 2012). Being a large shallow lake, winds in the area may have an influence on the water quality of the lake, and it is suspected that wind-induced resuspension of sediments are a contributing factor to lake clarity and nutrient release, potentially fueling algal blooms in the study area.

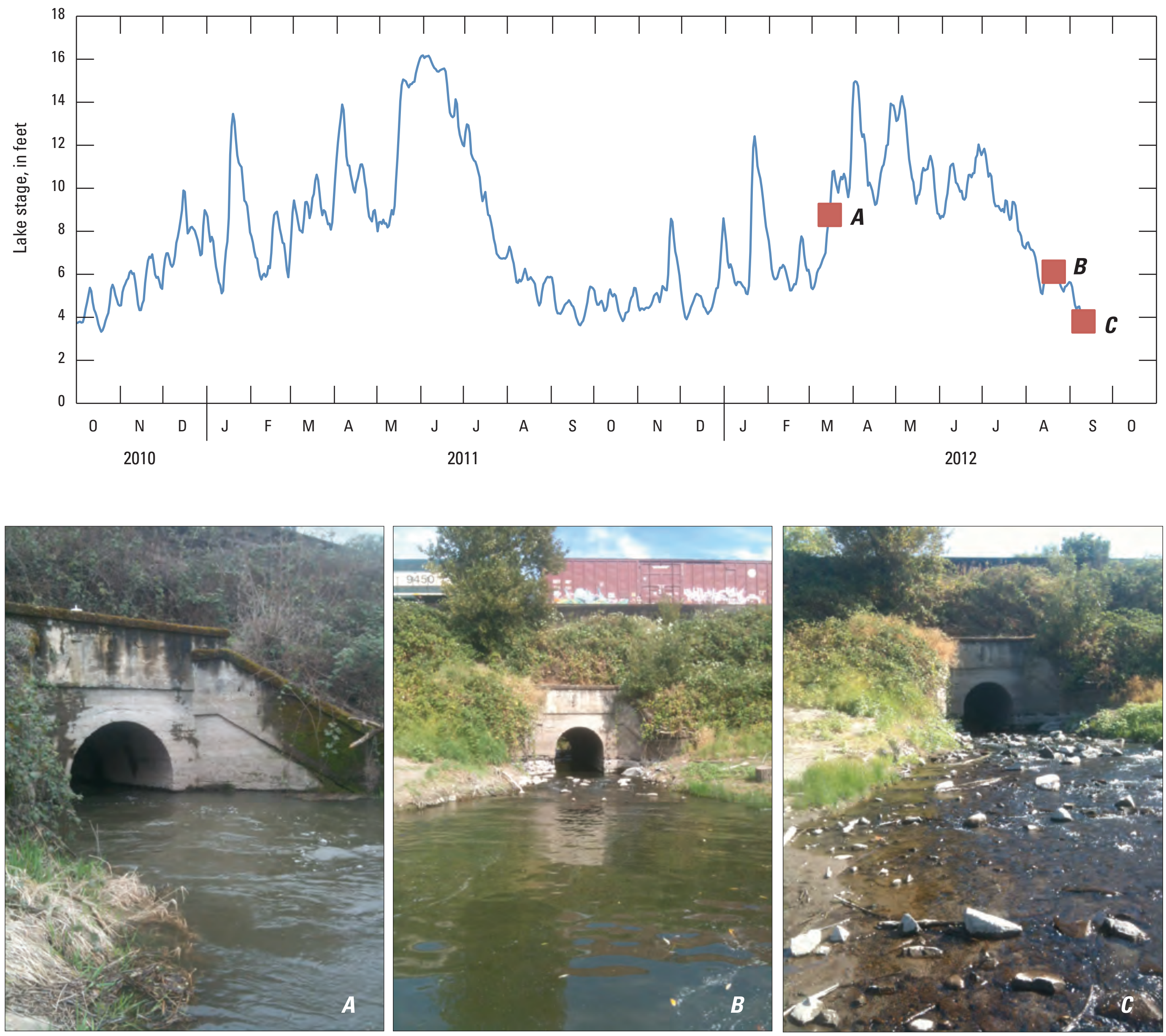
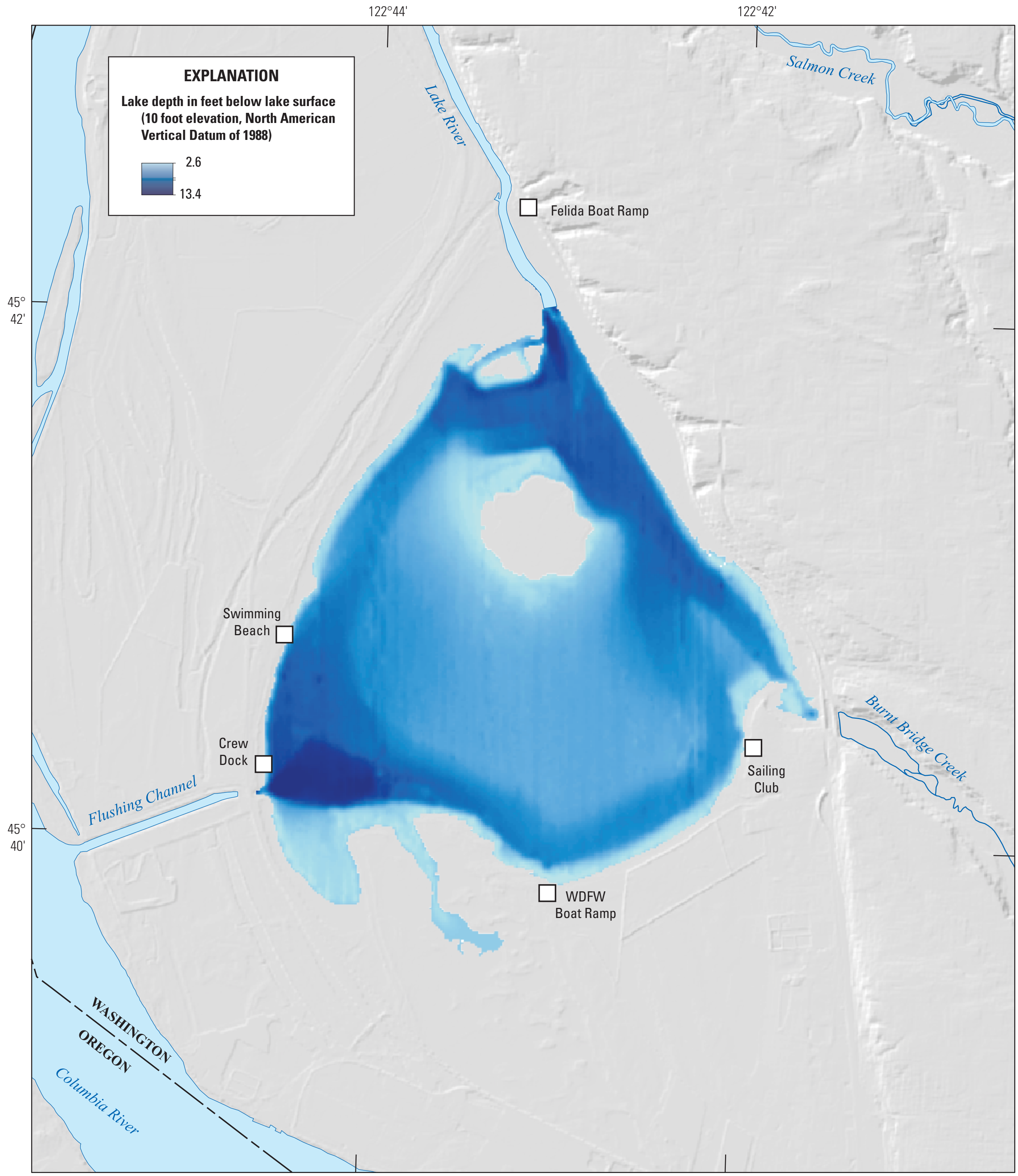


Figure 2. Lake stage at the Vancouver Lake Sailing Club, Vancouver Lake, Vancouver, Washington, October 2010–September 2012. Data provided by Dan Matlock, Pacific Groundwater Group (written commun., 2013). A lake stage of zero feet would indicate there is no water in the lake. Photographs were taken periodically during the year (shown as *A*, *B*, and *C* in the graph) looking towards the mouth of Burnt Bridge Creek to show how the lake level changes during the year. (Photographs taken by Rich Sheibley, U.S. Geological Survey, 2012.)



Base from U.S. Geological Survey digital data, 1:40,000
State Plane Washington South FIPS 4602 Feet,
Lambert Conformal Conic, North American Datum of 1983

0 0.125 0.25 0.5 0.75 1 MILES

0 0.125 0.25 0.5 0.75 1 KILOMETERS

Figure 3. Water depth and location of recreation areas of Vancouver Lake, Vancouver, Washington. Bathymetry measured by the U.S. Army Corps of Engineers, February 2008, when the lake elevation was 10 feet. WDFW is the Washington State Department of Fish and Wildlife.

Weather data collected at the Vancouver Lake Sailing Club from October 2010 to October 2012 (Foreman and others, 2014) showed that winds come primarily from the west-northwest (fig. 4).

There are several recreational uses of the lake and surrounding area (fig. 3). Vancouver Lake Park, located on the northwestern shore and maintained by the City of Vancouver, provides a beach and swimming access to an average of 100,000 visitors annually (Vancouver Lake Watershed Partnership, 2013). Private recreation facilities are located just north of Flushing Channel (Vancouver Lake Crew Club) and on the southeastern shore (Vancouver Lake Sailing Club). There also are two public boat ramps to access the lake, one on the southern shore operated by the Washington State Department of Fish and Wildlife (WDFW), and the Felida, Washington, boat ramp at Lake River to the north (fig. 3). North of the lake and along the western shore of Lake River the 5,300 acre Ridgefield National Wildlife Refuge (fig. 1) has been operating since 1965 and is a major winter nesting area for over 75 species of birds (U.S. Fish and Wildlife Service, 2010).

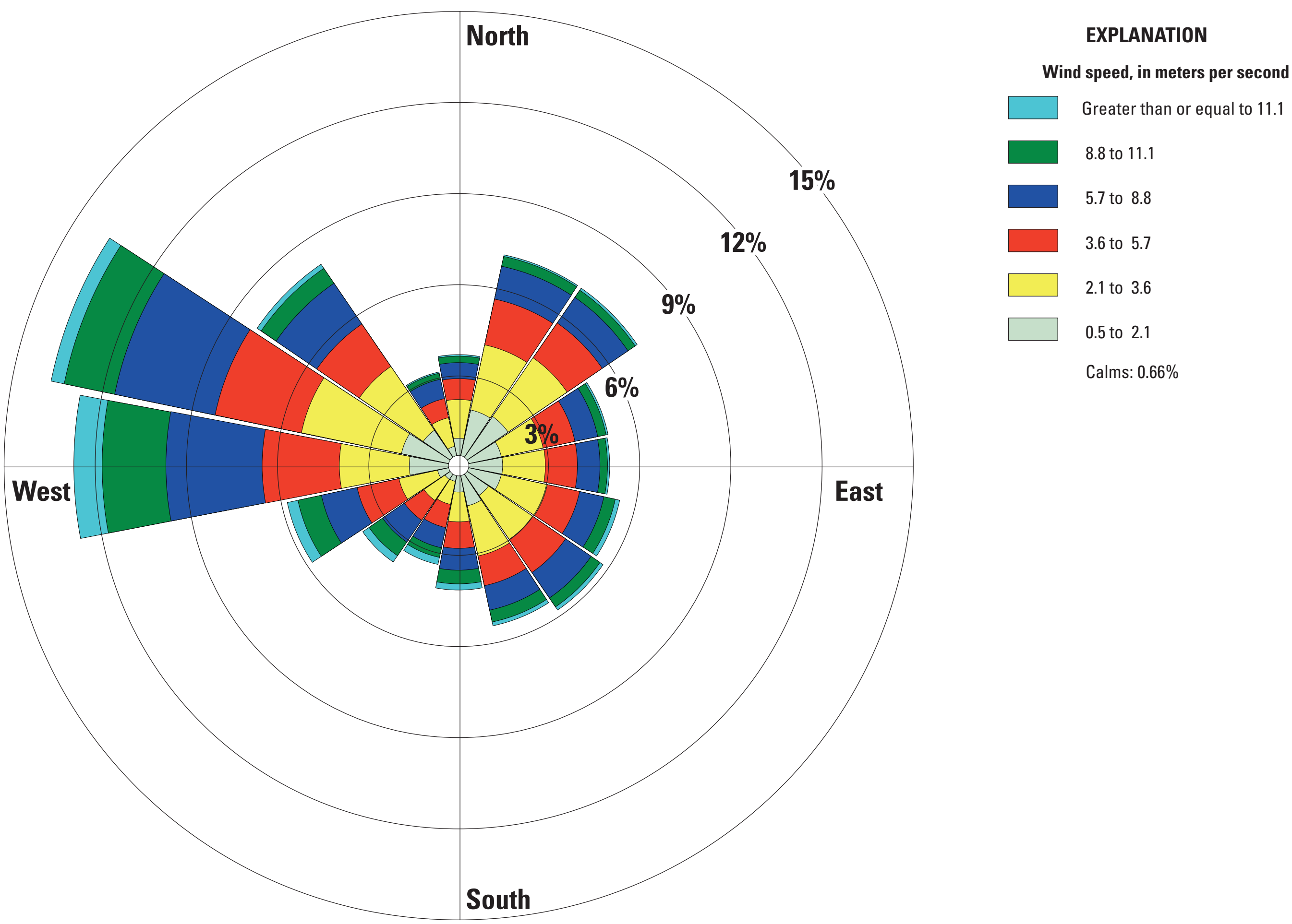


Figure 4. Wind speed and direction measured at the Vancouver Lake Sailing Club, Vancouver, Washington, October 2010–October 2012. Each concentric circle represents the frequency of wind coming from that particular direction, in percent (%) of the time. Calms is the percent of time that winds were zero or too low to measure, shown as the center circle.

Methods of Investigation

To determine the water and nutrient budget for Vancouver Lake for this investigation, the USGS operated three streamgages, seven surface water-quality sites, three groundwater-quality sites, a rain gage, and a weather station (fig. 5). For the purposes of this project, we limited our water and nutrient budget to Lake River at Felida, Washington, and at the mouths of Burnt Bridge Creek and Flushing Channel (fig. 5). Details of all field sites used for this project are provided in table 1. Water and nutrient budgets followed established approaches (Cooke and others, 2005; Buso and others, 2009; Rosenberry and Winter, 2009; Moran and others, 2013).

Table 1. Site, identification number, type, and location of all discharge and water-quality sites for the Vancouver Lake water and nutrient budget, Vancouver, Washington, October 2010–October 2012.

[**Latitude and longitude**: in decimal degrees, referenced to North American Datum of 1983 (NAD83). **Abbreviations**: WQ, water quality; –, not applicable; gage operated by Clark Public Utilities; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Site identifier	USGS site name	USGS site No.	Data collected	Latitude	Longitude
Flushing Channel	Flushing Channel at Vancouver Lake at Vancouver, WA	14144805	Continuous and instantaneous discharge, water quality, precipitation	45.66872718	-122.7448512
Burnt Bridge Creek at Vancouver Lake	Burnt Bridge Cr at Vancouver Lk nr Vancouver, WA	14211920	Water quality, instantaneous flow	45.67522	-122.692523
Burnt Bridge Creek near mouth	Burnt Bridge Creek near mouth at Vancouver Lake	14211902	Continuous discharge	45.661634	-122.669392
Lake River at Felida (IN and OUT)	Lake River at Felida, WA	14211955	Water quality, instantaneous flow	45.70317142	-122.7206547
Lake River at Ridgefield (IN and OUT)	Lake River at Ridgefield, WA	14213090	Continuous discharge	45.80746	-122.7403
Lake Site 1	Vancouver Lake Site 1 near Vancouver, WA	14211940	Lake water quality, core samples, porewater samples	45.68710824	-122.7085582
Lake Site 2	Vancouver Lake Site 2 near Vancouver, WA	14211925	Lake water quality, core samples, porewater samples, weather station, lake stage	45.673754	-122.700156
Lake Site 3	Vancouver Lake Site 3 near Vancouver, WA	14211929	Lake water quality	45.672697	-122.739906
Seep near Lake Site 1	UNNAMED SPRING 2.8 MI ABV SALMON CR NR FELIDA, WA	14211942	Seep water quality	45.68998056	-122.7077167
Seep near Lake River	UNNAMED SPRING 1.6 MI ABV SALMON CR NR FELIDA, WA	14211958	Seep water quality	45.70540556	-122.721375
Site 2 drivepoint	02N/01E-09G02	454026122415701	Shallow groundwater quality	45.67381944	-122.6991806
Salmon Creek at Lake River	Salmon Creek at Lake River nr Vancouver	14213050	Water quality, instantaneous flow	45.72594887	-122.7350996
Salmon Creek at Northcutt	Salmon Creek at Northcutt	–	Continuous discharge	45.710003	-122.638831

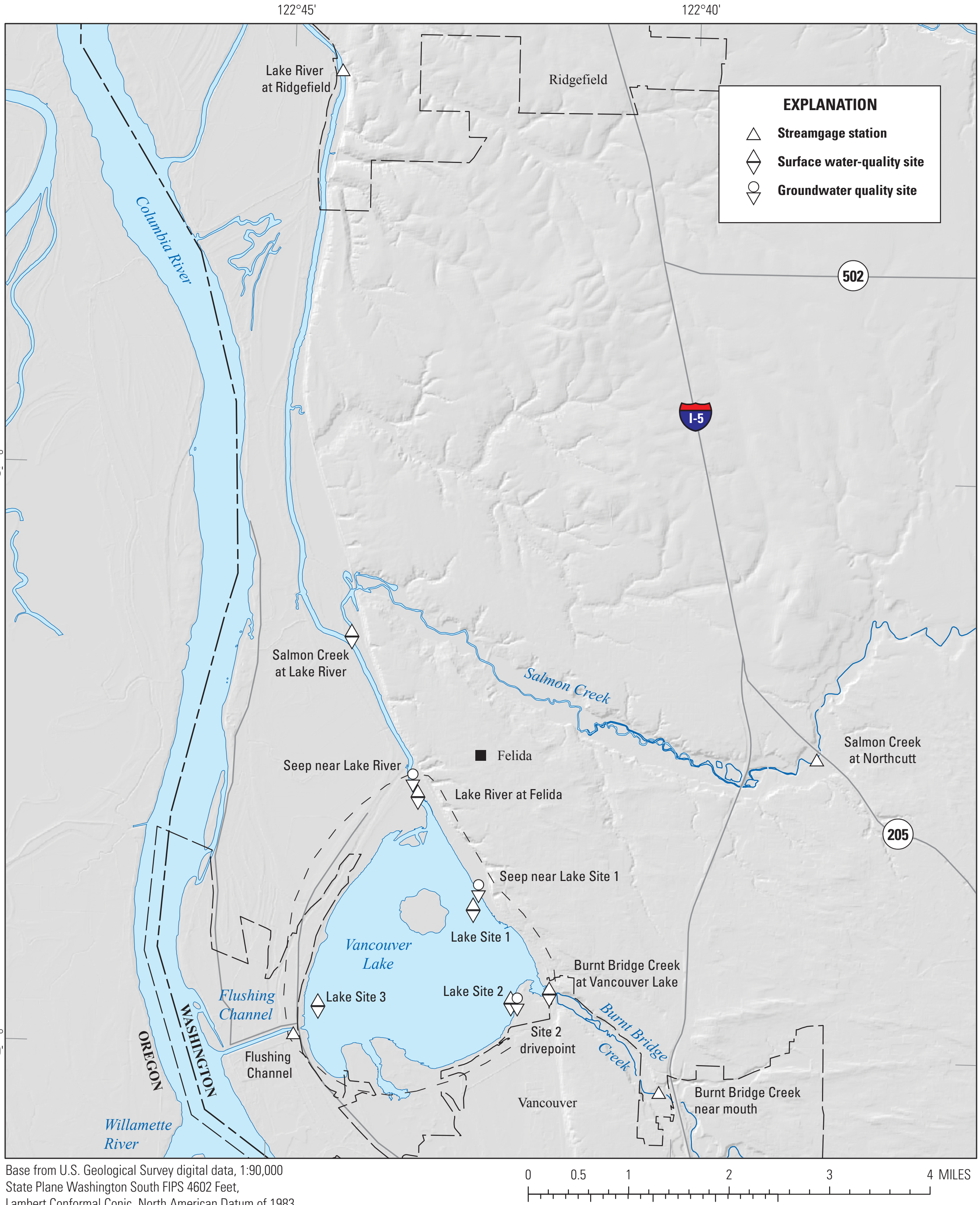


Figure 5. Location of field sites for determining a water and nutrient budget for Vancouver Lake, Vancouver, Washington, October 2010–October 2012. The water and nutrient budget boundary is shown by the dashed line. See table 1 for details on the type of data collected at each site.

Water Budget Methods

Determining the water budget for a water body is a fundamental first step in understanding how it functions as an ecosystem. Water carries nutrients, phytoplankton, essential minerals, and suspended sediments that are all important to energy flow within a lake ecosystem. Water moves through ecosystems in a conservative manner such that there is a balance between inputs and outputs. For Vancouver Lake, the water budget is defined as:

$$P + Q_{in} + GW = Q_{out} + E + \Delta S + R \qquad (1)$$

where

- P is precipitation volume,
- Q_{in} is the sum of all surface water inflows (Flushing Channel, Burnt Bridge Creek, and Lake River at Felida flowing into Vancouver Lake [Lake River IN]),
- GW is the groundwater inflow volume,
- Q_{out} is the surface water outflow (Lake River at Felida flowing out of Vancouver Lake [Lake River OUT]),
- E is evaporation from the lake surface,
- ΔS is change in lake volume (positive for an increase in storage), and
- R is the water budget residual.

Equation 1 assumes that there is no groundwater outflow from the lake and runoff from terrestrial areas is negligible. All terms are in units of acre-feet per month.

During the 2-year field study, the USGS measured all major surface water flows, precipitation, groundwater inflow, and evaporation from the lake surface. Lake stage was measured by the Pacific Groundwater Group (Dan Matlock, Pacific Groundwater Group, written commun., 2013) and lake-stage data were used with the bathymetric information provided by USACE to determine lake volume. The residual term was calculated by solving equation 1 for R and represents uncertainty of the measurements of all budget components plus any unmeasured terms in the water budget.

A monthly time step was used to estimate the water budget for 25 months from October 2010 to October 2012. Monthly water volumes from each source were summed to calculate an annual water budget for water year 2011 (October 1, 2010–September 30, 2011) and water year 2012 (October 1, 2011–September 30, 2012).

Surface Water Volumes

Surface water discharge data was obtained from three continuous streamgages operated for the study period and located at Flushing Channel, Burnt Bridge Creek, and Lake River at Ridgefield (fig. 5). The streamgage at Flushing Channel at Vancouver Lake at Vancouver, WA (14144805) is located on the southwestern shore of Vancouver Lake, roughly 0.8 mi from the Columbia River. At this location, there are two 7-ft diameter culverts connecting the Columbia River to Vancouver Lake. These structures include tide gates which only permit flow from the Columbia River into the lake. When the lake level is higher than the level of the Columbia River, the tide gates close to prevent flow out of the lake. The presence of the tide gates at Flushing Channel results in a period of zero flow lasting several hours, on average, almost every day. All values of flow recorded during a day, including periods of zero flow, were used to determine the mean daily flow.

The streamgage at Burnt Bridge Creek near Mouth at Vancouver, WA (14211902) is located approximately 1.5 mi from the inlet to Vancouver Lake (fig. 5). In a recent study of groundwater-surface water interactions on Burnt Bridge Creek by the Washington State Department of Ecology, a seepage run showed that flow differences between the location of the upstream streamgage and the mouth of the creek was less than 1 ft^3/s (Sinclair and Kardouni, 2012). Additionally, instantaneous discharge measurements were made during water-quality sample events where Burnt Bridge Creek enters the lake and were comparable to values at the continuous streamgage upstream (appendix A). Therefore, for the purposes of the water and nutrient budget, it was assumed throughout the study period that discharge measured upstream is the same as the discharge entering the lake.

The streamgage on Lake River (Lake River at Ridgefield, WA; 14213090) was located at the eastern entrance to the Ridgefield Wildlife Refuge and 7.8 mi north of the water and nutrient budget boundary (fig. 5). Flow in Lake River at Ridgefield is bidirectional and influenced by a combination of ocean tides, hydropower operations on the Columbia River, and the depth of Vancouver Lake. Throughout the study, flow at Lake River at Ridgefield alternated between positive values (flowing north; away from the lake) and negative values (flowing south; towards from the lake) almost daily. For the water budget, flow at the budget boundary (Lake River at Felida, WA; 14211955) had to be calculated from the continuous streamgage at Ridgefield. Between the streamgage at Ridgefield and the budget boundary location at Felida, the only major input of water is from Salmon Creek. As a result, it was necessary to construct an hourly flow record for Lake River at Felida by adding the Salmon Creek flow to the flow at Lake River at Ridgefield when flow was into the lake and by subtracting the Salmon Creek flow from the flow at Ridgefield when Lake River was flowing out of the lake. This procedure took place in multiple steps and is detailed in appendix A.

Once the hourly flow record for the water and nutrient budget location at Felida was created, it was treated as two independent terms; a surface-water input and as the only lake outlet. The estimated hourly discharge record for Lake River at Felida was divided into two separate records by separating the mean hourly flow from October 2010 through October 2012 into the positive and negative values. These hourly values were summed each day and divided by 24 to calculate a mean daily discharge value. This approach takes into account the period of a given day when flow was zero in a particular direction in order to calculate the true mean daily flow entering and the exiting the lake. Throughout this report, Lake River IN refers to the Lake River at Felida flowing into Vancouver Lake and Lake River OUT refers to the Lake River flowing out of the lake.

Manual streamflow measurements at each streamgage and water-quality site were made by USGS personnel using Price (AA) flowmeter, FlowTracker Handheld ADV® current velocity meters, and RDI Acoustic Doppler Current Profilers (ADCP) (fig. 6) according to standard techniques of the USGS (Rantz, 1982a, 1982b; Mueller and Wagner, 2009) periodically throughout the study.

The manual measurements, in combination with continuous data collected at streamgage stations (stage at Burnt Bridge Creek; stage and velocity at Flushing Channel and Lake River at Ridgefield), were used to develop discharge ratings to calculate discharge based on stage-discharge or index-velocity relationships. Using the ratings; corrections to gage heights based on reference gage comparisons; and scour and fill shifts to the ratings, final records of daily mean streamflow were produced according to USGS standards (Rantz, 1982a, 1982b; Levesque and Oberg, 2012). A detailed description of discharge measurement equipment and the methods and tables of mean daily flow at these sites are provided in Foreman and others (2014). Monthly surface water volumes into and out of the lake for the water budget were calculated by taking the mean daily flow for each day in cubic feet per second, multiplying by 86,400 seconds in a day and summed for each month. At Lake River at Ridgefield, the velocity meter was damaged, resulting in missed flow data from February 25th, 2011 until the meter was fixed on April 27th, 2011. Flow data for this time period was replaced by the flow data from the same time period in 2012 under the assumption that the flow was similar in both water years.

Figure 6. U.S. Geological Survey (USGS) hydrologic technician calibrating the Acoustic Doppler Current Profiler (housed in the orange pontoon) prior to measurement of surface water discharge near Burnt Bridge Creek, Washington. (Photograph taken by Rich Sheibley, USGS, November 2010.)

Groundwater Volume

Estimates of groundwater discharge into the lake were made from seven measurement locations around the perimeter of the lake (fig. 7) using Lee-type seepage meters (Lee, 1977). A seepage meter provides the most direct method for quantifying exchange across the sediment-water interface by isolating a part of the sediment-water interface and physically measuring the amount of exchange that occurs over time. Seepage meters have been successfully used to quantify exchange between groundwater and surface water in wetlands, ponds, lakes, estuaries, and oceans (Cable and others, 1997). With appropriate consideration to minimize several sources of error (Shaw and Prepas, 1990; Belanger and Montgomery, 1992; Shinn and others, 2002; Murdoch and Kelly, 2003); adjustment for meter inefficiencies (Rosenberry and Menheer, 2006); and effects of bioirrigation (Cable and others, 2006), measurements can be made to within about 10 percent of actual seepage rates.

The Lee-type seepage meters were made from the top part of a 55-gal steel drum with a cross-sectional area of 2,550 cm^2, cut off approximately 40 cm from the top edge. Handles were attached and a 2.5-cm hole was drilled near the top edge and fitted with 1.6-cm inside diameter (ID) tubing. Collection bags were 3.2-L plastic packing bags with attached 1.6-cm ID tube and valve assemblies. The collection bags were housed in a plastic box that was secured to the top of the seepage meter with a bungee cord to reduce the effects of waves and currents. Seepage meters were installed by pressing the open end of the steel drum approximately 10 cm into the sediment. Collection bags containing a known mass of lake water (about 1 kg) were connected to the seepage meter. The valve was then opened and the time noted. After an arbitrary period of time (before the collection bag could overfill), the valve was closed and the time noted. The collection bags were then reweighed, and the change in mass per unit time was calculated and converted to a flow velocity (in feet per day) by dividing by the sediment surface area isolated by the seepage meter. We assumed that the groundwater velocities measured across all sites was constant and groundwater continuously discharged at this rate for the entire 2-year period.

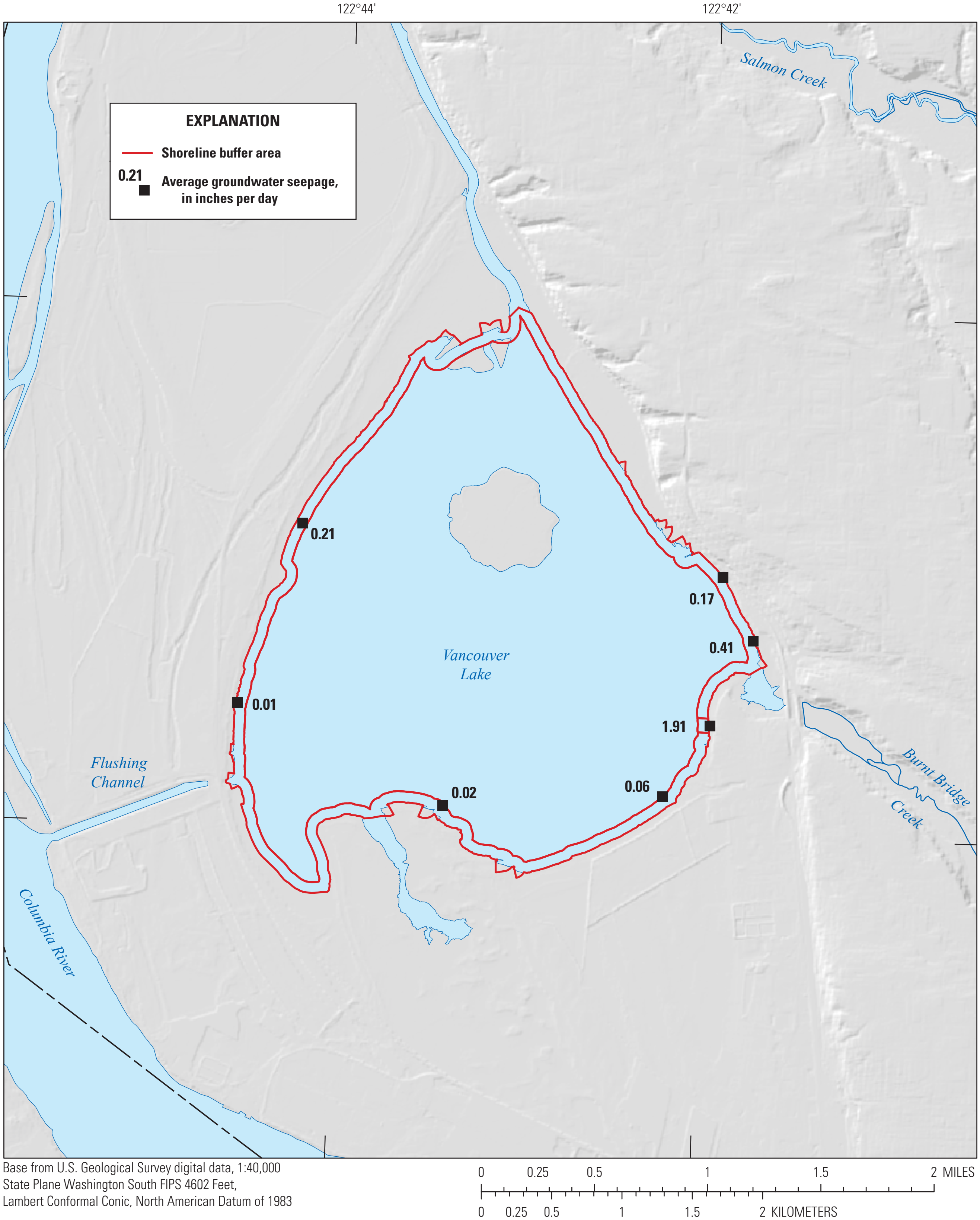


Figure 7. Location and values of groundwater seepage flux and associated shoreline buffer area used to calculate water volumes and nutrient mass entering the lake and used in the water and nutrient budgets, Vancouver Lake, Vancouver, Washington.

Groundwater velocities were used to estimate total groundwater flow into the lake assuming flow took place within 250 ft of the shoreline. The area of the 250-ft shoreline buffer that circled the lake was delineated from a GIS shapefile of the lake surface (fig. 7). This shoreline buffer had an area of 274 acres and the width (250 ft) was chosen because beyond this distance low permeability sediments existed. This observation was confirmed after several attempts at collecting groundwater from the end of a dock at the Vancouver Lake Sailing Club, which were unsuccessful because a thick clay layer in the upper sediment layers. Additionally, it has been shown that groundwater discharge generally decreases with distance from a lake shoreline (McBride and Pfannkuch, 1975; Pfannkuch, 1984). Therefore, we focused our measurements to areas close to the shoreline around the lake. Measurements of groundwater flux were made in August 2011 and again in August and September 2012 when the lake level was low and access to sample sites was easier. Monthly groundwater volumes were calculated by taking the average groundwater velocity in feet per day, multiplying by the buffer area (274 acres; about 12,000,000 ft^2), then summing the volume by the number of days in each month.

Precipitation Volume

Precipitation onto the lake surface was determined using a tipping bucket rain gage located at the Flushing Channel streamgage station (fig. 5). The rain gage was mounted on 15-ft pedestal with no overhead obstructions within a 100-ft radius, and precipitation totals were recorded daily to 0.01 in. The rain gauge was inspected on every site visit, and cleaned and oiled as required. The precipitation data were recorded and the rain gauge tested and calibrated annually per USGS specifications (U.S. Geological Survey Office of Surface Water Memorandum 2006.01, 2005, http://water.usgs.gov/admin/memo/SW/OSW_2006-01_Revised_02122010.pdf). Lake surface area varied less than 2 percent during the study; therefore, monthly precipitation totals were multiplied by the mean lake surface area during the study period (2,326 acres) to obtain the monthly water volume added to the lake.

Lake Storage

Lake storage (*S*) is defined as the volume of water contained in the lake at any given time. Change in lake storage (ΔS) over time represents differences between water entering and leaving the lake. When the lake stage increases during a time period because the lake gains volume, ΔS is positive; and ΔS is negative when the lake stage decreases during a time period because the lake loses volume. Change in lake storage is important to include in the water budget because it takes into account the non-equilibrium between water inflows and outflows, and allows for a more accurate estimate of the water budget residual. Daily lake volumes were calculated from the mean daily lake stage measured at the Vancouver Lake Sailing Club (VLSC) and collected by Pacific Groundwater Group (Dan Matlock, Pacific Groundwater Group, written commun., 2013) (fig. 2) and lake bathymetry (fig. 3) was measured by the USACE in 2008 (Sharon Schulz, U.S. Army Corps of Engineers, written commun., 2013). The bathymetry survey took place February 11–15, 2008 (Michael Booton, U.S. Army Corps of Engineers, written commun., 2013). Using the lake shapefile from the time of the survey and the surrounding 30-m resolution digital elevation model we established an initial reference volume for the lake (14,280 acre-ft); and, knowing the lake stage at the time of the bathymetry survey, we calculated daily volumes for a given average daily lake stage throughout the study period.

Daily lake storage was determined by calculating the difference between successive daily lake volumes using mean the daily lake stage. Monthly lake storage was determined by summing the daily changes in lake volume for each month.

Evaporation

A weather station was installed to collect climatic data (air temperature, relative humidity, wind speed and direction, net radiation, and surface water temperature) of the lake in order to estimate evaporation from the lake surface (fig. 8). Data were recorded at 5-minute intervals from the end of a dock at the VLSC (Lake Site 2; fig. 5) and data was downloaded approximately monthly. Detailed descriptions of the field equipment used and methods of data collection from this location are provided in Foreman and others (2014).

Figure 8. U.S. Geological Survey hydrologic technician making final adjustments to the weather station located at the Vancouver Lake Sailing Club dock near Lake Site 2, Vancouver Lake, Vancouver, Washington. Air temperature, relative humidity, wind speed and direction, net radiation, and surface water temperature, from the lake surface were determined from October 2010 through October 2012. (Photograph taken by Rich Sheibley, November 2010.)

Evaporation was calculated on a monthly time step using two methods: a mass-transfer method (Harbeck, 1962) and the Thornthwaite method (Thornthwaite, 1948). These two methods were shown to provide good estimates of 'true' evaporation measured by using rigorous energy balance methods in a recent review of lake evaporation techniques (Rosenberry and others, 2007).

The mass-transfer method calculates evaporation based on wind speed and vapor-pressure gradient using the following mass-transfer equation:

$$E = N\,u\,(e_0 - e_a) \qquad (2)$$

where

- E is evaporation in inches per day,
- N is 0.0023 and is the mass transfer coefficient proportional to lake surface area (Harbeck, 1962),
- u is mean daily wind speed in miles per hour,
- e_0 is saturation vapor pressure, in millibars (see eq. 3), and
- e_a is vapor pressure in the air, in millibars, at 2 m above the lake surface.

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

$$e_0 = 6.1078\exp[a(T - T^*)/(T - b)] \qquad (3)$$

where

- a is 17.27,
- T^* is 273.16 Kelvin,
- b is 35.86, and
- T is measured surface water temperature in Kelvin.

Vapor pressure (e_a) was calculated from equation 3 but using the mean daily air temperature 2 m above the lake surface, then multiplied by the relative humidity divided by 100.

The Thornthwaite method relies only on air temperature to calculate evaporation using (Thornthwaite, 1948):

$$E = 1.6 * (10T_a / I)^a \qquad (4)$$

where

- E is evaporation in centimeters per month,
- T_a is the mean monthly air temperature in degrees Celsius,
- I is 44.95, the annual heat index, and
- a is 1.2034, an exponent (see equation 6).

The annual heat index (I) is the sum of the monthly heat index, i, and given by:

$$I = \sum i, \text{ and } i = (T_a / 5)^{1.514} \qquad (5)$$

The exponent (a) in equation 4 is a function of the annual heat index, I, given by:

$$a = 0.000000675(I^3) - 0.00007711(I^2) + 0.01792(I) + 0.49239 \qquad (6)$$

Monthly evaporation totals from each method were converted to common units of feet per month and multiplied by the mean lake surface area (2,326 acres) to obtain the monthly water volume lost from the lake.

Nutrient Budget Methods

Nutrient budgets for nitrogen and phosphorus were compiled for Vancouver Lake from October 2010 to October 2012. Nutrient budgets are determined by calculating nutrient loads from sources into and out of the lake, and the load for a given source is the product of the volume of water and the concentration of that source for a given time step. For this study, monthly budgets of nitrogen and phosphorus were calculated according to the following equation:

$$PPT_{(n,p)} + SW_{\text{in}(n,p)} + GW_{(n,p)} + D_{(n,p)} = SW_{\text{out}(n,p)} + Sed_{(n,p)} + \Delta S_{(n,p)} + R_{(n,p)} \qquad (7)$$

where

- PPT is precipitation load,
- SW_{in} is the sum off all surface water loads (Flushing Channel, Burnt Bridge Creek, and Lake River IN),
- GW is the groundwater inflow load,
- D is the diffusive flux of nutrients from the sediment,
- SW_{out} is the surface water load leaving the lake (Lake River OUT),
- Sed is the amount of nutrient lost from sedimentation within the lake,
- ΔS is change of nutrient mass in lake storage,
- R is the nutrient budget residual, and
- n and p represent nitrogen or phosphorus.

Equation 7 assumes that groundwater outflow and runoff of nutrients from the terrestrial system are both negligible. In addition, inputs from water fowl and sediment resuspension are not directly measured. All terms are in units of pounds per month. Because nutrients can be altered from biological, chemical, and physical processes, the residual term (R) in the nutrient budget equation (eq. 7) represents the uncertainty in the mass balance plus any processes that are not being directly determined. Water volumes determined from monthly water budgets were used together with field samples of water quality to determine loads used in equation 7.

Surface Water Loads

Surface Water Quality Data Collection

Monthly surface water quality samples were collected at Flushing Channel, Burnt Bridge Creek, Lake River at Felida, and two lake locations (Lake Site 1 and Site 2) throughout the study (fig. 5). At the two lake sites, a surface water sample was collected within the upper 1–2 ft of the water column and a bottom sample was collected approximately 1 ft from the bottom of the lake. In addition, samples were collected from the mouth of Salmon Creek, located approximately 1.5 mi north of where Lake River joins Vancouver Lake. Salmon Creek does not flow directly into the lake, but does flow directly into Lake River, which intermittently flows towards the lake. Samples for water-quality analyses were collected from Salmon Creek just upstream of where it discharges to Lake River. The water-quality data from Salmon Creek were used to determine surface-water loads to Lake River in order to estimate the proportion of nutrient load entering Vancouver Lake from Lake River that originated from Salmon Creek.

Water-quality sampling location selection and field procedures followed the most recent version of the USGS National Field Manual (NFM) (U.S. Geological Survey, variously dated). Prior to field sample collection, the sample-collection bottles, churn splitters, caps and nozzles (used in the USGS DH-81 or DH-95 depth-integrating sampler), tubing, and filtration equipment used in processing were washed with a phosphate-free detergent solution, rinsed with tap water, rinsed with 5 percent hydrochloric acid solution, and given a final rinse with water from the USGS Washington Water Science Center reverse-osmosis (RO) system. The cleaned equipment was transported to the field sites in clean plastic bags.

At Burnt Bridge Creek, Lake River at Felida, and Salmon Creek, water-quality samples were collected using either an equal discharge interval (EDI) or equal width interval (EWI) at a minimum of five locations across the width of the reach with a standard USGS depth integrating sampler (DH-95 or DH-81) and composited into an 8-L churn splitter (fig. 9). At Flushing Channel, samples were collected from a 13 × 13 ft concrete vault located at the tide gate structure. The water in the vault was always well mixed and several depth-integrated samples were collected using a DH-95 depth-integrating sampler and churn splitter. These procedures resulted in a single width and depth-integrated sample at each location. The churn splitter was rinsed with native water three times prior to collection of the environmental sample.

Figure 9. U.S. Geological Survey (USGS) hydrologist collecting a width and depth-integrated water quality sample across the mouth of Burnt Bridge Creek, Washington. (Photograph taken by James Foreman, USGS, November 2010.)

The composite sample was churned to fully mix the sample while it was split directly into appropriate collection bottles for analysis of a set of whole water (unfiltered) samples. After the unfiltered samples were collected, a field peristaltic pump equipped (with C-flex® tubing) and a preconditioned (purged with 2 L of RO water), 0.45-micron capsule filter (Pall Aquaprep®) were used to collect filtered samples. All filtered sample bottles were rinsed three times with filtered water prior to sample collection. At the Lake Sites 1 and 2 (fig. 5), point samples were collected from the surface or bottom using a field peristaltic pump and a weighted length of tubing. Lake samples were collected directly into bottles for whole water (unfiltered) samples; for filtered samples, a 0.45-micron capsule filter (Pall Aquaprep®) was attached to the end of the tubing and samples were collected directly into appropriate bottles after rinsing three times with filtered sample.

Samples were analyzed for total and dissolved nutrients (nitrogen and phosphorus), suspended sediment, particulate carbon, particulate nitrogen, and particulate phosphorus. Lake samples were also analyzed for chlorophyll-*a* (Chl-*a*). All analyses except suspended sediment and particulate phosphorus were performed by the National Water Quality Lab (NWQL) in Denver, Colorado. Suspended sediment was analyzed by TestAmerica Laboratory in Arvada, Colorado, and particulate phosphorus was analyzed by the Chesapeake Biological Laboratory at the University of Maryland in Solomons, Maryland. A summary of all water quality parameters analyzed for this study is provided in table 2.

Table 2. Water quality parameters, U.S. Geological Survey parameter codes, and detection limits for analytes measured in surface water and groundwater for the Vancouver Lake nutrient budget, Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[The parameter code is unique to each parameter stored in the National Water Information System data base. **Abbreviations**: NWQL, National Water Quality Laboratory; TAL, TestAmerica Laboratory; USGS, U.S. Geological Survey; UMDCBL, University of Maryland Chesapeake Biological Laboratory; WAWSC, Washington Water Science Center; –, not applicable]

Parameter name	USGS parameter code	Analyzing entity	Detection limit
Dissolved oxygen, water, unfiltered, milligrams per liter	00300	WAWSC	–
pH, water, unfiltered, field, standard units	00400	WAWSC	–
Specific conductance, water, unfiltered, microsiemens per centimeter at 25 degrees Celsius	00095	WAWSC	–
Temperature, water, degrees Celsius	00010	WAWSC	–
Transparency, water, in situ, Secchi disc, feet	49701	WAWSC	–
Turbidity, water, unfiltered, monochrome near infra-red LED light, 780–900 nm, detection angle 90 ±2.5 degrees, formazin nephelometric units (FNU)	63680	WAWSC	–
Suspended solids, water, unfiltered, milligrams per liter	00530	TAL	1.1
Carbon (inorganic plus organic), suspended sediment, total, milligrams per liter	00694	NWQL	0.05
Ammonia, water, filtered, milligrams per liter as nitrogen	00608	NWQL	0.01
Nitrate plus nitrite, water, filtered, milligrams per liter as nitrogen	00631	NWQL	0.008
Nitrite, water, filtered, milligrams per liter as nitrogen	00613	NWQL	0.001
Orthophosphate, water, filtered, milligrams per liter as phosphorus	00671	NWQL	0.004
Particulate nitrogen, suspended in water, milligrams per liter	49570	NWQL	0.017
Particulate phosphorus, suspended in water, milligrams per liter	49567	UMDCBL	0.0021
Phosphorus, water, filtered, milligrams per liter as phosphorus	00666	NWQL	0.003
Phosphorus, water, unfiltered, milligrams per liter as phosphorus	00665	NWQL	0.004
Total dissolved nitrogen (nitrate + nitrite + ammonia + organic-N), water, filtered, analytically determined, milligrams per liter	62854	NWQL	0.05
Total nitrogen (nitrate + nitrite + ammonia + organic-N), water, unfiltered, analytically determined, milligrams per liter	62855	NWQL	0.05
Chlorophyll-*a*, phytoplankton, chromatographic-fluorometric method, micrograms per liter	70953	NWQL	0.1

Unfiltered total nitrogen (TN) and total phosphorus (TP) samples were acidified by adding a 1 mL solution of 4.5 normal sulfuric acid (H_2SO_4) to each bottle and then chilled before analysis at NWQL by digestion (Fishman, 1993; Patton and Kryskalla, 2003). Dissolved nutrients (ammonia, nitrate plus nitrite, nitrite, total dissolved nitrogen, and total dissolved phosphorus) were kept cold and shipped to NWQL for analysis using established methods (Fishman, 1993; Patton and Kryskalla, 2011; Patton and Kryskalla, 2013;). Particulate nitrogen and carbon samples were collected in baked, amber glass bottles; a known volume of sample was filtered through a 25–mm baked, glass fiber filter; and then the filter was folded and wrapped in aluminum foil. Analysis for particulate nitrogen and carbon at NWQL followed U.S. Environmental Protection Agency method 440.0 (U. S. Environmental Protection Agency, 1997). Chlorophyll-*a* samples were processed in a similar manner, except a larger 45-mm glass fiber filter was used before analysis by standard methods (Arar and Collins, 1997). Total suspended solids were determined gravimetrically by drying a known volume of unfiltered sample. Particulate phosphorus was determined after filtering a known volume of sample onto a 45-mm glass fiber filter which was processed using established methods (Aspila and others, 1976; U.S. Environmental Protection Agency, 1993; Keefe, 1994).

Field parameters (temperature, dissolved oxygen, specific conductance, turbidity, and pH) were determined every time a water-quality sample was collected using a multi-parameter, water quality sonde (Yellow Springs Instruments, model 6920 v2) equipped with optical dissolved oxygen (DO) and turbidity sensors. The sonde was calibrated prior to each use, and was maintained and operated following procedures established in the National Field Manual (U.S. Geological Survey, variously dated). A minimum of five field readings for each parameter were recorded, and the median values for each parameter were entered into the USGS National Water Information System (NWIS) database. At the lake sites, profiles for DO, temperature, specific conductivity, and pH were determined in three locations, Lake Site 1, Lake Site 2, and Lake Site 3 (fig. 5). Additionally, a measurement of water clarity was taken using a Secchi disk (8-in. diameter, with alternating black and white colored quadrants).

Modeling Surface Water Loads

Total nitrogen (TN), Total Phosphorus (TP), and orthophosphorus loads transported by Flushing Channel, Burnt Bridge Creek, Lake River IN and Lake River OUT, and Salmon Creek were estimated with the program LOADEST (LOAD ESTimation), developed and documented by Runkel and others (2004), and based on previous work by Cohn (1988), Cohn and others (1989), and Crawford (1991, 1996). LOADEST uses a calibration dataset consisting of instantaneous concentrations from monthly water-quality samples and a dataset composed of mean daily streamflows from streamgage sites for the period of interest. A regression model relating concentrations to flow was developed and this model was used to calculate concentration for the days when samples were not collected. LOADEST was run using a USGS add-on in the statistical software package Spotfire S+® (ver 8.1, TIBCO Software Inc.) that simultaneously evaluated nine different loading models. The best fit model was determined using Akaike Information Criterion and coefficients of the model were estimated using Adjusted Maximum Likelihood Estimate procedures in the LOADEST subroutines. Daily loads were computed by multiplying simulated daily concentrations and measured (Flushing Channel and Burnt Bridge Creek) or estimated (Lake River IN and OUT, and Salmon Creek) daily flows and then summing to determine the estimated monthly and annual TN, TP, and orthophosphate 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 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 with LOADEST to develop 95 percent prediction intervals for each estimate of mean load (Runkel and others, 2004). Finally, the percent error of load estimates is defined by taking the SEP divided by the load, then multiplying by 100 to get a percentage.

Groundwater Load

Throughout the study, shallow groundwater samples were periodically collected and analyzed for nutrients from three locations. Samples from two seeps along the eastern border of the lake (near Lake Site 1 and near Lake River at Felida) and from a shallow drivepoint well installed near the lakeshore at the VLSC (Site 2 drivepoint) (fig. 5; table 1), were used to characterize shallow groundwater concentrations entering the lake. Additional attempts to collect groundwater from multiple locations within the lake were unsuccessful because of the presence of low permeability sediments throughout the lake. In addition, seeps along the eastern shore of the lake were only accessible during summer when the lake level was low and the flow was too diffuse to accurately measure (fig. 10). Furthermore, monthly groundwater samples at the drive point location indicated little seasonal variability. As a result, we are assuming the groundwater concentrations from these three locations are characteristic for the area.

Figure 10. Diffuse groundwater seeps observed along the eastern shore of Vancouver Lake, Vancouver, Washington. The seeps, indicated by the iron-stained sediments, were only visible during low lake levels in late summer. Flow in these seeps was too low to accurately quantify. (Photographs taken by Rich Sheibley, U.S. Geological Survey, September 2012.)

Samples were collected from the Site 2 drivepoint using a field peristaltic pump and tubing that was inserted to within a few inches of the bottom of the well. Sample collection did not begin until the drivepoint water was clear of stirred up sediments that had accumulated in the well between sample events and field parameters (temperature, dissolved oxygen, pH, and specific conductivity) had stabilized (fig.11). Samples were collected for dissolved nutrients (total dissolved nitrogen and phosphorus, ammonia, and nitrate plus nitrite) from filtered samples, and TN and TP from unfiltered samples. Filtered samples were collected by attaching a capsule filter to the end of the tubing using a field peristaltic pump. At the seeps, samples were pumped directly from the flow of the seep, or pumped from a sample collected into a clean 1-L bottle that was rinsed three times with native water. All filtered groundwater samples were filtered into clean bottles that were rinsed three times with filtered water. All equipment was cleaned, and each capsule filter preconditioned, with 2 L of RO water prior to sample collection, in the same manner as surface water samples. Shallow groundwater nutrients were analyzed at the USGS NWQL in Denver, Colorado using the same methods described for surface water samples.

Figure 11. U.S. Geological Survey hydrologic technician recording field water-quality parameters during collection of shallow groundwater from a drivepoint installed at the Vancouver Lake Sailing Club, Vancouver Lake, Washington. (Photograph by Rich Sheibley, U.S. Geological Survey, August 2011.)

Shallow groundwater load into the lake was calculated by taking the average groundwater TN, TP, or orthophosphate concentrations from all samples and multiplying by the volume of shallow groundwater entering the lake that was calculated in the water budget for each month. The daily groundwater flow volume was assumed to be constant; therefore, monthly groundwater loads only varied by the number of days in a given month.

Precipitation Load

Monthly nutrient load from precipitation was calculated from the product of monthly precipitation volume and a characteristic dissolved nutrient concentration in precipitation. The setup and operation of a rigorous precipitation chemistry station was beyond the scope of this study. Instead, we used data from regional sources for nitrogen and phosphorus precipitation concentrations. Monthly precipitation-weighted concentration data from six sites in western Oregon and Washington collected by the National Atmospheric Deposition Program (NADP) were used to estimate precipitation chemistry for nitrogen loads at Vancouver Lake (fig. 12). Monthly data for dissolved nitrogen (the sum of nitrate and ammonia) from October 2010 to October 2012 were downloaded from the NADP database (National Atmospheric Deposition Program, 2013) for each station and averaged to get a monthly dissolved nitrogen concentration for precipitation on the lake. NADP does not currently publish phosphorus data because this parameter is not stable in unfiltered samples. Therefore, phosphorus loads from precipitation were estimated using published total phosphorus concentrations in precipitation from studies in Washington that were recently summarized by Roberts (2013). Loads from precipitation for nitrogen and phosphorus should be considered underestimates because the samples were from wet deposition only, and do not account for dry deposition.

Change in Lake Storage

The change in total mass of nutrient contained in the lake (storage) was determined by multiplying the change in lake storage from the monthly water budget and the monthly nutrient concentration in the lake. The monthly concentrations of TN, TP, and orthophosphate for the lake were calculated by taking the average of four samples (Lake Site 1 surface and bottom; Lake Site 2 surface and bottom) each month.

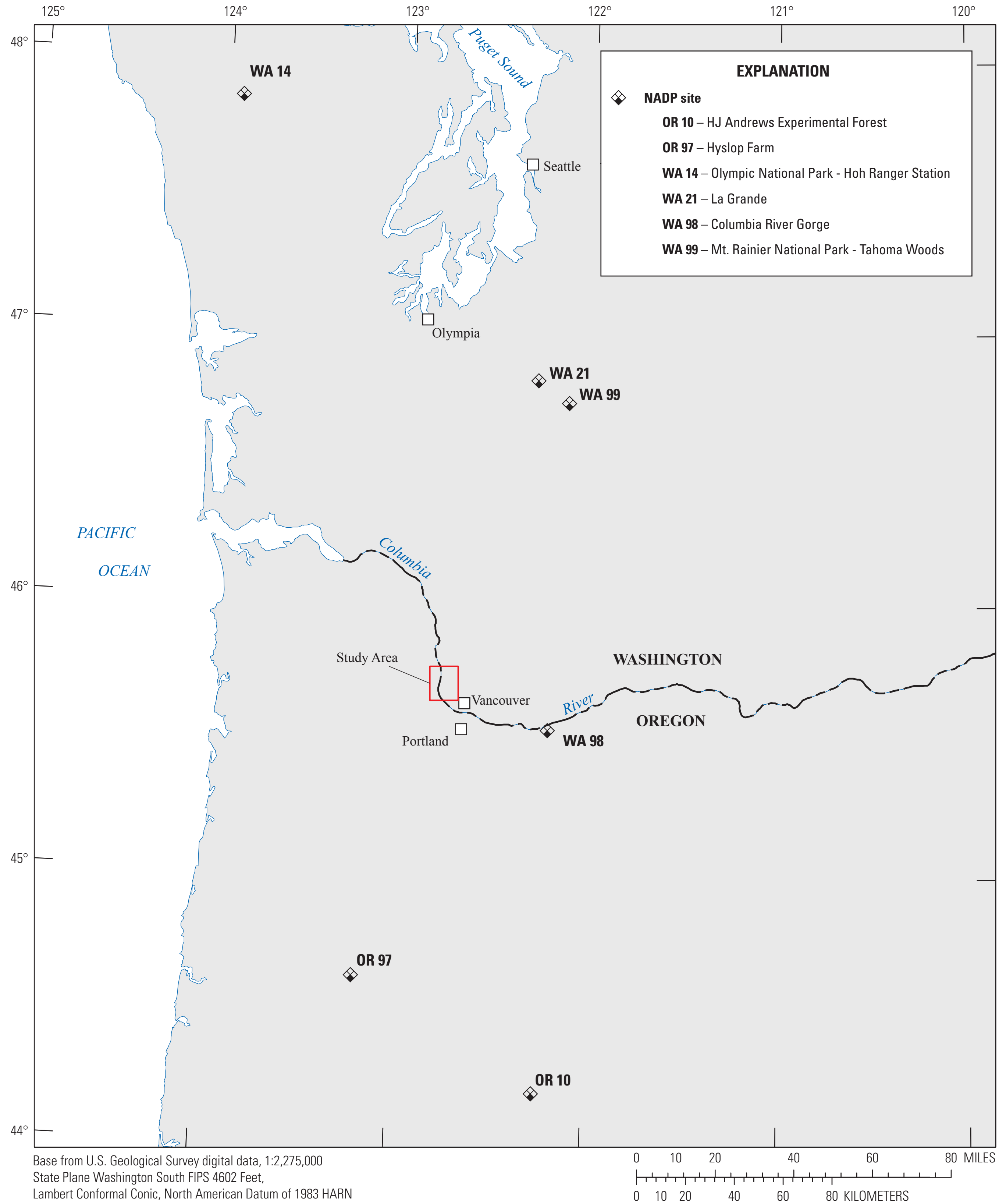


Figure 12. Locations of National Atmospheric Deposition Program (NADP) precipitation chemistry sites used to estimate dissolved inorganic nitrogen load to Vancouver Lake, Washington, October 2010–October 2012.

Internal Load from Diffusive Flux

Concentration gradients in sediment porewater near the sediment-water interface of a lake can result in the release or uptake of nutrients to and from, respectively, the overlying water by the process of diffusion. This diffusive flux can cause an internal load of nutrients that can be equal in magnitude to, or greater than, surface water inputs in some locations (Kuwabara and others 2009a, 2009b). Therefore, estimating this potential source is important for understanding the overall nutrient budget of the lake. If nutrient concentrations in deep porewater are greater than concentrations near the upper sediment, the diffusive flux will cause a release of nutrient into the water column. If nutrient concentration in the upper porewater is greater than the concentration in deeper sediments, the opposite takes place, and nutrients tend to be removed from the water column. Therefore, estimating the diffusive flux at the sediment-water interface and scaling these fluxes up to the whole lake area provides an estimate of total internal nutrient load from diffusion.

One technique for estimating benthic diffusive fluxes is by measuring porewater nutrient profiles in the sediment and using this information to calculate concentration gradients at the sediment-water interface (Sheibley and Paulson, 2014). Typically, the calculated flux (*F*) is based on Fick's law of diffusion and represents diffusional flux into or out of the sediment:

$$F = Ds \times \theta \times dC / dz \qquad (8)$$

where

- F is the calculated flux in units of (mg/ft^2)/day;
- Ds is the whole sediment diffusion coefficient, in units of cm^2/sec, which is the molecular diffusion coefficient (Do) corrected for bottom water temperature (Li and Gregory, 1974) and tortuosity (Ullman and Aller, 1982);
- dC/dz is the concentration gradient at $z = 0$, the sediment-water interface; and
- θ is the sediment porosity.

For most lake sediments, porosity at the sediment-water interface can be quite high (> 0.80). For sediments with porosity of 0.7 or greater, the relation between Ds and Do can be approximated by $Ds = (\theta)^2 Do$ (Ullman and Aller, 1982).

Sediment porewater samples were collected at Lake Site 1 and Lake Site 2 in August 2011 and August 2012 to determine the concentration gradient near the sediment-water interface for use in equation 8. Cores were collected by boat using a 30-cm long push corer and the cores were extruded in the field at 2-cm intervals and placed into 50-mL centrifuge tubes. Sediment samples were spun at 10,000 rpm for 10 minutes and the overlying water was removed using a 10-cc syringe and filtered into clean 2-fl. oz sample bottles using 25-mL syringe filters. Filtered samples were frozen until analysis for ammonia, nitrate plus nitrite, and orthophosphate using the same methods described previously for surface-water samples. Porewater samples were processed and frozen within 4 hours of collection. Sediment porosity (θ) was determined from replicate sediment cores by calculating the difference in mass between the wet and dry (60 °C for 48 hours) sediments and the volume of each 2-cm sediment slice, using standard methods (Flint and Flint, 2002).

Porewater concentration gradients were determined from a linear regression of the three to four data points closest to the sediment-water interface. A simple linear regression of the porewater data was used instead of more complex curve-fitting methods (Klump and Martens, 1981) because curve-fitting methods work better on finer spatial resolution datasets (usually 0.5 cm or less). The statistical software Spotfire S+® (ver. 8.1, TIBCO® Software Inc.) was used to test whether the slope of concentration versus depth curves were statistically different from zero. Slopes with a p-value of 0.1 or less were used to calculate diffusive fluxes. Porewater profiles where the slope of the concentration compared to depth was not significant ($p>0.1$) indicate that biogeochemical processes could be influencing porewater concentrations in this region of the sediment, and that concentrations are not solely controlled by diffusion. Non-significant slopes also may indicate that the sampling interval was too large and did not allow the calculation of accurate concentration gradients near the sediment-water interface. This would be especially true for solutes where this gradient was steep near the sediment-water interface.

The Fick's law model does not incorporate the contributions to the flux from wind resuspension or benthic fauna, and therefore are considered underestimates of the true benthic flux (Kuwabara and others, 2012).

Sedimentation of Nitrogen and Phosphorus

Nutrient loss can take place as a result of sedimentation of particulate matter in a lake. An estimate of the sedimentation rate of the lake is needed to conduct this analysis and is typically determined through the use of radioisotope tracers, such as 210-lead or 137-Cesium. At Vancouver Lake, this approach would be difficult to employ because there is likely a large sediment mixing zone from the large changes in lake level coupled with wind resuspension of surface sediments, resulting in large errors in determining the recent sedimentation rate of the lake. As a result, we used a lake sediment balance to calculate the amount of sediment that accumulates in or is exported from the lake each month. The sediment budget was estimated by simulating total suspended sediment (TSS) loads in Flushing Channel, Burnt Bridge Creek, Lake River IN and OUT using LOADEST from TSS concentration and flow data. Changes in monthly storage of sediment in the lake were calculated from the change in storage volume from the water budget multiplied by the average monthly lake TSS concentration. In order to estimate the amount of nitrogen or phosphorus contained in the suspended sediment, the ratio of particulate nitrogen (N) or phosphorus (P) concentration to TSS concentration was calculated from lake samples to compute a milligram of N (or P) per milligram of TSS; then knowing how much sediment is accumulated in the lake, or exported from the lake, an estimate of the amount of N or P stored in the lake or exported from the lake can be estimated.

Quality of Data

The quality of all water-quality data was assessed from the analysis of laboratory and field blanks, field replicates, and standard reference samples. All quality-control data are provided in appendix B. Because the goal of the report is to present TN, TP, and orthophosphate budgets for the lake, analysis of data quality will focus on these three parameters. There were no detections for TN, TP, and orthophosphate across 19 different blank samples (table B1). Therefore, there was no indication that procedures followed during sample collection and processing were a source of contamination during this study. A statistical analysis of the upper limit of potential contamination from blank samples showed that for TP and orthophosphate, the potential contamination, with 96 percent confidence, is less than or equal to 0.004 mg/L as P in at least 80 percent of the samples. For TN, the potential contamination, with 96 percent confidence, is less than or equal to 0.05 mg/L as N.

The standard deviation of field replicates was used to evaluate the amount of variability in the environmental samples for TN, TP, and orthophosphate. Using the mean standard deviation across all field replicates, the 90 percent confidence interval was calculated. Eleven replicate pairs for TN ranged in concentration from 0.24 to 2.76 mg/L as N and the relative percent difference between replicate pairs was always less than 10 percent (table B2). Variability of these replicate samples was ±0.025 mg/L as N with a 90 percent confidence interval of ±0.041 mg/L as N. Relative percent difference for total phosphorus and orthophosphate was almost always less than 10 percent (table B2). The 90 percent confidence interval of the data was ±0.006 mg/L as P for TP, and ±0.003 mg/L as P for orthophosphate.

Overall, quality-control data indicate that we have a low degree of bias from contamination, and low amount of variability in our environmental data. Therefore, concentration data used for the calculation of nutrient budgets are of good quality.

During the course of this project, two method changes were put into effect by the USGS Office of Water Quality and NWQL. The first was a change in analytical method used to determine nitrate concentration, and the second was a change in reporting TN concentrations. Quality-control data to support these changes and details on how these changes affected this project are detailed in appendix B. Most notable, for all the TN load model simulations we used a TN concentration based on the sum of particulate nitrogen and total dissolved nitrogen (TN, calculated), rather than a TN concentration from a whole-water digested sample (TN, digested). This decision was based on work showing that for turbid waters, a negative bias was present in digested TN concentrations (appendix B).

Water Budget for Vancouver Lake

Surface Water Hydrology

Hydrographs for Flushing Channel and Burnt Bridge Creek are shown in figure 13 and were compiled from mean daily discharge data presented in Foreman and others (2014). Mean daily flow at Flushing channel ranged from 6 to 176 ft^3/s and an overall mean flow of 76 ft^3/s during the study period (fig. 13*A*). Low flows during both years at this site began in summer and persisted through early autumn (July through November) when flows began to increase throughout the winter and spring (January through June). Flows peak in June of both years. Hourly flow data indicated discharge was zero approximately 3 hours a day on average because of the tide gate at this site (data not shown). Monthly flow volumes at Flushing Channel ranged from 2,100 to 8,500 acre-ft during October 2010–October 2012 (table 3).

Flow at Burnt Bridge Creek was closely linked to watershed processes and had high flows in the winters and spring when storms were more common, with dramatic reductions in flow during the dry summers and early autumn. Mean daily flow ranged from 6 to 132 ft^3/s with an overall mean flow of 27 ft^3/s during the study period (fig. 13*B*). Monthly flow volumes ranged from 400 to 3,400 acre-ft during the study (table 3).

Mean daily discharge for Lake River at Felida was calculated from flow at the Lake River at Ridgefield streamgage and flow from Salmon Creek at Lake River are provided in Appendix A. Discharge in Lake River at Felida were much greater than Flushing Channel and Burnt Bridge Creek, and sometimes displayed pronounced swings in flow on a day to day basis (fig. 14). Discharge at this site was highly influenced by the Columbia River stage and experienced bidirectional flow most days. The discharge record at Lake River at Felida was split into two modified records, one for the portion of flow entering the lake (Lake River IN) the other for the portion of the flow exiting the lake (Lake River OUT). Mean daily discharge of Lake River IN ranged from 4 to 4,900 ft^3/s, with an overall mean of 683 ft^3/s during the two year study (fig. 14*A*). Lake River OUT ranged from 3 to 2,400 ft^3/s with an overall mean flow of 719 ft^3/s from October 2010 to October 2012 (fig. 14*B*).

Table 3. Measured water budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[All values in acre-feet per month, except where indicated. **Change in storage**: Negative values for storage indicate a loss in lake volume for that month. **Abbreviations**: %, percentage; –, not calculated (stage was not available for this month, therefore the change in storage and the residual could not be determined for October 2012); NA, not applicable; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Month	Inputs					Outputs		Change in storage	Residual	Residual as % of inputs
	Flushing Channel	Burnt Bridge Creek	Lake River IN	Ground-water	Precip-itation	Lake River OUT	Evap-oration			
October 2010	2,600	1,100	36,800	110	790	36,100	330	1,900	3,000	7
November 2010	2,100	2,100	38,600	100	1,200	36,500	170	1,900	5,400	12
December 2010	3,700	3,400	47,900	110	1,200	44,600	120	8,300	3,300	6
January 2011	5,000	2,600	49,100	110	810	57,400	90	-2,100	2,200	4
February 2011	3,100	1,600	35,600	100	870	44,000	120	-3,100	200	0
March 2011	5,000	3,100	53,600	110	1,200	37,200	180	6,300	19,200	30
April 2011	5,700	2,700	52,800	100	670	49,700	340	-1,900	13,900	22
May 2011	7,100	1,900	60,000	110	430	31,700	490	17,600	19,800	28
June 2011	8,500	1,000	28,300	100	160	52,600	630	-9,400	-5,700	-15
July 2011	6,000	900	35,200	110	210	57,300	850	-12,200	-3,500	-8
August 2011	3,800	600	40,600	110	0	43,800	970	-2,100	2,600	6
September 2011	3,000	500	34,100	100	100	36,700	640	-1,500	2,000	5
October 2011	3,000	800	33,600	110	170	36,800	320	-700	1,200	3
November 2011	2,700	1,700	36,000	100	1,100	35,600	150	2,200	3,700	9
December 2011	2,900	1,200	38,200	110	490	33,700	80	6,400	2,800	7
January 2012	4,700	2,700	43,400	110	1,000	48,600	90	-1,600	4,900	9
February 2012	3,000	1,700	34,400	100	500	38,700	170	-4,000	4,800	12
March 2012	5,300	3,000	61,600	110	1,400	35,500	240	17,600	18,000	25
April 2012	7,300	2,200	42,200	100	480	50,900	360	-500	1,500	3
May 2012	7,100	1,500	34,800	110	470	58,100	520	-11,000	-3,600	-8
June 2012	7,500	1,200	47,200	100	460	40,600	570	6,300	9,000	16
July 2012	7,200	700	37,200	110	10	54,200	850	-10,100	200	0.4
August 2012	3,700	500	39,500	110	10	44,800	900	-3,800	2,000	5
September 2012	2,900	400	31,100	100	10	35,900	610	-4,400	2,400	7
October 2012	2,800	1,000	34,600	110	910	32,300	390	–	–	–
Monthly minimum	2,100	400	28,300	100	0	31,700	80	-12,200	-5,700	-15
Monthly maximum	8,500	3,400	61,600	110	1,400	58,100	970	17,600	19,800	30
Monthly average	**4,700**	**1,630**	**41,330**	**110**	**570**	**43,360**	**410**	**4**	**4,554**	**9**

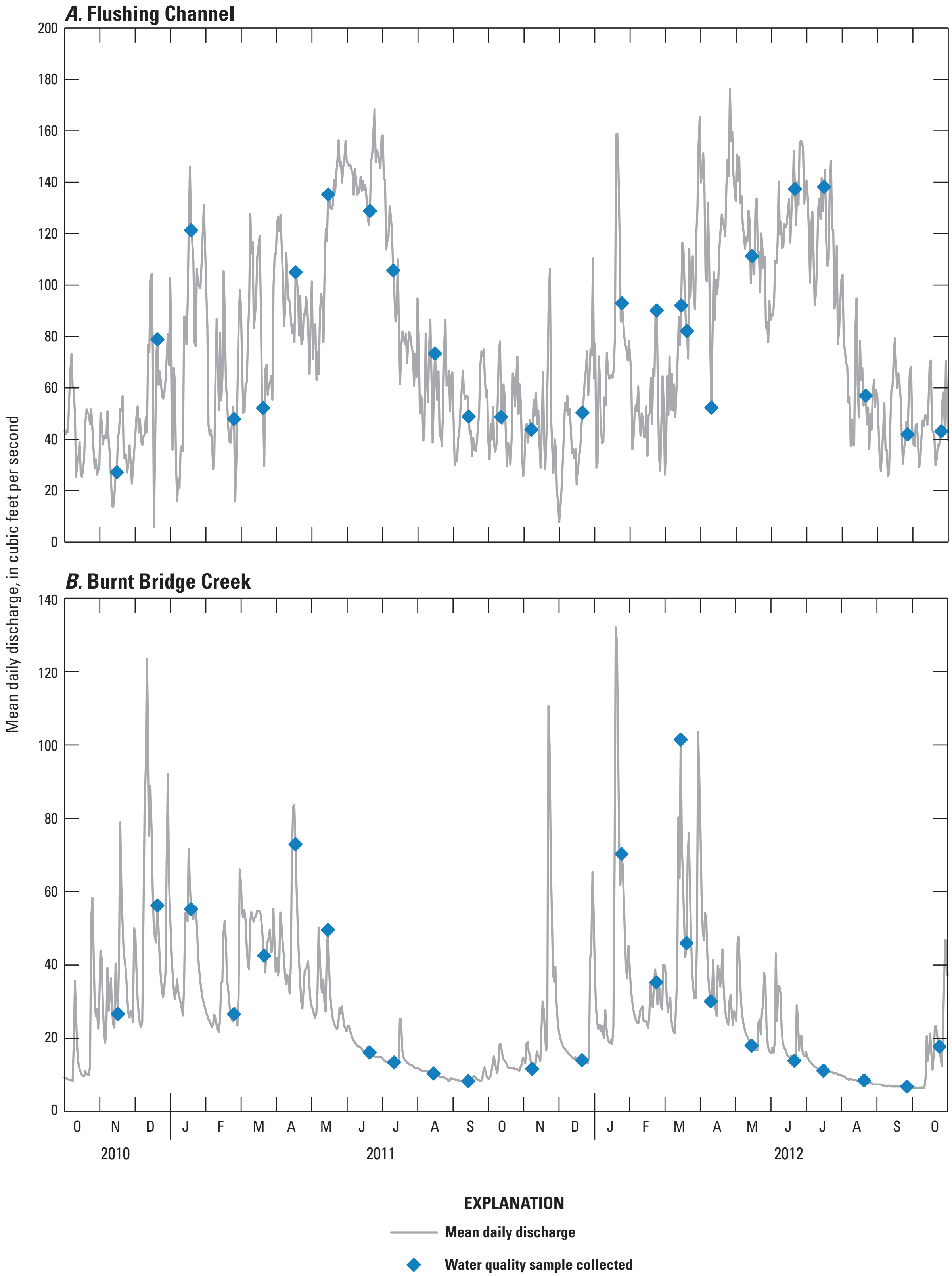


Figure 13. Mean daily discharge at (*A*) Flushing Channel at Vancouver Lake (14144805); and (*B*) Burnt Bridge Creek near mouth at Vancouver (14211902), Vancouver, Washington, October 2010–October 2012.

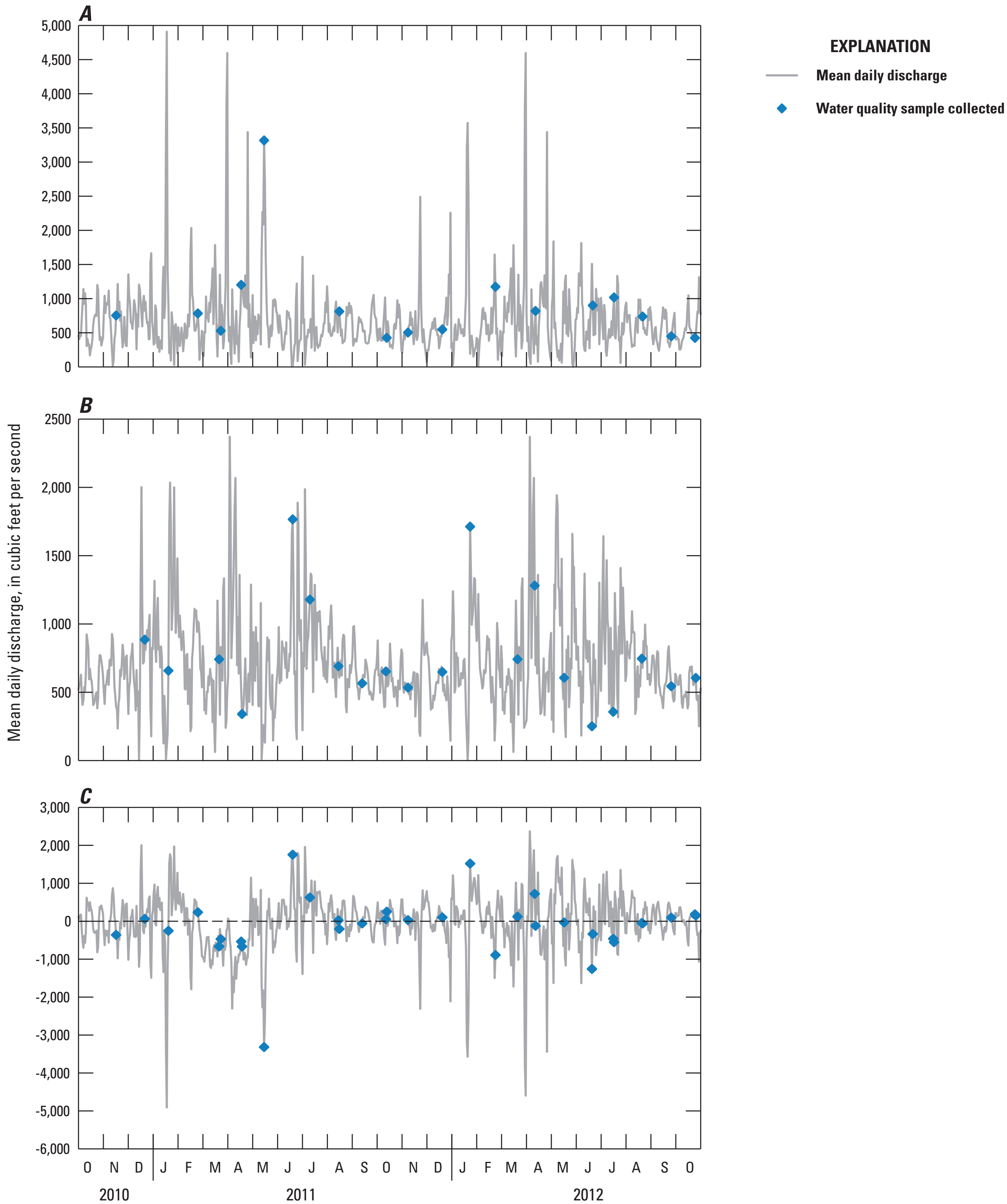


Figure 14. Mean daily flow at Lake River at Felida (14211955), for (*A*) flow into the Vancouver Lake; (*B*) flow out of the lake; and (*C*) the overall mean daily discharge, Vancouver, Washington, October 2010–October 2012.

The combined mean daily discharge (from the original flow record) showed a similar range in flow from -4,900 to 2,400 ft^3/s, where negative discharge is flow entering the lake (fig. 14*C*). The overall mean daily discharge showed that flow was exiting the lake (positive values) a majority of the time and had an overall mean discharge of -21 ft^3/s during the study. Using hourly discharge data from Lake River at Felida (hourly data not shown) the proportion of each month that Lake River Felida was either flowing IN or OUT of the lake was determined (fig. 15). During the study period, Lake River at Felida was flowing out of the lake 53 percent of the time, on average, each month.

Monthly flow volumes flowing toward the lake ranged from 28,300 to 61,600 acre-ft and flow volumes flowing away from the lake ranged from 31,700 to 58,100 acre-ft during the study period (table 3). These flow volumes were an order of magnitude or more greater than either Flushing Channel or Burnt Bridge Creek.

Precipitation to the Lake

Monthly precipitation measured at the Flushing Channel rain gage varied between 0–7 in. during the study period (fig. 16). August 2011 was the only month where no measured rain was recorded, and the wettest months were during winter months (December through March). Using the average lake area during the study period (2,326 acres), precipitation volumes ranged from zero to 1,400 acre-ft (table 3).

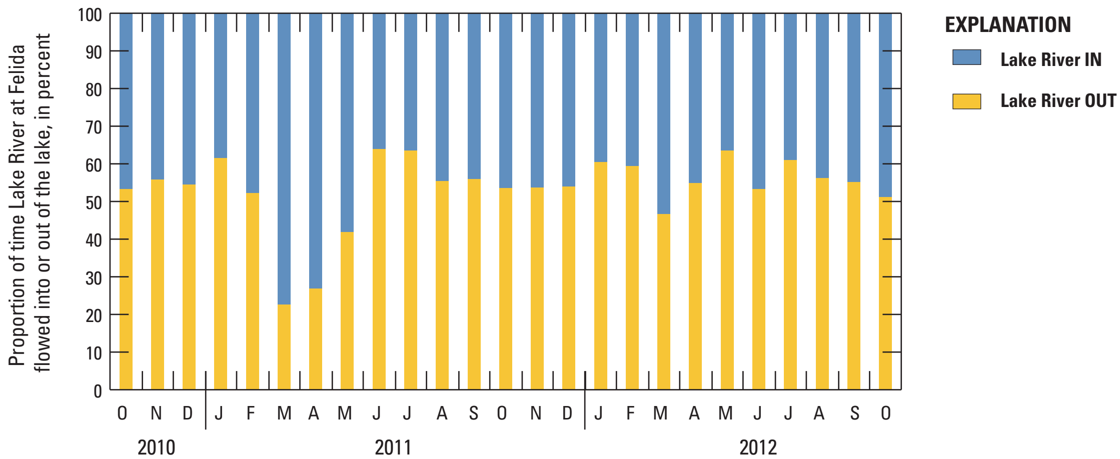


Figure 15. Percentage of monthly flow entering (Lake River IN) Vancouver Lake compared to flow exiting (Lake River OUT) as measured at Lake River at Felida (14211955), Vancouver, Washington, October 2010–October 2012.

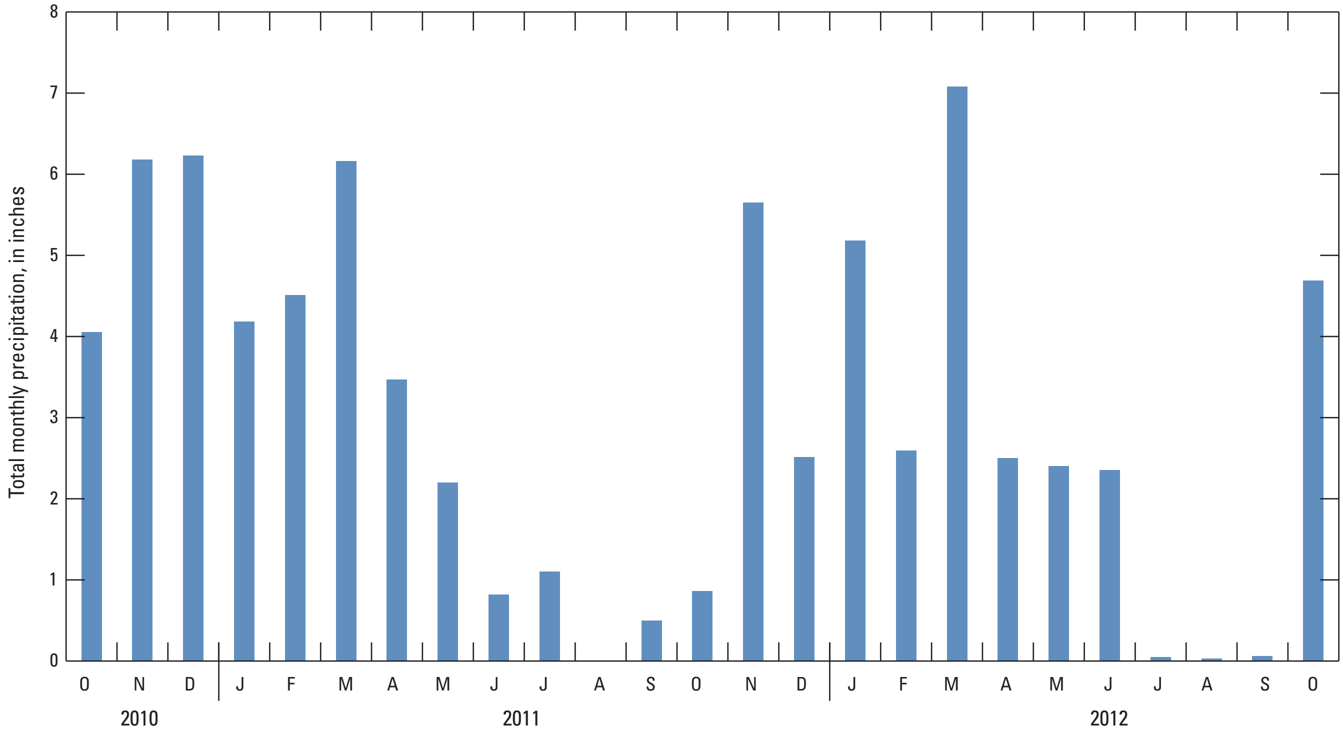


Figure 16. Monthly precipitation measured at the Flushing Channel at Vancouver Lake rain gage 14144805, Vancouver, Washington, October 2010–October 2012.

Groundwater Discharge

Measurement of shallow groundwater seepage took place during the summer at 7 locations around the lake (fig. 7). In general, access to the lake bottom in many locations was only possible in summer when the lake level was low. We assume that seepage rates during this time are representative of other seasons in the year. Summer seepage rates ranged from 0.01 to 1.91 in/d (fig. 7) across all sites. Notable seepage flux was only observed at one site, down gradient of the VLSC (1.91 in./d) compared to all other measurements (mean 0.32 in./d). Because the seepage rates from the other six locations were similar, we divided the groundwater shoreline buffer zone into two zones. Zone 1, for the area just in front of the VLSC, and the Zone 2 for the remaining portion of the buffer. The water volume through each of these areas was calculated by multiplying the area of the zone and the seepage flux for that zone, and then multiplied by the number of days for each month. These seepage fluxes were assumed to be constant in time, and volumes only changed slightly from month to month because of variation in the number of days each month. The groundwater inflow was estimated to contribute 100–110 acre-ft of water to the lake each month during this study. These volumes convert to an annual, continuous groundwater discharge of approximately 1.6 ft^3/s. This value was lower than the estimate of 20 ft^3/s from Bhagat and Orsborn (1971) and from a regional groundwater model of the Portland Basin (Morgan and McFarland, 1996); however, our value for groundwater discharge closely matches the estimate of 2.9 ft^3/s from a recent groundwater model of the Vancouver Lake lowlands (Parametrix, 2008; Dan Matlock, Pacific Groundwater Group, written commun., 2014). This low flow rate from groundwater is not surprising as there is a layer of recent alluvium consisting of silts about 30–40 ft deep and underlying the lake (Parametrix, 2008). These silts may be acting like a confining layer effectively reducing groundwater seepage through the lake bottom.

Change in Lake Storage

Change in lake storage volumes were highly variable on a month to month basis during the study (table 3), and reflects the dynamic changes in lake stage at Vancouver Lake, which can exceed 10–15 ft during the course of a year (fig. 2). The average lake volume was 19,400 acre-ft, and varied from 7,500 to 37,800 acre-ft during the period of study. The greatest increases in storage occurred in winter months and greatest loss in storage took place in summer each water year. The monthly range of the change in lake storage was -12,200–17,600 acre-ft and was variable throughout the study.

We verified the calculated change in lake storage volumes by comparing the change in lake stage (calculated by dividing the monthly storage volume by the average lake surface area [2,326 acres]) to the measured change in lake stage measured near Lake Site 2.There was a close agreement between calculated and measured lake stage changes (fig. 17) and only in October 2011 the direction of the calculated lake stage was the opposite of the measured lake stage. Absolute differences between the calculated and measured monthly lake stage ranged from 0.1 to 1.1 ft during the study.

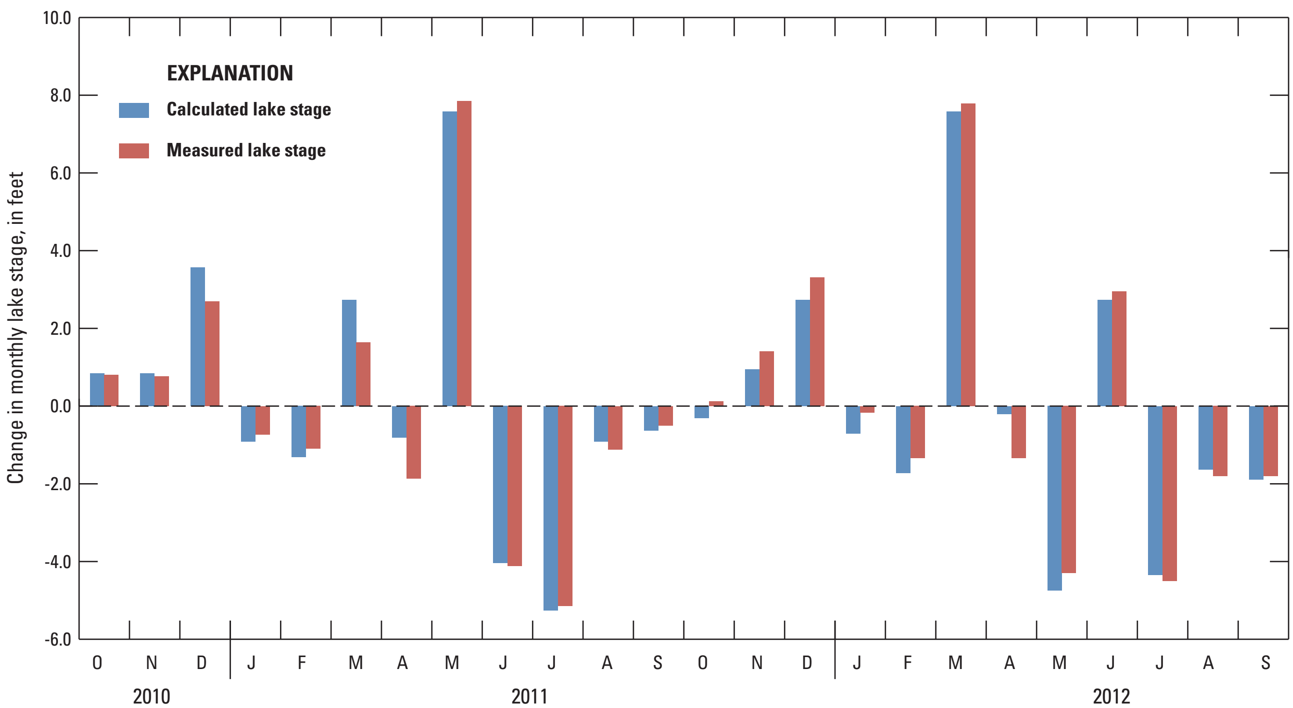


Figure 17. Comparison of calculated and measured changes in monthly lake stage, Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

Evaporation

Evaporation rates were determined using two different methods and averaged to estimate the monthly loss of water from the lake surface. The evaporation rate using the Thornthwaite method ranged from 0.5 to 3.7 in/month, with annual totals of 23.2 and 24.1 in. for water years 2011 and 2012, respectively. The mass-transfer (Harbeck, 1962) method, which uses wind speed and vapor pressure, produced slightly higher results ranging from 0.2 to 6.4 in/month. Annual evaporation rates using mass-transfer method were 27.9 and 26.0 in. for water years 2011 and 2012, respectively. Average annual evaporation rates from these two methods were almost the same for water years 2011 and 2012 at 25.5 in. 25.1 in., respectively. These annual values are in close agreement to the annual rate of evaporation from free water surfaces for this region (25 in.) published by Farnsworth and others (1982). Evaporation volumes ranged from 80 to 970 acre-ft per month during the study (table 3).

Water Budget Summary

A summary of monthly water budget components for Vancouver Lake from October 2010 to October 2012 showed that the residuals were low for most months, and almost always positive (fig. 18; table 3). The residual represents a combination of unaccounted sources of water gain or loss from the lake and the inherent uncertainties associated with the methods used to measure the water budget of the lake. Monthly residuals ranged from -5,700 to 19,800 acre-feet during the study. The highest residuals were calculated in March–April 2011, when the Lake River at Ridgefield streamgage was damaged; during this period, we assumed flow was the same as March–April 2012. Therefore, the higher residuals may be the result of this flow substitution and not an indication that our budgets are less accurate during these months. On a monthly basis, residuals ranged from -15 to 31 percent of the total inputs to the lake, with 16 of 24 months within ±10 percent. The monthly lake residence time, or flushing rate, was calculated by taking the average monthly lake volume divided by the total outflow from Lake River at Felida, and ranged from 8 to 27 days, with an average residence time of 13 days during the study.

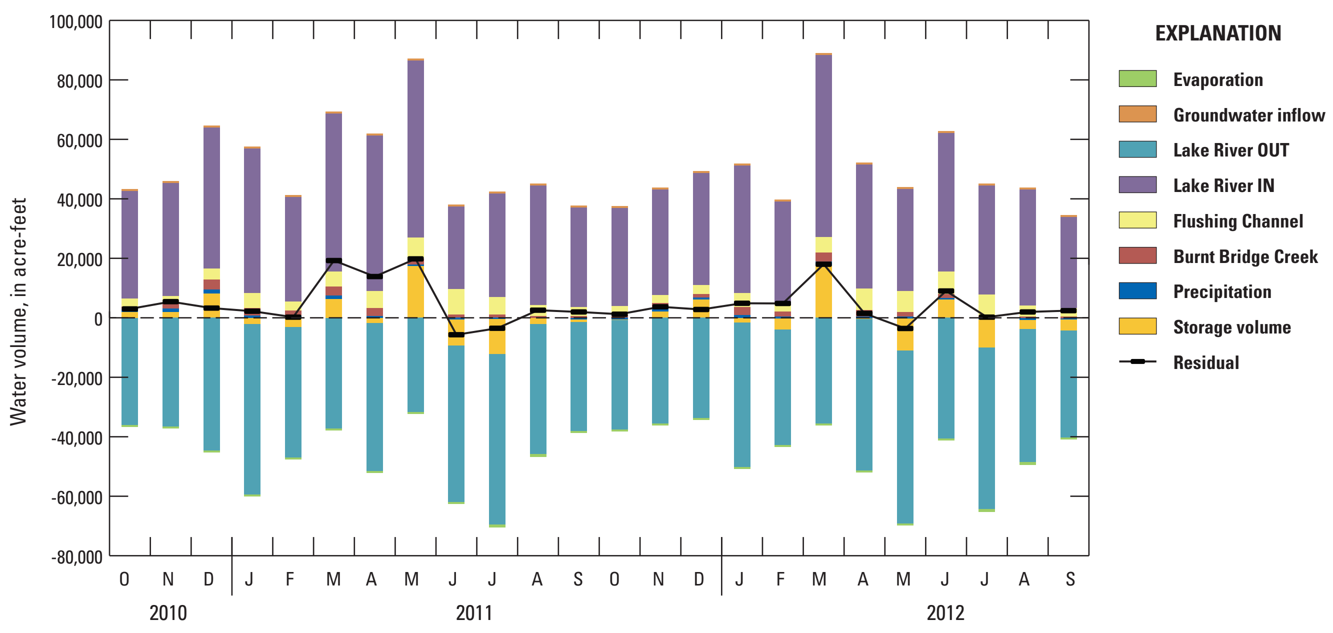


Figure 18. Monthly water budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

Annually, the water budgets between the two water years were similar and the 2-year average annual water-budget residual was 5 percent of the total water budget (all measured inputs and outputs plus the absolute values of change in storage and the residual) (table 4, fig. 19). The low residual indicates that the water budgets presented here are representative of the major hydrological characteristics of the lake. By far, the greatest source of water to and from the lake is through Lake River, which makes up 88 percent of the total annual budget. Water from Flushing Channel (5 percent) is about two times that of Burnt Bridge Creek (2 percent) on an annual basis. The remaining water budget components (groundwater inflow, precipitation, and evaporation) represent 1 percent or less of the total annual budget. Although the lake level fluctuates dramatically throughout the year, the annual change in storage of the lake is minimal, representing 1 percent or less of the total water budget.

Prior to the construction of the Flushing Channel in 1984, a water budget for Vancouver Lake was compiled by Bhagat and Orsborn (1971) reporting annual flow rates (in ft^3/s) for surface waters, groundwater, and precipitation. To put our annual water budget numbers into context, we took the 2-year annual average water volumes from our water budget components, and converted to flow rates in ft^3/s. A comparison of these two water budgets is provided in table 5. There is close agreement to annual flow rates for Burnt Bridge Creek and precipitation. However, the previous estimates Lake River at Felida, Salmon Creek, and groundwater differ greatly compared to our current water budget. The water budget presented here refines the previous efforts by providing continuous flow data on all the major surface water inputs to the lake.

Table 4. Annual water budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[All values in acre-feet per year, except where indicated. Negative values for change in storage indicate a loss in lake volume for the year. Negative values for the residual indicate that more water is exiting the system than is entering for that year. **Abbreviations**: WY, water year; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake; –, not applicable]

Water budget component	WY 2011	WY 2012	2-year average	Percentage of total budget	Percentage of inflow or outflow
Flushing Channel	55,600	57,200	56,400	5	10
Burnt Bridge Creek	21,600	17,600	19,600	2	3
Lake River IN	512,600	479,200	495,900	43	85
Groundwater	1,300	1,300	1,300	<1	<1
Precipitation	7,600	6,100	6,800	1	1
Lake River OUT	527,400	513,300	520,400	45	99
Evaporation	4,900	4,900	4,900	<1	1
Residual	62,400	46,900	54,600	5	–
as a percentage of inflow	10	8	9	–	–
as a percentage of outflow	12	9	10	–	–
Change in Storage	3,900	-3,700	122	<1	–
as a percentage of inflow	1	1	<1	–	–
as a percentage of outflow	1	1	<1	–	–

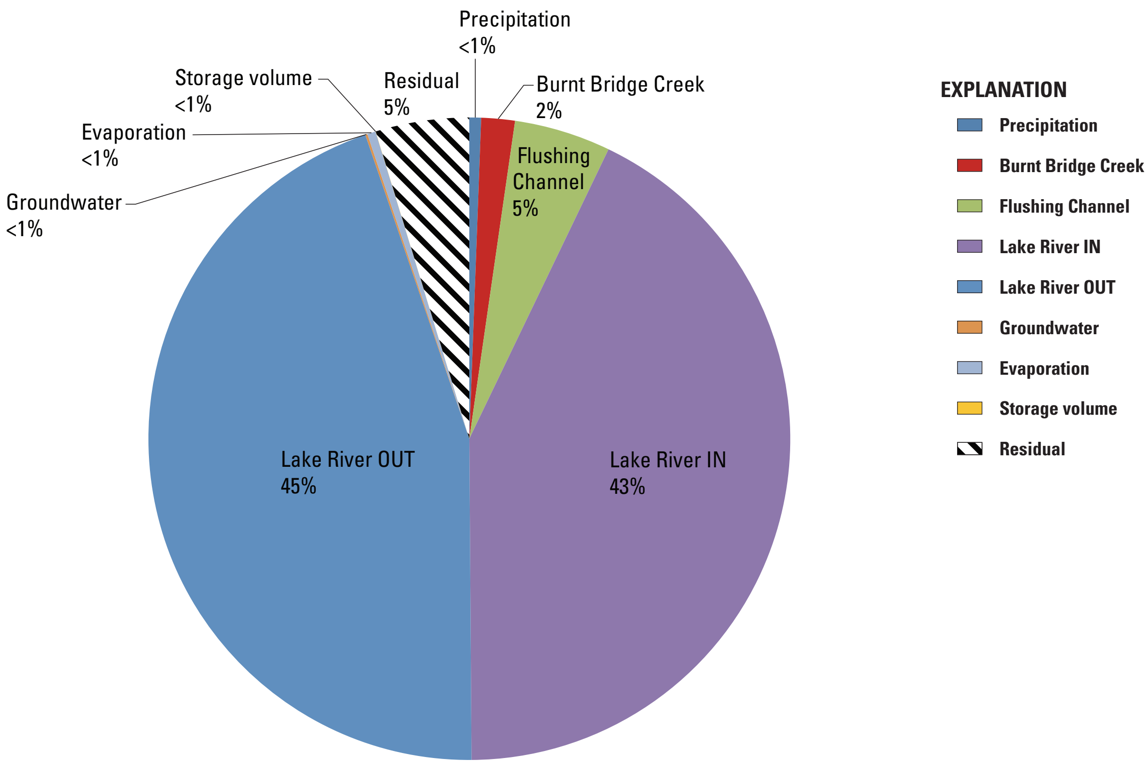


Figure 19. 2-year average of the total water budget for Vancouver Lake, Vancouver, Washington, October 2010–October 2012. (Lake River IN, Lake River at Felida flowing into Vancouver Lake; Lake River OUT, Lake River at Felida flowing out of Vancouver Lake.)

Table 5. Comparison of annual water budget flow rates from Bhagat and Orsborn (1971) and the current study, Vancouver Lake, Vancouver, Washington.

[All values in cubic feet per second. **Abbreviations**: –, not determined; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Water budget component	Bhagat and Orsborn (1971)	Current study
Flushing Channel	–	76
Burnt Bridge Creek	20	27
Salmon Creek	100	253
Groundwater	20	2
Precipitation	12	10
Lake River IN	300	683
Lake River OUT	300	719
Evaporation	–	7

Summary of Water-Quality Data

All water-quality data collected for this study is provided in appendix C and selected parameters are summarized in tables 6–9. Water-quality data collected at the two different lake sites were very similar, as well as samples collected at the surface and bottom locations, indicating that the lake was well mixed throughout the study (tables C4 and C5). In addition, 31 lake profiles for water temperature, pH, specific conductance, dissolved oxygen, and turbidity, measured periodically at three stations in the lake during the study, showed that in most months, the lake was well mixed (see appendix D for all profile data). There were occasional differences between surface and bottom temperature and dissolved oxygen when the lake was deepest, but these differences were not substantial. As a result, all lake data are summarized in tables 6–9 and average monthly values were used in calculating nutrient budgets for the lake. Similarly, groundwater data collected from multiple sites (seeps and piezometers) also were similar and are summarized in tables 6–9 with monthly average concentrations used in the nutrient budget analysis. Detailed data for all groundwater sites are provided in table C6.

Measured field parameters showed a clear distinction between surface-water and groundwater characteristics with groundwater having higher temperatures, specific conductance, lower pH, and dissolved oxygen compared to surface-water sites (table 6). Median values for temperature, specific conductance, pH, and dissolved oxygen were similar across all surface-water sites. Nitrogen and phosphorus concentrations varied across sites (tables 7 and 8).

Table 6. Summary statistics of field parameters collected, near Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[**Abbreviations**: °C, degrees Celsius; µS/cm, microseimens per centimeter at 25 degrees Celsius; mg/L, milligram per liter; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Water source	Temperature (°C)			Specific conductance (µS/cm)		
	Median	Range	Sample size	Median	Range	Sample size
Flushing Channel	12.1	4.40–21.7	22	145	114–187	22
Burnt Bridge Creek	10.7	6.20–23.0	22	163	74.0–219	23
Lake River IN	11.5	4.60–22.0	16	135	71.0–176	16
Lake River OUT	12.6	4.60–22.7	18	137	79.0–176	18
Salmon Creek	11.3	5.40–22.2	22	124	51.0–198	22
Vancouver Lake average	10.9	4.50–24.5	91	143	102–177	91
Groundwater	13.8	7.80–21.7	25	246	150–322	26

Water source	pH			Dissolved oxygen (mg/L)		
	Median	Range	Sample size	Median	Range	Sample size
Flushing Channel	7.98	6.73–8.41	21	11.9	9.10–13.9	21
Burnt Bridge Creek	7.63	7.07–9.15	22	10.7	7.40–18.3	21
Lake River IN	7.88	7.23–8.44	16	11.0	6.30–13.6	16
Lake River OUT	7.8	7.37–8.83	17	10.5	7.20–13.6	18
Salmon Creek	7.53	6.9–8.35	20	11.3	7.70–14.4	21
Vancouver Lake average	8.06	7.21–9.17	86	11.0	3.40–14.4	89
Groundwater	6.76	6.23–7.93	26	6.65	3.10–11.4	24

Table 7. Summary statistics of nitrogen data collected, near Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[**Abbreviations**: mg/L, milligram per liter; N, nitrogen; <, less than; –, no data, samples not analyzed for these parameters; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Site	Nitrate plus nitrite (mg/L as N)			Ammonia (mg/L as N)			Particulate nitrogen (mg/L)		
	Median	Range	Sample size	Median	Range	Sample size	Median	Range	Sample size
Flushing Channel	0.191	0.030–0.619	25	0.015	<0.010–0.226	25	0.080	0.017–0.195	25
Burnt Bridge Creek	0.966	0.476–2.08	24	0.034	<0.010–0.271	24	0.096	0.033–0.529	24
Lake River IN	0.200	<0.010–0.860	16	0.010	<0.010–0.038	16	0.380	0.114–0.624	16
Lake River OUT	0.021	<0.008–0.714	19	0.015	<0.010–0.102	20	0.247	0.026–1.00	20
Salmon Creek	0.881	<0.010–1.34	23	0.017	<0.010–0.121	23	0.081	0.025–0.391	23
Vancouver Lake average	0.108	<0.008–0.753	95	0.011	<0.010–0.410	95	0.316	0.029–1.19	94
Groundwater	2.19	<0.010–3.74	26	0.013	<0.010–0.181	26	–	–	–

Site	Organic nitrogen, calculated (mg/L as N)			Total nitrogen, calculated (mg/L as N)		
	Median	Range	Sample size	Median	Range	Sample size
Flushing Channel	0.156	0.047–0.619	25	0.508	0.252–0.900	25
Burnt Bridge Creek	0.354	0.062–0.920	24	1.61	0.943–2.48	24
Lake River IN	0.293	0.118–0.473	16	0.905	0.508–1.49	16
Lake River OUT	0.359	0.116–1.29	20	0.938	0.381–1.81	20
Salmon Creek	0.298	0.137–0.711	23	1.32	0.421–1.78	23
Vancouver Lake average	0.268	0.116–0.823	24	0.889	0.277–1.50	24
Groundwater	–	–	–		0.186–4.26	26

In general, median groundwater concentrations of nitrate and orthophosphate were greater and ammonia was comparable to corresponding concentrations in surface water. Among the surface-water sites, nitrate and orthophosphate made up most of the dissolved nutrient pools (tables 7 and 8) with Burnt Bridge Creek having the highest concentrations, followed closely by Salmon Creek (fig. 20). At Lake River at Felida, median ammonia and orthophosphate concentrations for Lake River IN and Lake River OUT were comparable, but median nitrate concentrations were much greater when Lake River at Felida was flowing into the lake compared to when it flowed out of the lake (0.200 as opposed to 0.021 mg/L as N; table 7). When Lake River at Felida flowed out of the lake, median concentrations of dissolved nutrients were similar to lake water concentrations.

Median TN followed a similar pattern as dissolved nutrients, with Burnt Bridge Creek and Salmon Creek having the highest median concentration values (table 7, fig. 20). Median concentrations of TP were more uniform, with most sites about 0.1 mg/L as P, with the exception of Flushing Channel which was 0.03 mg/L as P. Median TN and TP concentrations at Lake River IN and OUT were comparable (fig. 20). Total suspended solids (TSS) were highest in Lake River IN (median 30 mg/L) with Lake River OUT and the lake itself also high (median 15–20 mg/L) whereas all the other surface-water sites had median values of TSS that were less than 7 mg/L (table 9). There was a similar pattern in turbidity as Lake River IN and OUT and the lake were more turbid than other sites (table 9). Lake clarity throughout the study was low with a median Secchi depth of 1.6 ft (range 0.5–5.8 ft) and lake productivity, as measured by Chl-*a* concentration, was variable (median 20 µg/L, range 4.0–62 µg/L).

Table 8. Summary statistics of collected phosphorus data , near Vancouver Lake, Vancouver Washington, October 2010–October 2012.

[**Abbreviations**: mg/L, milligram per liter; P, phosphorus; <, less than; –, no data; samples not analyzed for these parameters; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Site	Orthophosphate (mg/L as P)			Particulate phosphorus (mg/L)		
	Median	Range	Sample size	Median	Range	Sample size
Flushing Channel	0.013	<0.004–0.023	25	0.016	0.005–0.028	25
Burnt Bridge Creek	0.055	0.024–0.097	24	0.027	0.011–0.131	24
Lake River IN	0.011	<0.004–0.029	16	0.708	0.022–0.105	16
Lake River OUT	0.010	<0.004–0.025	19	0.046	0.025–0.158	20
Salmon Creek	0.021	0.005–0.054	23	0.026	0.010–0.174	23
Vancouver Lake average	0.009	<0.004–0.032	95	0.050	0.009–0.160	94
Groundwater	0.126	0.029–0.427	26	–	–	–

Site	Organic phosphorus, calculated (mg/L as P)			Total phosphorus (mg/L as P)		
	Median	Range	Sample size	Median	Range	Sample size
Flushing Channel	0.007	0.003–0.028	25	0.034	0.019–0.066	25
Burnt Bridge Creek	0.017	0.001–0.042	24	0.100	0.073–0.198	24
Lake River IN	0.019	0.009–0.042	16	0.104	0.051–0.165	16
Lake River OUT	0.020	0.010–0.081	20	0.081	0.041–0.263	20
Salmon Creek	0.015	0.007–0.026	23	0.073	0.034–0.162	23
Vancouver Lake average	0.020	0.002–0.050	24	0.082	0.025–0.226	24
Groundwater	–	–	–	0.4035	0.114–0.951	22

Table 9. Summary statistics of collected suspended sediment, and turbidity, near Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[**Abbreviations**: mg/L, milligrams per liter; FNU, formazin nephelometric units; –, no data; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Site	Total suspended solids (mg/L)			Turbidity (FNU)		
	Median	Range	Sample size	Median	Range	Sample size
Flushing Channel	6.0	2.4–17	25	3.7	2.4–15	15
Burnt Bridge Creek	6.2	1.1–16	24	5.6	2.9–91	18
Lake River IN	30	4.0–47	16	14.6	4.4–69	12
Lake River OUT	15	5.2–65	20	17.5	4.7–187	15
Salmon Creek	6.0	1.1–29	23	7.4	3.6–128	17
Vancouver Lake average	20	2.4–81	94	16.4	1.7–142	68
Groundwater	–	–	–	–	–	–

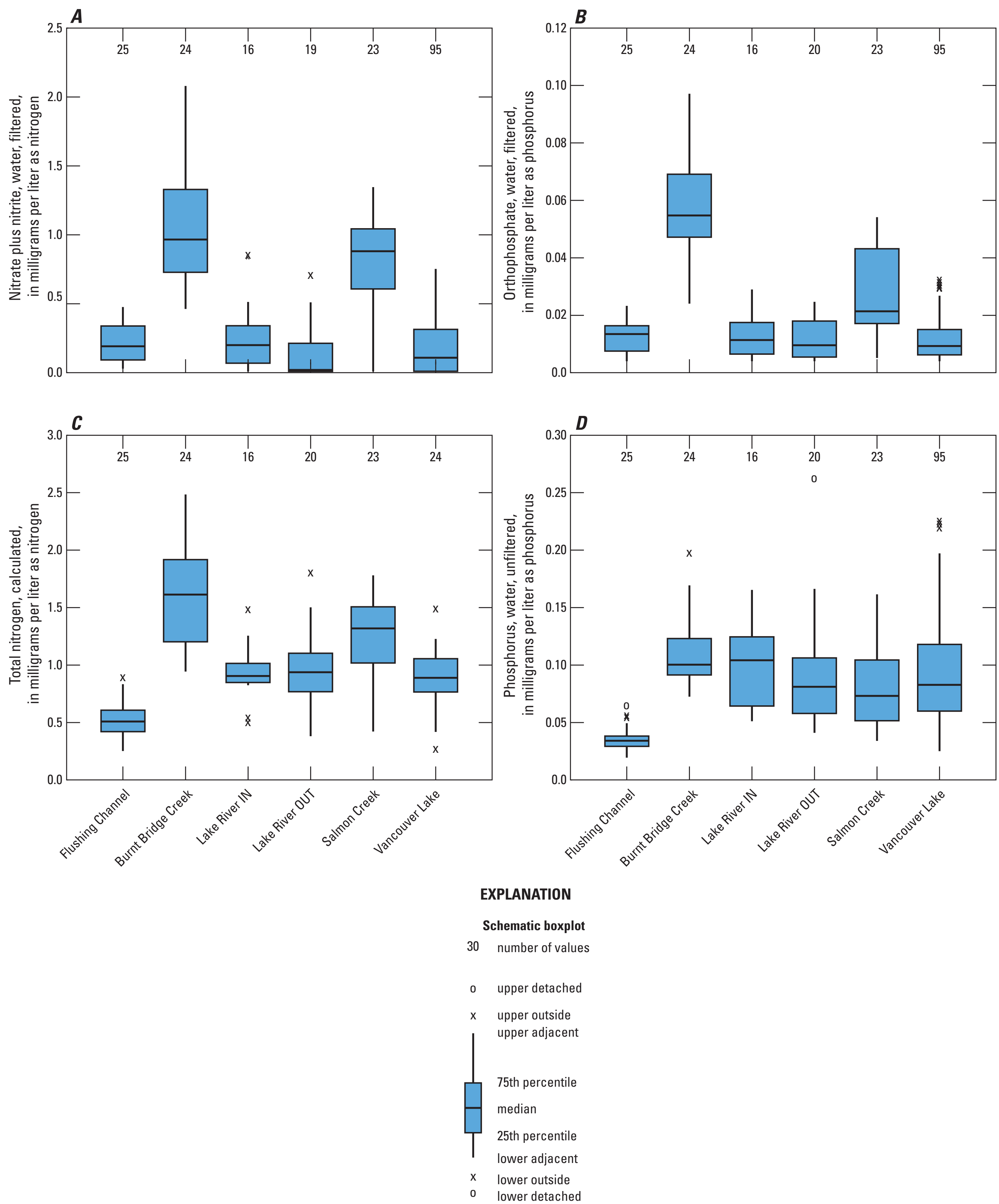


Figure 20. Comparison of (*A*) nitrate plus nitrite, (*B*) orthophosphate, (*C*) total nitrogen and (*D*) total phosphorus in surface water samples collected from Vancouver Lake, Vancouver, Washington, October 2010–October 2012. (Lake River IN, Lake River flowing into the lake at Felida ; Lake River OUT, Lake River flowing out of the lake at Felida)

Total nitrogen and TP also were variable at each site over time. At Flushing Channel, TN was elevated during two time periods, one from January to April 2011, and the second during April to June 2012 (fig. 21*A*). The largest peak for TP at Flushing Channel was from September to October 2011, with a few smaller peaks in April and September 2012 (fig. 21*B*). The TN pool at Flushing Channel was primarily made up of nitrate and organic nitrogen, with particulate nitrogen and ammonia comprising less than 20 percent of the total nitrogen pool during the 2-year study. The TP pool at Flushing Channel was comprised of similar amounts of dissolved inorganic and particulate forms (approximately 40 percent each), with organic phosphorus making up the balance (approximately 20 percent) during the study period.

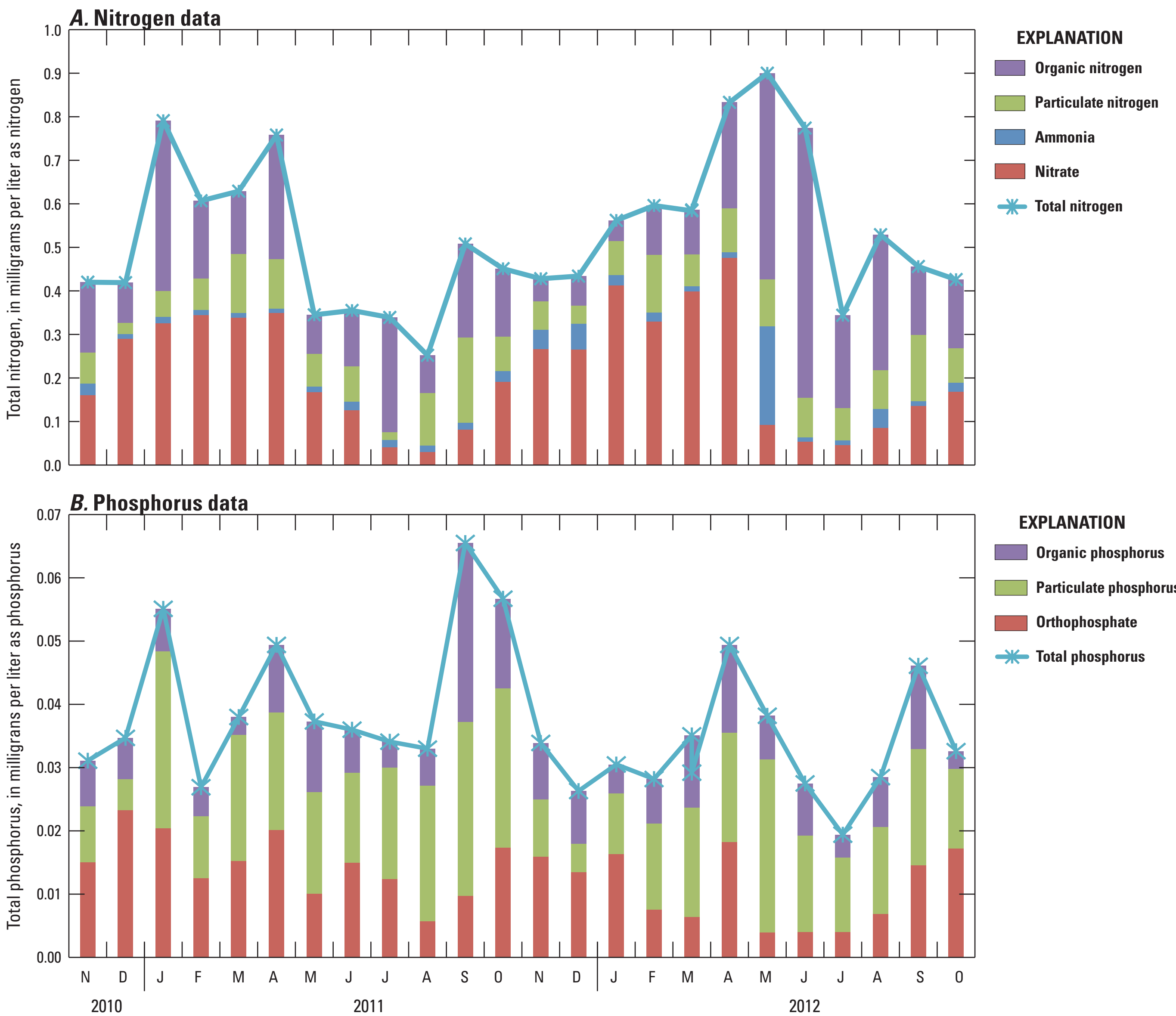


Figure 21. Monthly nutrient data for Flushing Channel, Vancouver, Washington, November 2010–October 2012. The stacked bar plots show (*A*) organic nitrogen, particulate nitrogen, ammonia, nitrate, and total nitrogen concentrations; and (*B*) organic phosphorus, particulate phosphorus, orthophosphate, and total phosphorus concentrations.

At Burnt Bridge Creek, TN concentrations were variable showing a peak in winter 2011, and minima in the summers of 2011 and 2012 (fig. 22*A*). TP concentrations were fairly uniform during the study, about 0.1 mg/L as P, except a small peaks July and September 2011 (fig. 22*B*). The TN pool at Burnt Bridge Creek was dominated by nitrate during the study (65 percent), followed by organic nitrogen (approximately 20 percent), with ammonia and particulate nitrogen both less than 10 percent of the total nitrogen pool. The TP pool was dominated by orthophosphate (55 percent), followed by particulate phosphorus (25 percent), then organic phosphorus (20 percent).

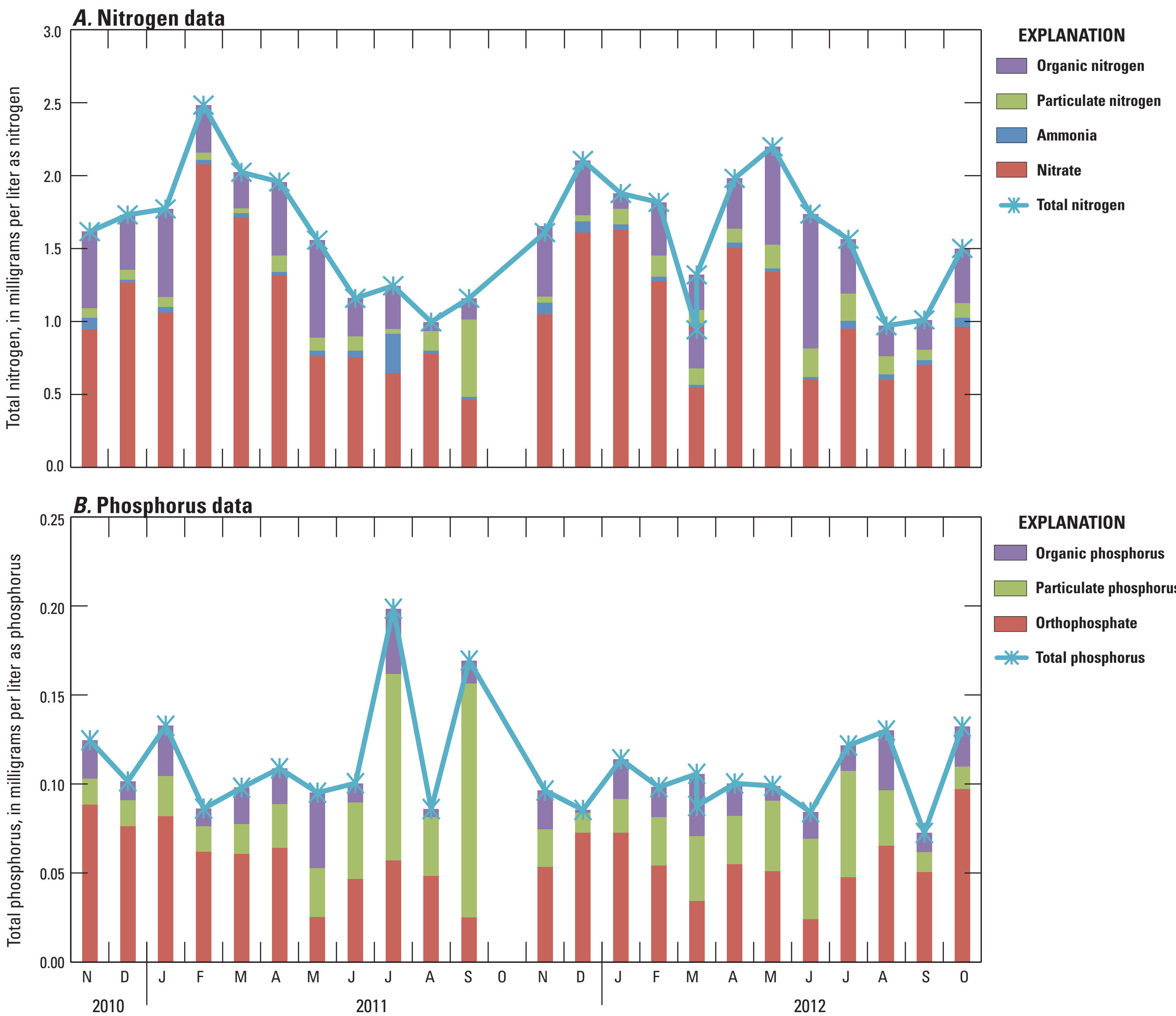


Figure 22. Monthly nutrient data for Burnt Bridge Creek, Vancouver, Washington, November 2010–October 2012. The stacked bar plots show (*A*) organic nitrogen, particulate nitrogen, ammonia, nitrate, and total nitrogen concentrations; and (*B*) organic phosphorus, particulate phosphorus, orthophosphate, and total phosphorus concentrations.

For Salmon Creek, monthly TN and TP concentrations varied throughout the study period (fig. 23) but did not follow consistent patterns year to year. Nitrate made up the majority of the TN pool (approximately 70 percent), followed by organic nitrogen, particulate nitrogen, and ammonia. The TP pool was made up of about equal parts orthophosphate and particulate phosphorus (approximately 40 percent each), with the organic fraction making up the balance.

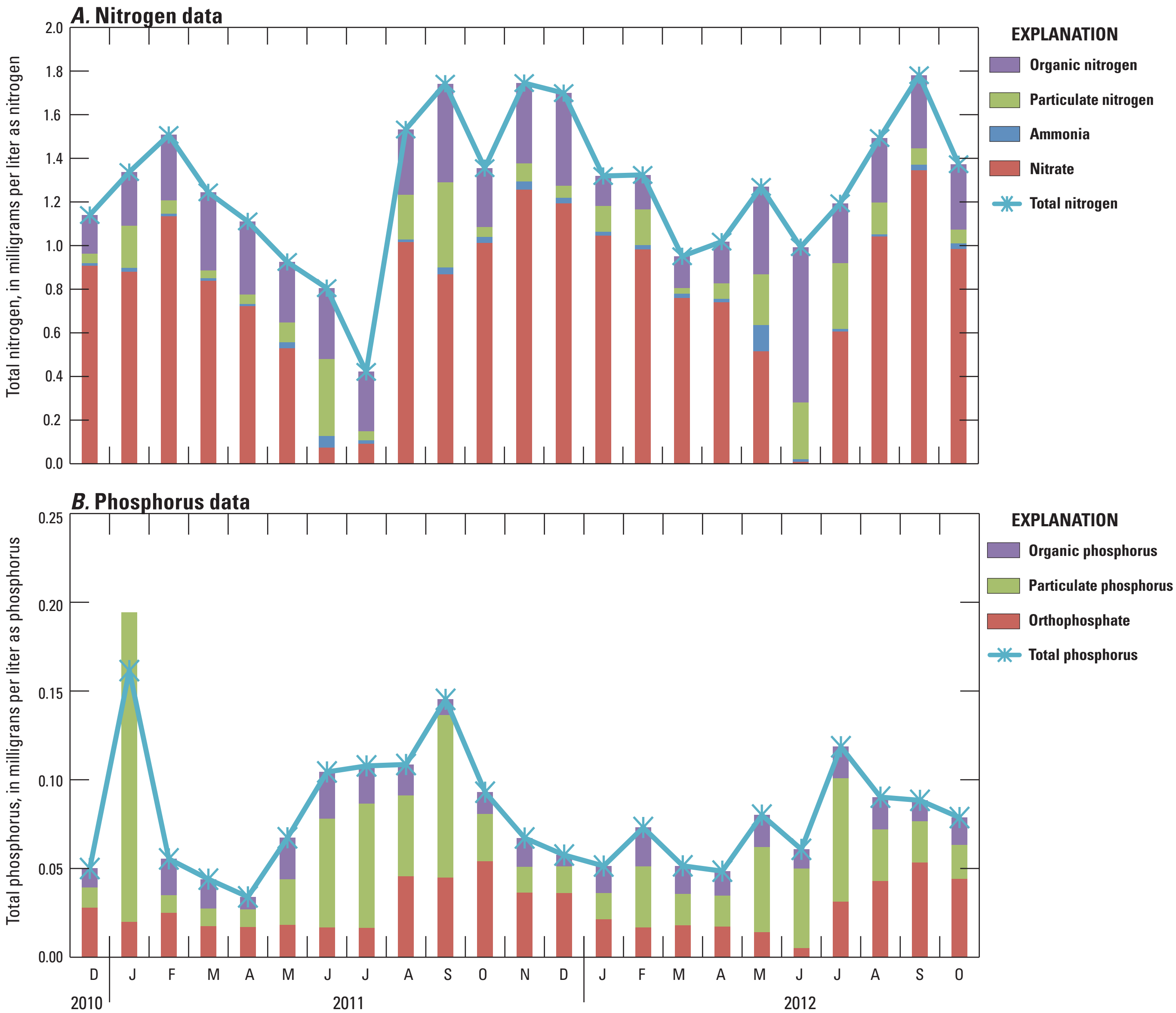


Figure 23. Monthly nutrient data for Salmon Creek, Vancouver, Washington, December 2010–October 2012. The stacked bar plots show (*A*) organic nitrogen, particulate nitrogen, ammonia, nitrate, and total nitrogen concentrations; and (*B*) organic phosphorus, particulate phosphorus, orthophosphate, and total phosphorus concentrations.

Concentrations of TN and TP for Lake River IN showed less of a seasonal pattern when compared to Lake River OUT (figs. 24 and 25). Peaks in TN and TP for Lake River OUT were observed in summer months (fig. 25), and was likely due to similar patterns in the overall lake average concentrations which also showed peaks in TN and TP (fig. 26). The summer peak was pronounced for TP from August to September 2011, when concentrations were more than double relative to other months. In contrast to the other water-quality sites, the TN and TP pools at Lake River at Felida were composed of mainly of particulate forms. In general, about 40 percent of the nitrogen pool and about 60–65 percent of the phosphorus pool was in particulate forms (figs. 24*B*, 25*B*, and 26*B*).

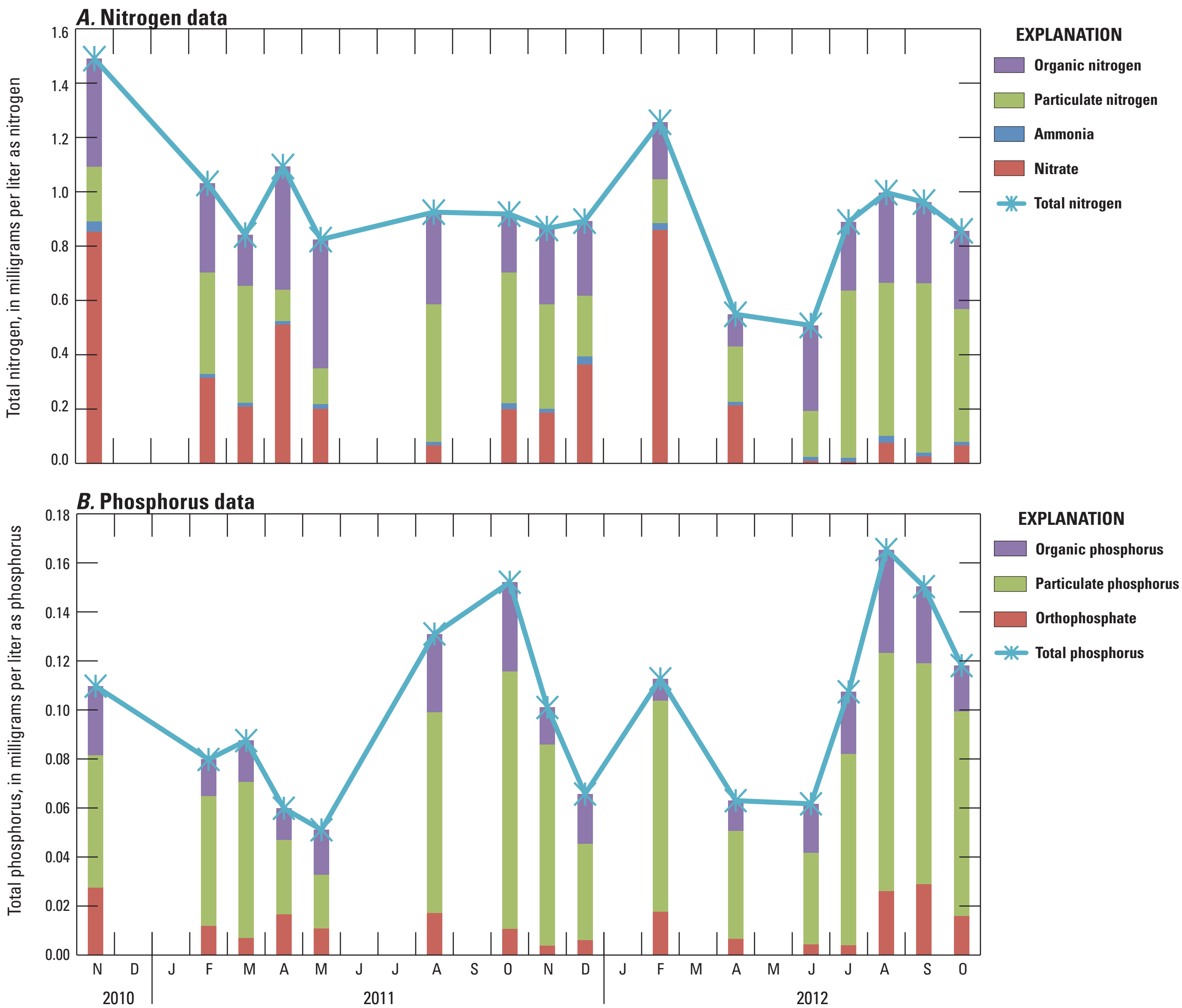


Figure 24. Monthly nutrient data for Lake River at Felida flowing into Vancouver Lake, Vancouver, Washington, November 2010–October 2012. The stacked bar plots show (*A*) organic nitrogen, particulate nitrogen, ammonia, nitrate, and total nitrogen concentrations; and (*B*) organic phosphorus, particulate phosphorus orthophosphate, and total phosphorus concentrations for each month .

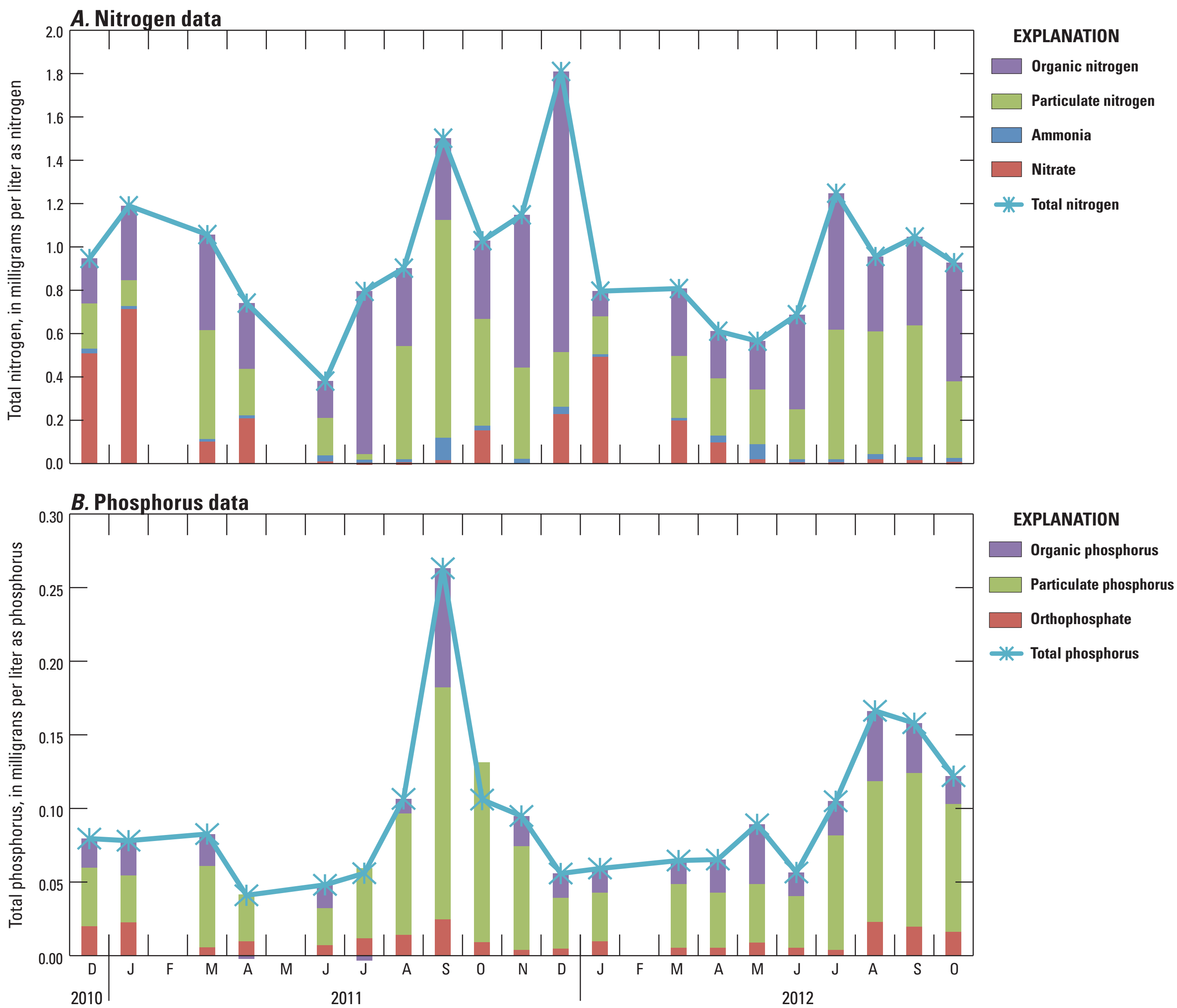


Figure 25. Monthly nutrient data for Lake River at Felida flowing out of Vancouver Lake, Vancouver, Washington, November 2010–October 2012. The stacked bar plots show (*A*) organic nitrogen, particulate nitrogen, ammonia, nitrate, and total nitrogen concentrations; and (*B*) organic phosphorus, particulate phosphorus, orthophosphate, and total phosphorus concentrations.

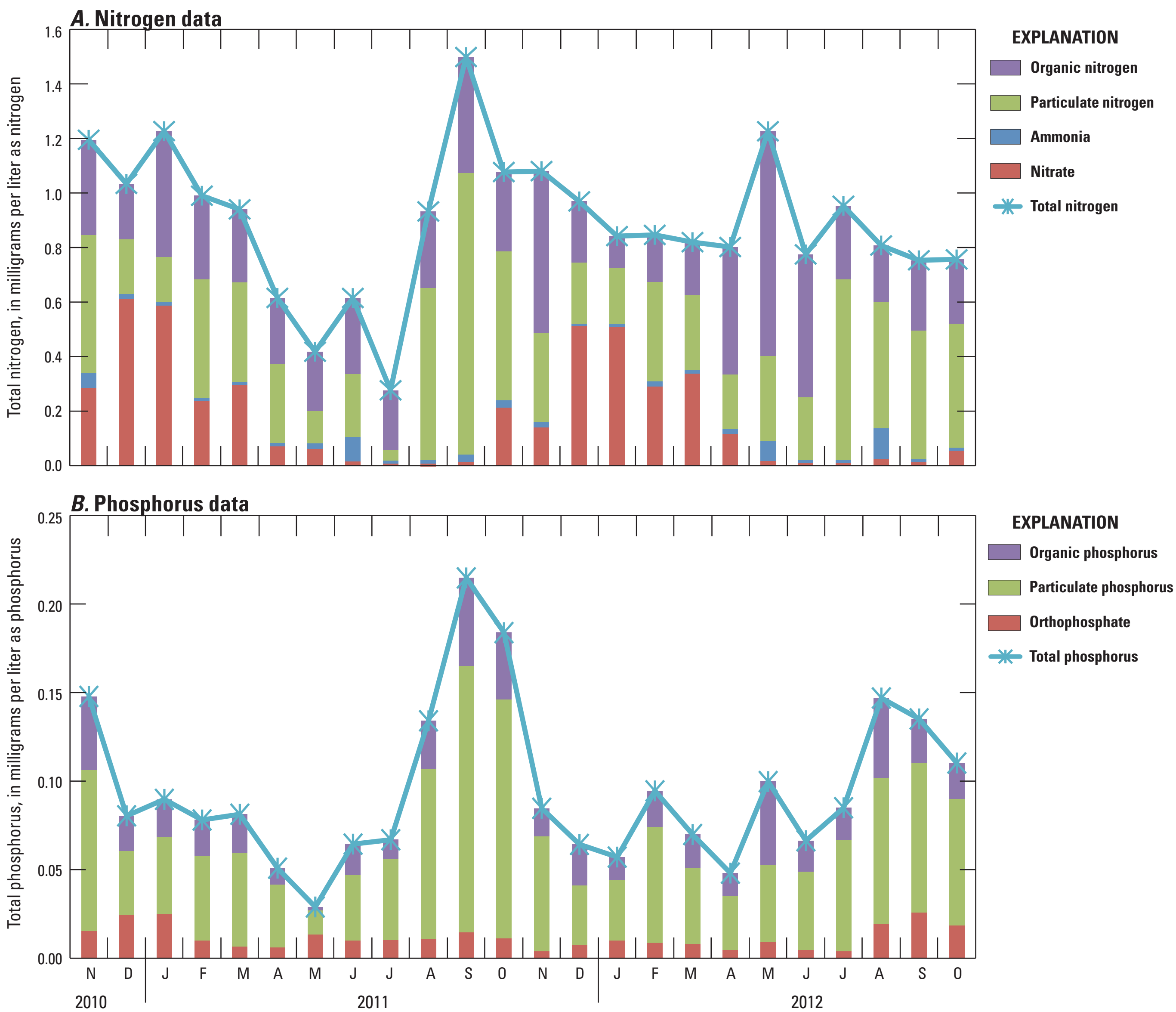


Figure 26. Average monthly nutrient data for Vancouver Lake, Vancouver, Washington, November 2010–October 2012. The stacked bar plot showing (*A*) organic nitrogen, particulate nitrogen, ammonia, nitrate, and total nitrogen concentrations; and (*B*) organic phosphorus, particulate phosphorus, orthophosphate, and total phosphorus concentrations.

Trophic Status and Nutrient Limitation of the Lake

The trophic status was assessed monthly by calculating the Trophic State Index (TSI) . The TSI (Carlson, 1977) is an calculation based on Secchi depth (Secchi), TP, or Chl-*a*, and gives a value between 0–100; a score of 100 means the lake is highly eutrophic (productive) and score of 0 means the lake is ultraoligotrophic (very low production). The TSI is calculated three ways:

$$\mathrm{TSI(Secchi)} = 10[6 - \ln(\mathrm{Sechhi}) / \ln 2] \quad (9)$$

$$\mathrm{TSI(Chl\text{-}}a) = 10\{6 - [2.04 - 0.68 \ln(\mathrm{Chl\text{-}}a)] / \ln 2\} \quad (10)$$

$$\mathrm{TSI(TP)} = 10\{6 - [\ln(48 / \mathrm{TP}) / \ln 2]\} \quad (11)$$

where

Secchi is the lake Secchi depth in m;

Chl-*a* is the lake Chlorophyll-*a* concentration in mg/m^3, and

TP is the lake total phosphorus concentration in mg/m^3.

In theory, the TSI calculated from these equations should be approximately equal, and follow similar patterns throughout the year. Deviations from this behavior can provide insight into lake functioning. For Vancouver Lake, the TSI was calculated based on monthly average Secchi depth, TP, and Chl-*a* data (fig. 27); several observations can be made from these calculations. First, the TSI values was almost always over 50 and averaged about 70, this indicates that the lake is eutrophic. Second, each major division (10, 20, and 30) of the TSI represents an approximate doubling in algal biomass (Carlson, 1977). Therefore, the peak from August to October 2011 (fig. 27) signals a period where algal biomass increases, but in general, the TSI is less variable during the remainder of the study. Third, the three TSI values are similarly track each other except during a few times when TSI (Chl-*a*) is less than TSI (Secchi) and TSI (TP). This implies that the productivity of the lake is controlled more by TP and Chl-*a* during these times and is supported by the mean TSI (TP) being greater than the mean TSI (Chl-*a*) during the study. These deviations may be the result of resuspension events in the lake where turbidity and TP would increase without a subsequent increase in Chl-*a* (algal biomass).

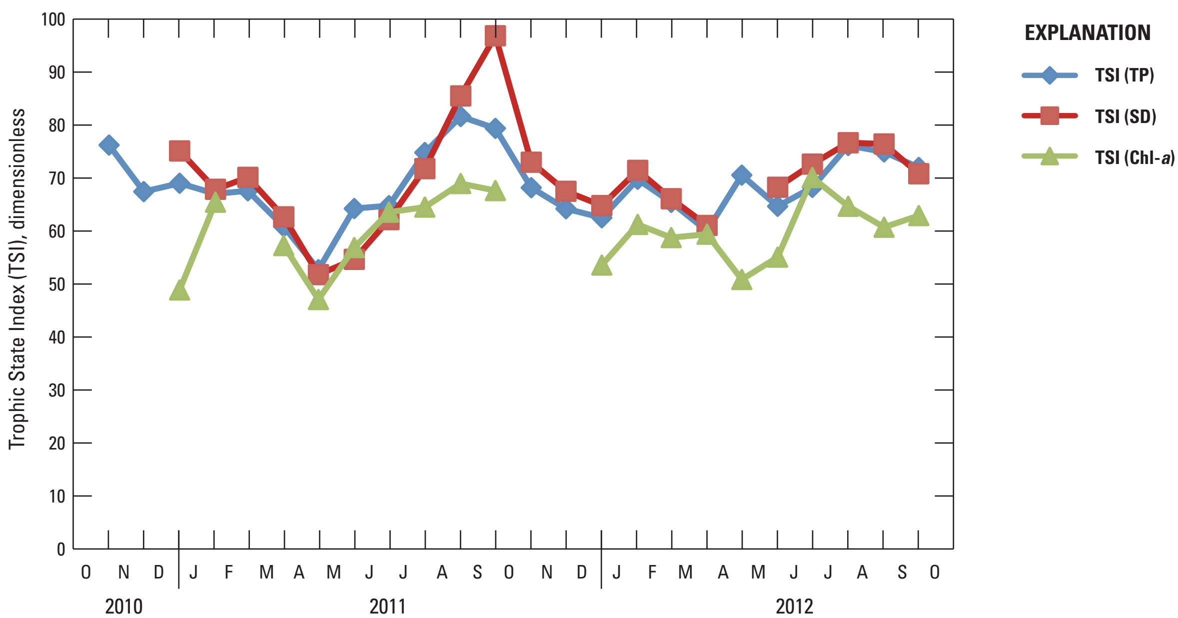


Figure 27. Monthly trophic state index (TSI) determined from Secchi depth (SD), total phosphorus (TP) concentration, and Chlorophyll-*a* (Chl-*a*) concentration for Vancouver Lake, Vancouver, Washington.

Nutrient limitation of the lake was determined by calculating the monthly average TN:TP ratio, or N:P ratio. Redfield (1958) showed that the N:P ratio is approximately 7:1 by weight in marine phytoplankton; aquatic scientists often use the N:P value to ascertain the nutrient that is most limiting to algal growth. N:P ratios less than 7:1 indicate that more P is present than is needed for growth, therefore N is limiting growth. For ratios greater than 7:1, more N is present than is required, and P limitation of algal growth exists. For Vancouver Lake, monthly N:P ratios were almost always greater than 7:1, except for July and October 2011 and August and September 2012 (fig. 28). These data imply that Vancouver Lake is P-limited most of the time. However, more accurate methods for examining nutrient limitation can be done with laboratory or field scale bioassays.

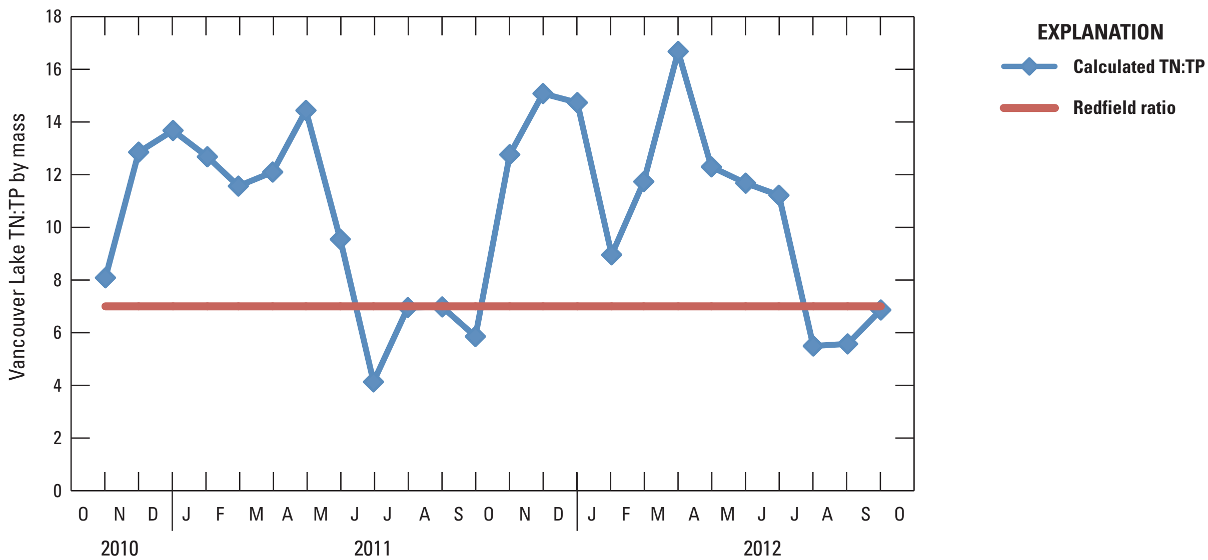


Figure 28. Total nitrogen to total phosphorus ratio (TN:TP) calculated from monthly average of total nitrogen and total phosphorus concentrations in Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

Nutrient Budget for Vancouver Lake

Surface Water Nutrient Loads

Surface water loads for TN, TP, and orthophosphate, estimated from LOADEST model simulations, were highly variable during the study (tables 10–12). Nutrient loads in Flushing Channel and Burnt Bridge Creek followed expected seasonal patterns, with peaks in winter and spring months when flows were high, and minima in late summer when flows decreased (figs. 29*A* and 29*B*); however, seasonal peaks were more pronounced in Burnt Bridge Creek. Flushing Channel seasonality was dampened because of the tide gate which regulated flows on a daily basis. In general, nutrient loads were similar in magnitude at Flushing Channel and Burnt Bridge Creek. At Lake River at Felida, nutrient loads did not show a pronounced seasonal pattern (figs. 29*C* and 29*D*), and were an order of magnitude greater than any other source or sink to the lake (tables 10–12). On average, Lake River IN composed approximately 88, 91, and 76 percent of all monthly inputs for TN, TP, and orthophosphate, respectively during the study.

Table 10. Monthly total nitrogen loads from surface water, groundwater, precipitation, change in lake storage, and associated residuals for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[All values in pounds of nitrogen per month. **Sedimentation**: Positive values for sedimentation represent a loss of nitrogen. **Change in storage**: Negative values for storage indicate a loss in lake volume for that month. **Abbreviations**: –, no data; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake; %, percentage]

Month	Inputs					Outputs				
	Flushing Channel	Burnt Bridge Creek	Lake River IN	Ground-water	Precip-itation	Lake River OUT	Sedimen-tation	Change in storage	Residual	Residual as % of inputs
October 2010	2,400	4,300	133,700	560	100	121,000	12,500	6,300	1,300	1
November 2010	2,300	8,900	145,700	540	180	127,700	13,100	6,300	10,600	7
December 2010	4,600	13,500	177,200	560	120	139,100	36,200	23,300	-7,900	-4
January 2011	7,100	13,700	156,000	560	110	143,000	8,300	-7,100	30,900	17
February 2011	5,100	10,300	96,200	500	130	114,900	6,900	-8,200	760	1
March 2011	8,300	16,200	132,500	560	250	88,200	21,700	16,200	35,000	22
April 2011	9,200	13,000	118,300	540	230	87,500	6,200	-3,100	43,200	31
May 2011	10,100	9,100	132,300	560	250	64,700	39,200	20,000	31,400	21
June 2011	10,300	4,600	57,800	540	60	94,500	-38,900	-15,700	26,400	36
July 2011	6,600	3,300	80,400	560	80	111,700	-3,700	-9,200	-6,100	-7
August 2011	4,000	2,000	107,700	560	0	109,100	-5,400	-5,400	23,700	21
September 2011	3,100	1,700	98,200	540	20	109,000	-1,900	-6,000	5,900	6
October 2011	3,300	3,000	102,300	560	50	123,300	2,300	-2,100	-12,300	-11
November 2011	3,400	6,700	113,300	540	120	123,300	14,800	6,400	-18,500	-15
December 2011	4,400	6,400	113,000	560	50	118,500	17,900	16,800	-31,300	-25
January 2012	7,800	12,600	116,200	560	110	135,600	10,800	-3,800	-11,000	-8
February 2012	5,900	10,700	79,000	520	100	106,400	3,900	-9,200	-4,300	-4
March 2012	10,300	14,600	130,000	560	200	83,900	35,000	39,300	4,800	3
April 2012	13,300	11,500	79,500	540	190	91,300	-7,200	-1,000	7,100	7
May 2012	12,000	7,400	62,000	560	160	96,900	-8,400	-36,800	30,800	38
June 2012	10,800	5,100	90,500	540	150	81,200	8,500	13,400	9,600	9
July 2012	9,100	2,600	74,100	560	10	107,200	-105,200	-26,200	76,300	88
August 2012	4,500	1,500	89,500	560	10	111,300	-4,900	-8,400	3,400	4
September 2012	3,500	1,100	74,600	540	10	107,300	-3,900	-9,000	-10,100	-13
October 2012	3,700	3,900	91,100	560	120	110,400	19,200	–	–	–
Monthly minimum	2,300	1,100	57,800	500	0	64,700	-105,200	-36,800	-31,300	-25
Monthly maximum	13,300	16,200	177,200	560	250	143,000	39,200	39,300	76,300	88
Monthly average	**6,600**	**7,500**	**106,100**	**550**	**110**	**108,300**	**3,080**	**-130**	**9,980**	**8**

Table 11. Monthly total phosphorus loads from surface water, groundwater, precipitation, change in lake storage, and associated residuals for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[All values in pounds of phosphorus per month. **Sedimentation**: Positive values for sedimentation represent a loss of phosphorus. **Change in storage**: Negative values for storage indicate a loss in lake volume for that month. **Abbreviations**: –, no data; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake; %, percentage]

Month	Inputs					Outputs				
	Flushing Channel	Burnt Bridge Creek	Lake River IN	Ground-water	Precip-itation	Lake River OUT	Sedimen-tation	Change in storage	Residual	Residual as % of inputs
October 2010	270	410	13,900	130	50	12,600	1,900	780	-540	-4
November 2010	220	730	13,800	130	80	11,100	2,400	780	760	5
December 2010	370	1,100	14,800	130	80	10,200	6,400	1,800	-2,800	-17
January 2011	490	720	11,200	130	50	9,600	2,200	-520	750	6
February 2011	320	400	7,100	120	60	7,800	700	-650	280	4
March 2011	490	830	9,800	130	80	6,200	3,100	1,400	1,100	10
April 2011	560	760	9,200	130	40	7,300	700	-260	2,300	22
May 2011	680	550	11,900	130	30	6,500	4,200	1,400	1,500	11
June 2011	800	320	6,200	130	10	12,100	-4,200	-1,600	410	5
July 2011	580	290	9,600	130	10	16,200	-4,300	-2,200	3,000	28
August 2011	380	210	13,800	130	0	15,600	-740	-780	1,500	10
September 2011	310	170	12,600	130	10	13,800	-270	-850	1,000	8
October 2011	310	250	12,400	130	10	13,000	550	-370	290	2
November 2011	280	590	12,200	130	70	10,500	2,900	500	-370	-3
December 2011	300	350	10,900	130	30	8,400	2,700	1,100	-870	-7
January 2012	460	780	9,800	130	70	9,200	1,800	-260	-390	-3
February 2012	310	410	6,800	120	30	7,100	680	-1,000	1,100	14
March 2012	520	820	11,000	130	90	5,900	5,500	3,300	-1,000	-8
April 2012	690	600	7,500	130	30	7,600	-1,000	-60	370	4
May 2012	680	430	6,700	130	30	10,200	-1,100	-3,000	1,900	24
June 2012	710	380	11,200	130	30	10,200	1,500	1,100	570	5
July 2012	690	230	10,400	130	0	15,300	-10,000	-2,300	5,200	45
August 2012	370	170	13,400	130	0	16,000	-880	-1,500	1,400	10
September 2012	300	130	11,200	130	0	13,500	-660	-1,600	1,300	11
October 2012	290	360	12,800	130	60	11,200	3,000	–	–	
Monthly minimum	220	130	6,200	120	0	5,900	-10,000	-3,000	-2,800	-17
Monthly maximum	800	1,100	14,800	130	90	16,200	6,400	3,300	5,200	45
Monthly average	**460**	**480**	**10,800**	**130**	**40**	**10,680**	**680**	**-200**	**780**	**7**

Table 12. Monthly orthophosphate loads from surface water, groundwater, precipitation, change in lake storage, and associated residuals, Vancouver Lake, Washington, October 2010 to October 2012.

[All values in pounds of phosphorus per month. **Change in storage**: Negative values for storage indicate a loss in lake volume for that month. **Abbreviations**: –, no data; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake; %, percentage]

	Inputs					Outputs			
	Flushing Channel	Burnt Bridge Creek	Lake River IN	Ground-water	Precip-itation	Lake River OUT	Change in storage	Residual	Residual as % of inputs
October 2010	160	240	1,800	40	50	4,700	80	-2,500	-109
November 2010	150	500	2,000	40	80	3,500	80	-800	-29
December 2010	240	710	2,500	40	80	3,000	550	0	0
January 2011	280	540	2,600	40	50	2,800	-140	900	26
February 2011	170	300	1,200	30	60	1,700	-80	100	6
March 2011	210	470	1,700	40	80	1,100	120	1,300	52
April 2011	190	360	1,600	40	40	1,400	-30	900	40
May 2011	190	240	1,700	40	30	800	640	700	32
June 2011	190	130	600	40	10	1,700	-250	-400	-41
July 2011	150	110	1,000	40	10	2,000	-340	-400	-31
August 2011	110	80	1,400	40	0	1,600	-60	200	12
September 2011	110	80	1,400	40	10	1,200	-60	500	30
October 2011	120	150	1,600	40	10	1,100	-20	900	47
November 2011	130	370	1,900	40	70	830	20	1,700	68
December 2011	140	270	1,800	40	30	620	130	1,600	70
January 2012	180	500	2,200	40	70	830	-40	2,100	70
February 2012	110	310	1,100	30	30	580	-100	1,100	70
March 2012	140	420	2,100	40	90	510	390	1,900	68
April 2012	150	300	1,100	40	30	830	-10	800	49
May 2012	130	190	800	40	30	1,200	-270	200	17
June 2012	120	150	1,200	40	30	1,100	80	400	26
July 2012	110	90	1,000	40	0	2,000	-110	-700	-56
August 2012	70	60	1,400	40	0	2,100	-200	-300	-19
September 2012	70	50	1,200	40	0	1,800	-310	-100	-7
October 2012	80	220	1,700	40	60	1,600	–	–	
Monthly minimum	70	50	600	30	0	510	-340	-2,500	-109
Monthly maximum	280	710	2,600	40	90	4,700	640	2,100	70
Monthly average	**150**	**270**	**1,550**	**40**	**40**	**1,620**	**3**	**410**	**20**

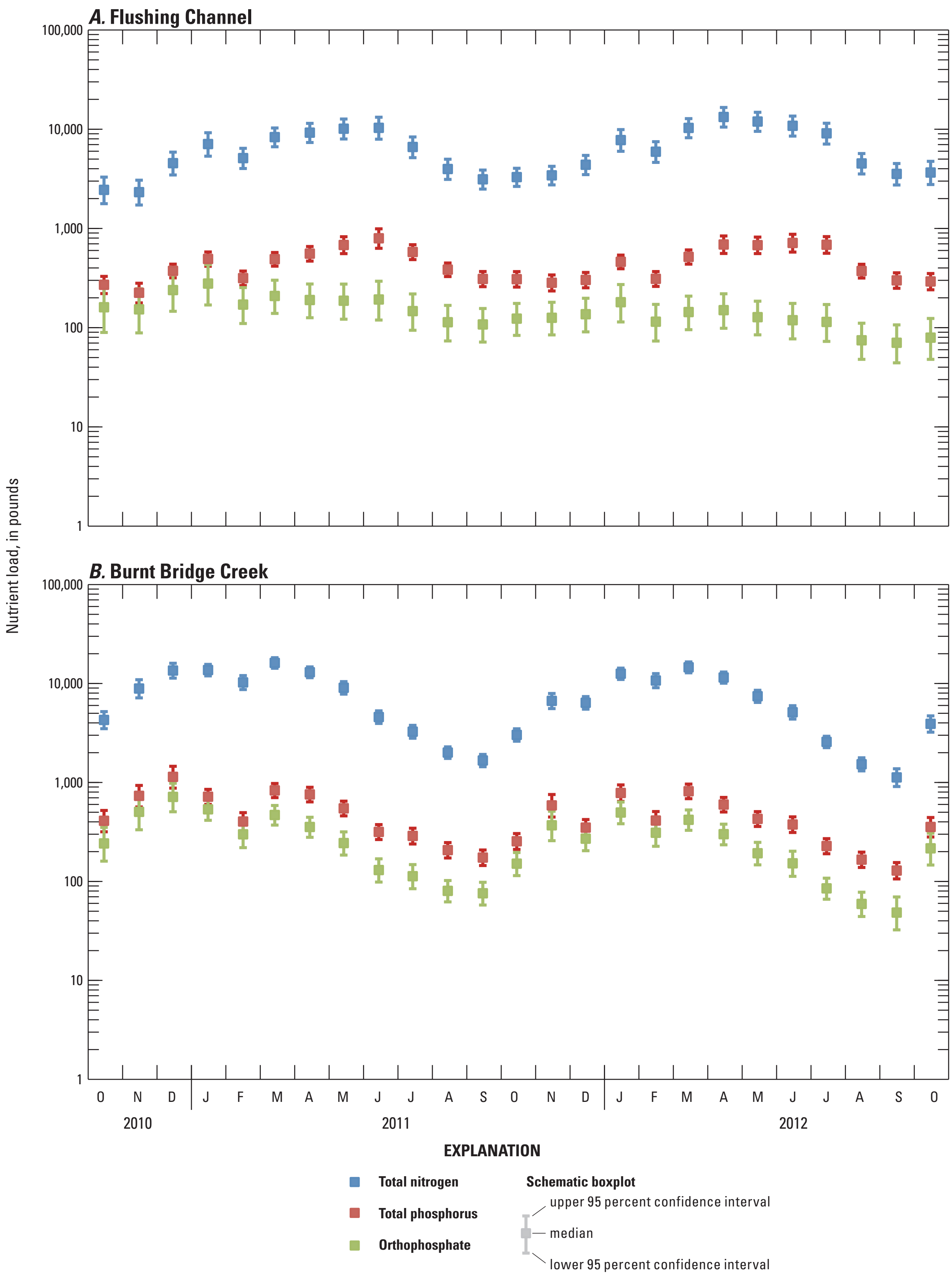


Figure 29. Patterns of monthly nitrogen and phosphorus loads from surface water stations, Vancouver Lake, Vancouver, Washington. Data represent monthly load, determined from LOAD ESTimation model, plus or minus the 95 percent confidence interval for (*A*) Flushing Channel, (*B*) Burnt Bridge Creek, (*C*) Lake River at Felida flowing into the lake (Lake River IN), and (*D*) Lake River at Felida flowing out of the lake (Lake River OUT).

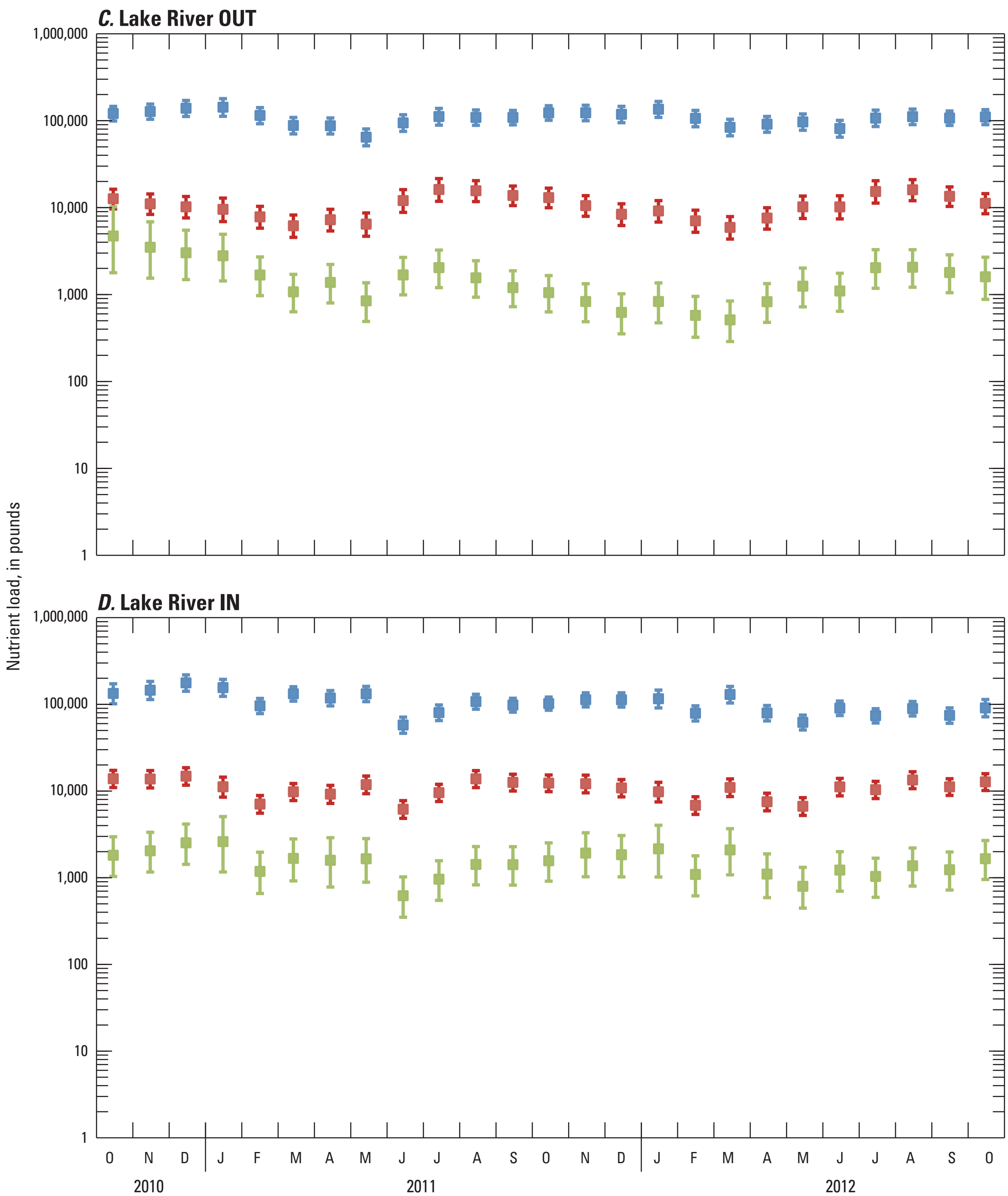


Figure 29.—Continued

The proportion of the TP load that was orthophosphate varied across months and locations during the study (fig. 30). Overall, orthophosphate made up the highest proportion of the TP load at Burnt Bridge Creek, and the lowest in Lake River at Felida. This implies that particulate phosphorus load is greater in Lake River at Felida compared to the other surface water sources.

The SEP calculated from LOADEST was used to estimate the uncertainty in monthly loads for all surface water sites and is summarized in detail in appendix F. The percent error (the monthly SEP divided by the monthly load) across all surface water sites ranged from 4 to 8 percent for TN, 5 to 8 percent for TP, and 9 to 17 percent for orthophosphate (table 13). In general, Burnt Bridge Creek showed the lowest uncertainty across water years; and, parameters modeled with Lake River at Felida usually had the highest error across all surface-water sites.

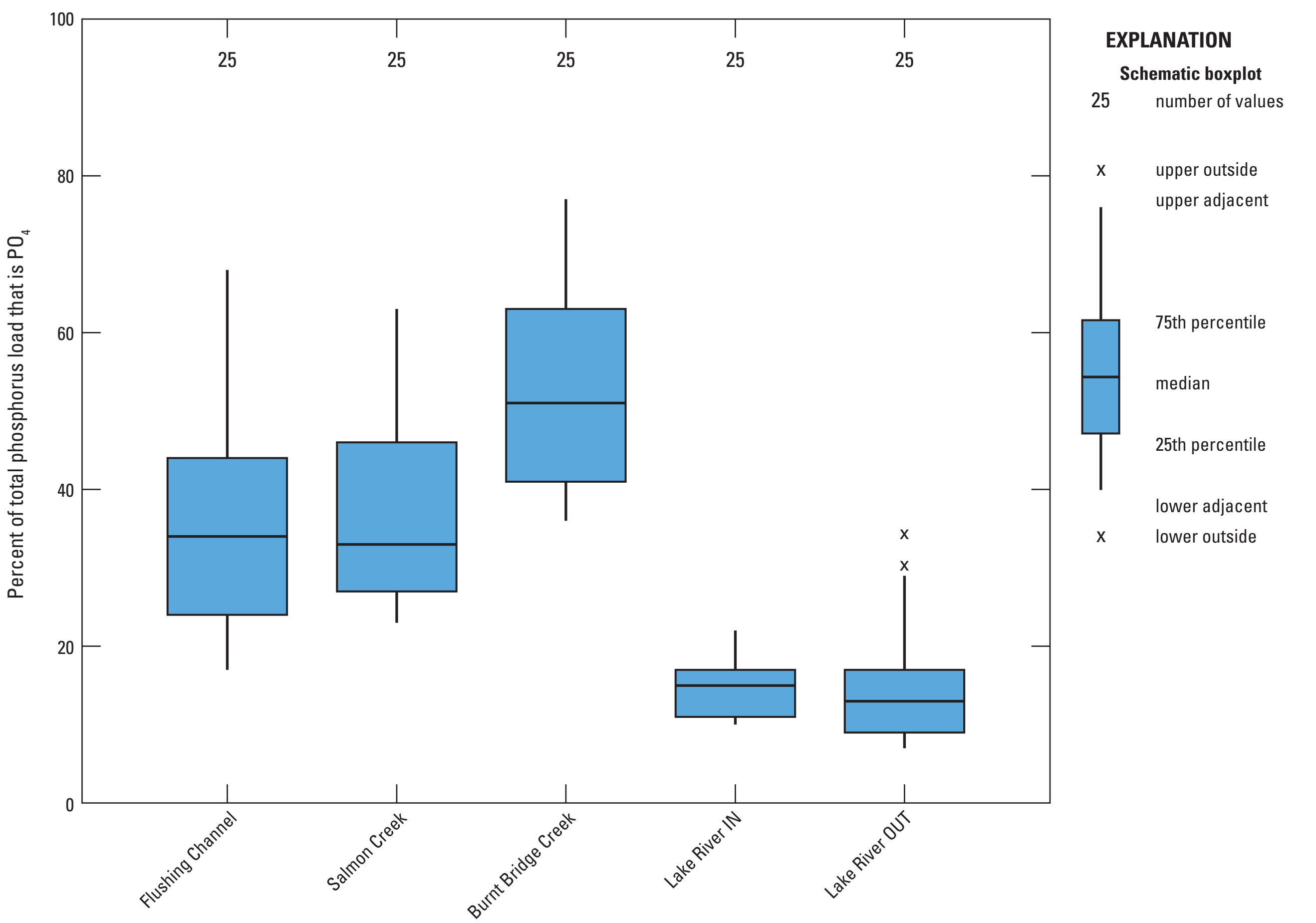


Figure 30. Proportion of the monthly total phosphorus (TP) load from orthophosphate (PO_4) for all surface water sites, Vancouver, Washington.

Table 13. Summary of uncertainty in surface loads to and from Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[**Abbreviations**: SEP, standard error of prediction; yr, year; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Site	Total nitrogen									
	Water year 2011					Water year 2012				
	Total nitrogen load (pounds)	SEP (pounds/yr)	Percent error	Lower 95 percent prediction interval (pounds/yr)	Upper 95 percent prediction interval (pounds/yr)	Total nitrogen load (pounds)	SEP (pounds/yr)	Percent error	Lower 95 percent prediction interval (pounds/yr)	Upper 95 percent prediction interval (pounds/yr)
Flushing Channel	73,300	6,100	8	62,100	85,900	88,300	6,700	8	76,000	102,100
Burnt Bridge Creek	100,400	4,500	4	91,900	109,400	83,200	3,500	4	76,700	90,300
Lake River IN	1,436,200	104,600	7	1,242,100	1,651,800	1,124,100	68,200	6	996,400	1,263,500
Lake River OUT	1,310,400	104,800	8	1,168,500	1,464,700	1,286,300	73,400	6	1,148,500	1,436,000

Site	Total phosphorus									
	Water year 2011					Water year 2012				
	Total phosphorus load (pounds)	SEP (pounds/yr)	Percent error	Lower 95 percent prediction interval (pounds/yr)	Upper 95 percent prediction interval (pounds/yr)	Total phosphorus load (pounds)	SEP (pounds/yr)	Percent error	Lower 95 percent prediction interval (pounds/yr)	Upper 95 percent prediction interval (pounds/yr)
Flushing Channel	5,500	300	6	4,800	6,200	5,600	400	6	5,000	6,400
Burnt Bridge Creek	6,500	400	6	5,800	7,300	5,100	300	5	4,600	5,700
Lake River IN	133,900	8,600	6	117,700	151,600	123,400	7,800	6	108,900	139,300
Lake River OUT	130,000	10,400	8	110,700	127,900	127,300	10,200	8	1,100	1,500

Site	Orthophosphate									
	Water year 2011					Water year 2012				
	Orthophosphate load (pounds)	SEP (pounds/yr)	Percent error	Lower 95 percent prediction interval (pounds/yr)	Upper 95 percent prediction interval (pounds/yr)	Orthophosphate load (pounds)	SEP (pounds/yr)	Percent error	Lower 95 percent prediction interval (pounds/yr)	Upper 95 percent prediction interval (pounds/yr)
Flushing Channel	2,100	300	15	1,600	2,800	1,500	200	12	1,200	1,900
Burnt Bridge Creek	3,800	300	9	3,100	4,500	2,900	200	8	2,500	3,300
Lake River IN	19,500	3,300	17	13,900	26,700	17,500	2,800	16	12,600	23,500
Lake River OUT	25,500	4,100	16	15,600	39,500	13,500	2,200	16	10,000	17,900

Site	Total suspended solids									
	Water year 2011					Water year 2012				
	Total suspended sediment load (pounds)	SEP (pounds/yr)	Percent error	Lower 95 percent prediction interval (pounds/yr)	Upper 95 percent prediction interval (pounds/yr)	Total suspended sediment load (pounds)	SEP (pounds/yr)	Percent error	Lower 95 percent prediction interval (pounds/yr)	Upper 95 percent prediction interval (pounds/yr)
Flushing Channel	986,700	108,700	11	790,800	1,216,200	1,021,900	114,600	11	815,600	1,264,400
Burnt Bridge Creek	452,100	98,000	22	290,300	672,500	362,800	76,000	21	236,600	533,000
Lake River IN	33,245,000	5,294,200	16	24,075,800	44,770,900	30,308,300	5,338,100	18	24,275,300	45,142,000
Lake River OUT	29,503,500	2,679,800	9	24,599,800	35,094,800	29,368,400	2,660,400	9	24,499,400	34,918,600

Groundwater Nutrient Loads

Groundwater nutrient loads were fairly constant throughout the study period based on our assumption that measured shallow groundwater concentrations and measured seepage rates were constant. Therefore, monthly loads varied slightly and differed by the number of days in that particular month. The average monthly total nitrogen load was 550 lb (range 500–560 lb) (table 10). The total phosphorus groundwater loads ranged from 120 to 130 lb/month, with an overall monthly average of 130 lb (table 11). Orthophosphate loads ranged from 33 to 36 lb/month (table 12).

Precipitation Loads

Dissolved inorganic nitrogen concentrations were fairly consistent across all of the NADP sites surveyed for estimating the precipitation load to Vancouver Lake (fig. 31). Dissolved inorganic nitrogen (sum of nitrate and ammonia) concentrations increased during April–August in 2011 and 2012, whereas other months remained at or less than 0.1 mg/L as N. The TP concentration in precipitation in Washington was recently summarized by Roberts (2013) during an assessment of phosphorus loads to Lake Loma. In Roberts' (2013) study, an average value of 24 µg/L of TP was used to estimate loading to the lake, and we use the same value for Vancouver Lake.

Precipitation loads varied monthly and was highest in spring months and lowest in summer months in both 2011 and 2012. For total nitrogen, these loads represent only the dissolved load because data collected by the NADP program are not whole water samples. In addition, we are not accounting for particulate nitrogen or phosphorus in dry deposition, so our precipitation loads should be considered underestimates. The average monthly total nitrogen load was 110 lb (range 0–250 lb) during the study (table 10). The total phosphorus and orthophosphate loads were assumed equal, because we do not have estimates of orthophosphate concentrations in rainwater, and ranged from 0 to 90 lb/month, with an average of 40 lb/month for the period of study (tables 11 and 12). For phosphorus, these loads are consistent with previously published estimates of watershed loading from precipitation in Gilliom (1983), Ebbert (1985), and Embrey and Inkpen (1998), indicating that our assumption for phosphorus concentration in precipitation is reasonable.

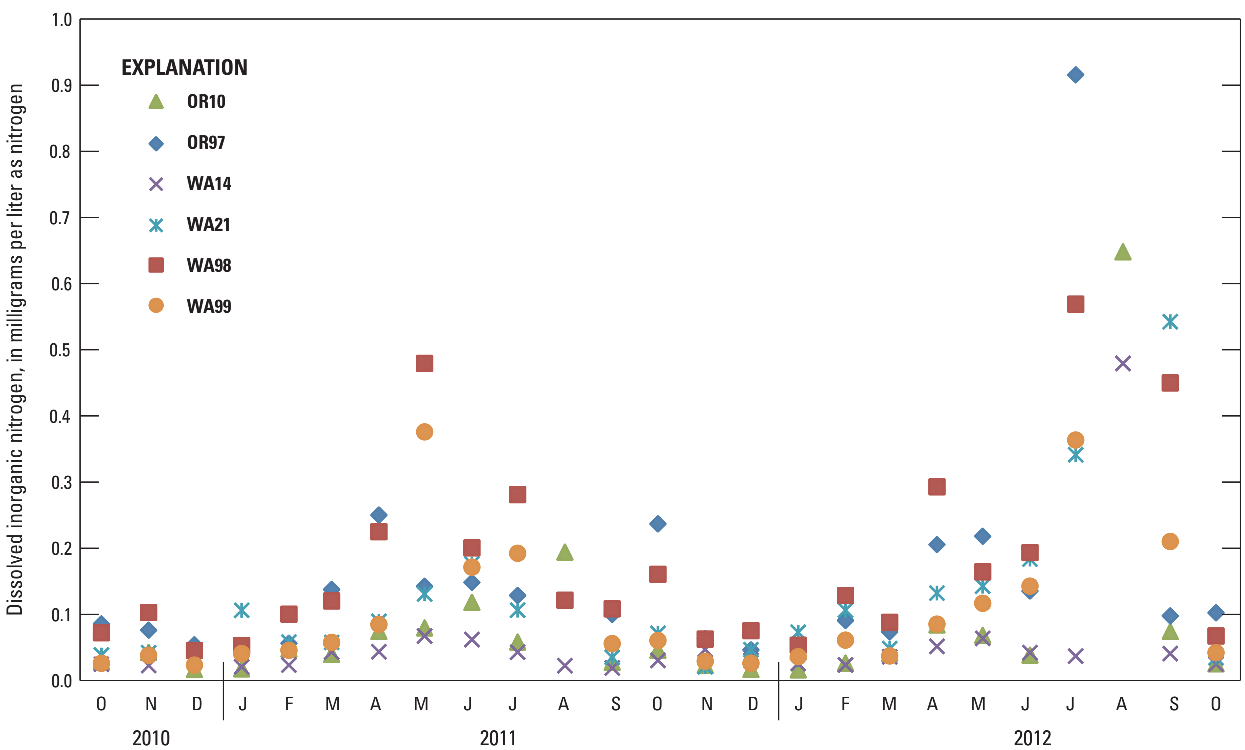


Figure 31. Monthly dissolved inorganic nitrogen concentrations in precipitation from six National Atmospheric Deposition Program sites in Washington and Oregon. See figure 12 for location of all sites.

Change in Nutrients in Storage Within the Lake

Change in the amount (mass) of nutrients within the lake reflected the dynamic nature of the lake with some months showing a net increase in storage, and others showing a loss in storage. A positive value for nutrient storage means that either the lake volume increased in that month when there was not change in nutrient concentration, or the lake volume was unchanged and there was an increase in nutrient concentration, or both. A negative value for nutrient storage means either lake volume decreased when there was no change nutrient concentration, or the lake volume was unchanged and there was a decrease in nutrient concentration. For total nitrogen, the change in storage ranged from -36,800 to 39,300 lb, with a monthly average of -130 lb (table 10). For total phosphorus, the change in storage ranged from -3,000 to 3,300 lb with a monthly average of -200 lb during the period of study (table 11). Finally, orthophosphate storage loads ranged from -340 to 640 lb, with a 2-year monthly average of 3 lb (table 12).

Internal Load from Diffusion

Porewater nutrient was data collected in August 2011 and 2012 from Lake Site 1 and Site 2 and porewater profile concentrations were consistent between sites over the 2 years (fig. 32). Nitrate profiles were flat, with concentrations low and approximately 0.020 mg/L as N in all samples except in a deep sample (approximately 29–31cm) at Lake Site 2 (figs. 32*B* and 32*D*). Phosphate profiles were also relatively flat except for a peak in concentration around 5 cm deep (fig. 32), that declined closer to the sediment-water interface. At Lake Site 1, ammonia concentrations were high at depth, and declined closer to the sediment-water interface (figs. 32*A* and 32*C*). Ammonia profiles at Lake Site 2 were slightly different with a peak in concentration at depth and a decline closer to the sediment-water interface. All profile concentration data are provided in appendix G.

Benthic flux of nitrogen and phosphorus across the sediment-water interface was negligible for each site in 2011 and 2012. The slope of the concentration set against the depth curve near the sediment-water interface was not statistically different from zero ($p>0.05$) and a diffusive flux was not calculated for the lake. If porewater data were collected on a smaller depth interval, it may be possible to calculate a statistically significant slope. Therefore, based on the porewater data collected for this study, we are assuming that diffusive flux of nitrogen and phosphorus into the lake is negligible.

Sedimentation of Nitrogen and Phosphorus

Results of the suspended sediment budget showed that for 16 of 25 months, the lake accumulated sediment (positive monthly values, table 14). These results are consistent with the fact that the lake has been getting more shallow over time. Negative sediment balance numbers indicate an export of sediment from the lake that took place in summer months when the lake level was low. Based on lake water particulate nutrient data, loss of nitrogen and phosphorus through sedimentation was comparable to some surface water loads. For TN and TP, the loss of nutrients through sedimentation was greater than the combined inputs from Flushing Channel and Burnt Bridge Creek. Monthly sedimentation was variable across months and water years. For TN, the range of loss from sedimentation was 2,300 (October 2011) to 39,200 lb (May 2011) (table 10). Export of sediment bound nitrogen occurred from June to September in 2011 and almost every month from April to September in 2012. These periods correspond to low lake levels when there is greater chance for interaction between the lake water and sediment interface. For TP, the loss through sedimentation ranged from 550 lb (October 2011) to 6,400 lb (December 2010), and showed export of sediment bound phosphorus during the same months as nitrogen (table 11). Since orthophosphate is a dissolved form of phosphate, there is no sedimentation term for the orthophosphate budget (table 12).

Nutrient Budget Summary

Nutrient budgets calculated here include all measured inputs, outputs, sedimentation loss (for TN and TP), the change in storage, and the associated budget residual. The residuals in nutrient budgets include the uncertainty in measured terms plus unaccounted for processes that might change the overall mass of nutrient in the system. For example, biological processing was not directly quantified and could help to close our nutrient budgets. Overall, nitrogen loads were an order of magnitude greater than phosphorus loads across all sources. A summary of monthly nutrient budget components for Vancouver Lake from October 2010 to October 2012 showed that the residuals were variable, and more often positive than negative (figs. 33–35; tables 10–12). For total nitrogen, residuals ranged from -31,300 to 76,300 lb, with a monthly average of 9,980 lb and were relatively large in some months when expressed as a percent of total inputs (table 10). However, the average monthly residual of the TN was 8 percent. For TP, residuals ranged from -2,800 to 5,200 lb with a monthly average of 780 lb. For orthophosphate, residuals ranged from -2,500 to 2,200 lb and the monthly average was 410 lb. The average monthly residuals for TP and orthophosphate were 7 and 20 percent when expressed as a percent of total inputs.

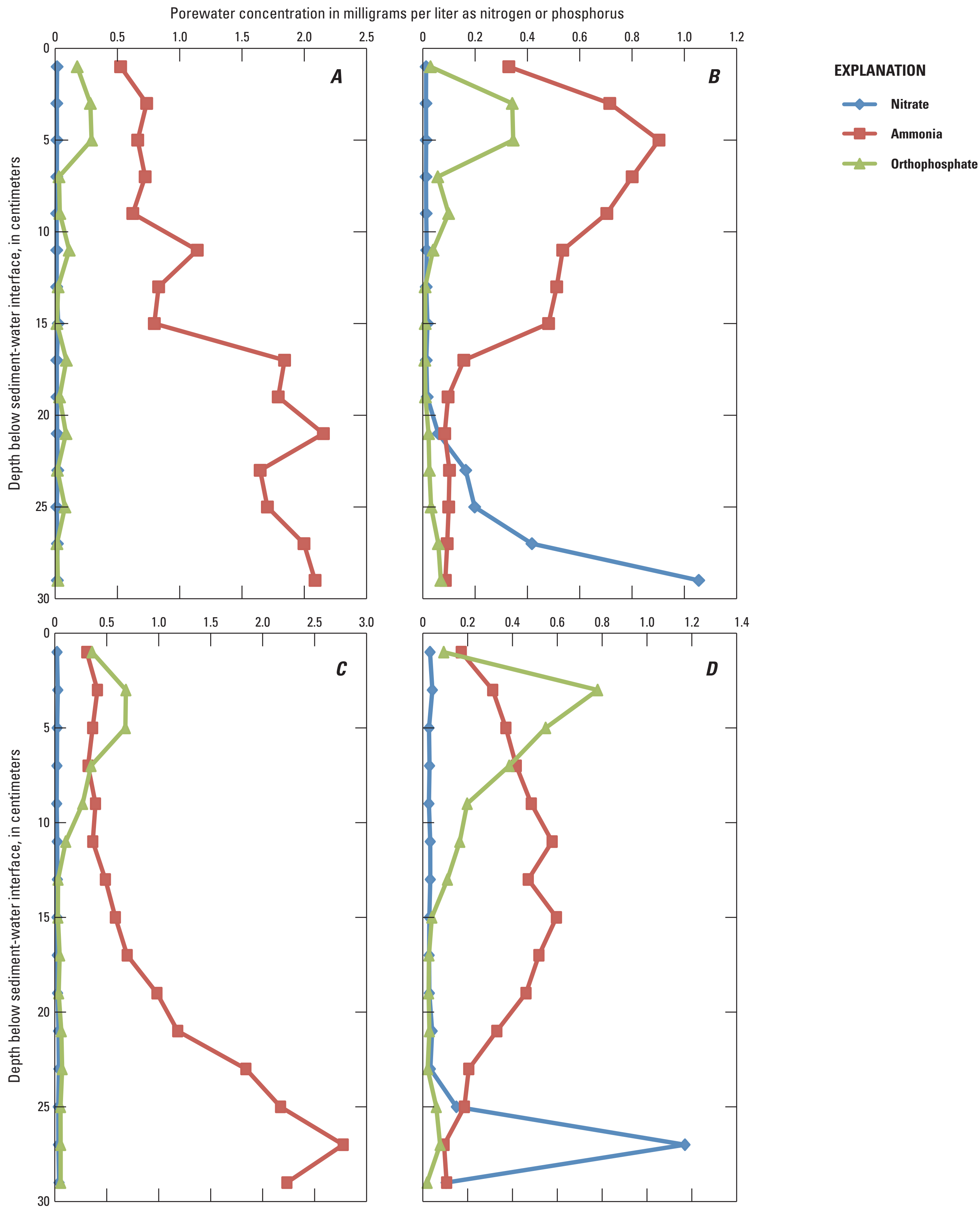


Figure 32. Porewater concentration data for nitrate (NO_3), ammonia (NH_4), and orthophosphate (PO_4), Vancouver Lake, Vancouver, Washington. Data were collected in August 2011 for (*A*) Lake Site 1 and (*B*) Lake Site 2 and in August 2012 at (*C*) Lake Site 1 and (*D*) Lake Site 2.

Table 14. Monthly total suspended sediment loads from surface water inputs and outputs to Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[All values in pounds of suspended sediment per month. The sediment balance term is the sum of inputs minus outputs and change in storage, positive values suggest that suspended sediment is deposited within the lake for that month. **Abbreviations**: –, no storage data (for these three months, sediment balance should be considered as a rough estimate); Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake]

Month	Inputs			Outputs	Change in storage	Sediment balance
	Flushing Channel	Burnt Bridge Creek	Lake River IN	Lake River OUT		
October 2010	38,100	22,700	4,055,700	3,524,000	–	592,500
November 2010	29,800	44,200	4,202,200	2,970,600	–	1,305,600
December 2010	60,400	75,800	4,408,900	2,392,700	267,700	1,884,700
January 2011	90,500	54,800	2,847,100	1,828,100	247,000	917,300
February 2011	49,800	33,600	1,719,200	1,579,300	-103,500	326,800
March 2011	87,500	67,600	2,083,100	1,226,800	-178,600	1,190,100
April 2011	104,400	58,200	1,741,700	1,242,900	362,400	299,100
May 2011	137,500	38,700	2,197,500	1,312,100	-89,700	1,151,300
June 2011	170,500	20,100	1,211,500	2,342,800	210,900	-1,151,600
July 2011	110,000	16,300	2,032,800	3,393,400	-391,100	-843,300
August 2011	61,800	11,000	3,330,800	3,917,600	-300,700	-213,300
September 2011	46,400	9,200	3,414,400	3,773,200	-197,200	-106,100
October 2011	45,600	14,200	3,639,300	3,645,700	-237,500	290,900
November 2011	41,700	35,700	3,640,700	2,821,300	-141,600	1,038,400
December 2011	45,600	24,600	3,178,100	2,161,800	137,100	949,300
January 2012	81,500	59,100	2,508,000	1,920,800	244,800	483,000
February 2012	47,200	34,500	1,677,300	1,493,800	-41,400	306,600
March 2012	95,100	65,500	2,259,600	1,170,600	-331,400	1,581,000
April 2012	141,000	46,700	1,458,700	1,325,400	620,700	-299,700
May 2012	135,600	30,500	1,272,600	1,752,300	-12,500	-301,200
June 2012	147,300	23,600	2,190,600	2,152,200	-390,500	599,800
July 2012	137,400	12,900	2,214,900	3,214,900	409,800	-1,259,400
August 2012	59,300	8,800	3,245,300	4,003,600	-357,200	-333,000
September 2012	44,500	6,800	3,023,300	3,706,200	-336,100	-295,500
October 2012	42,000	19,900	3,769,600	3,187,000	-465,100	1,109,600
Monthly minimum	29,800	6,800	1,211,500	1,170,600	-465,100	-1,259,400
Monthly maximum	170,500	75,800	4,408,900	4,003,600	–	644,500
Monthly average	**82,000**	**33,400**	**2,692,900**	**2,482,400**	**-46,700**	**368,900**

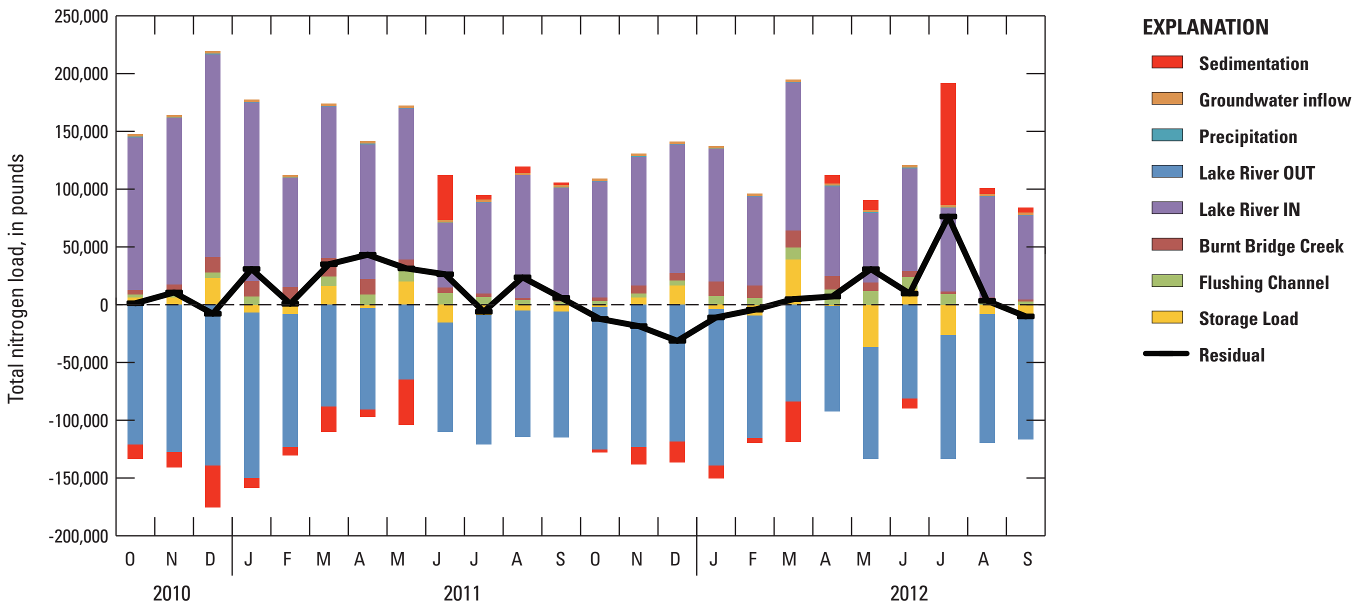


Figure 33. Monthly total nitrogen budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

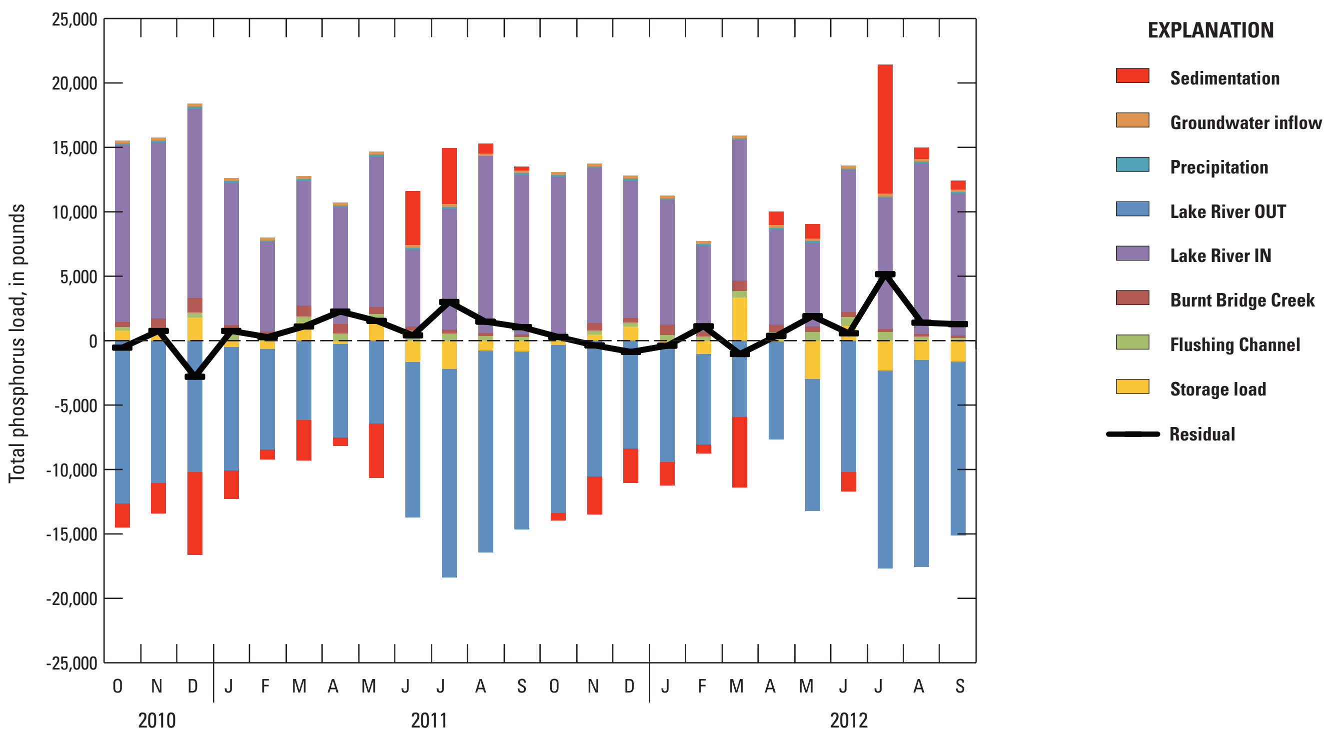


Figure 34. Monthly total phosphorus budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

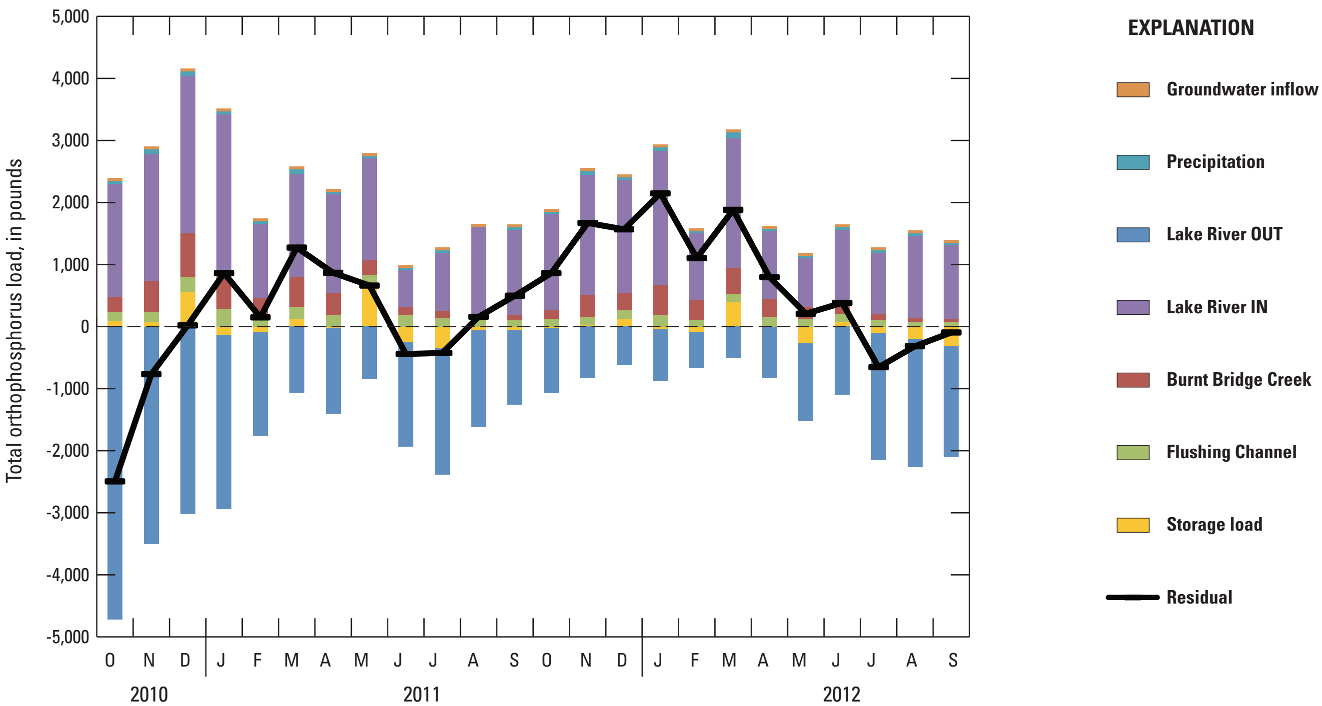


Figure 35. Monthly orthophosphate budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

Annual nutrient loads from each source were similar for each source between water years 2011 and 2012 (tables 15–17). Average annual residuals for total nitrogen, total phosphorus, and orthophosphate were 4, 3, and 10 percent of the total budgets, respectively. For all nutrients, Lake River at Felida loads were much greater than any other source, whereas the groundwater and precipitation loads for total nitrogen, total phosphorus, and orthophosphate were each 1 percent or less of the total budget (figs. 36–38). For total nitrogen, Lake River IN and OUT at Felida loads composed 89 percent of the total budget, with Flushing Channel and Burnt Bridge Creek each contributing 3 percent (fig. 36). For total phosphorus, Lake River IN and OUT at Felida loads composed 89 percent of the total budget, with Flushing Channel and Burnt Bridge Creek each contributing 2 percent (fig. 37). Finally orthophosphate loads from Lake River IN and OUT at Felida compose 77 percent of the total budget, with Flushing Channel and Burnt Bridge Creek contributing 4 and 7 percent, respectively (fig. 38). In terms of total inputs, Lake River IN represented 88, 91, and 76 percent of total inputs for TN, TP, and orthophosphate, respectively (tables 15–17).

Interestingly, although the lake was very dynamic on a month to month basis with respect to changes in lake stage, the overall annual change in storage and sedimentation of the lake were small.

Table 15. Annual total nitrogen budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[All values in pounds of nitrogen per year. Positive values for sedimentation represent a loss of nitrogen. Negative values for storage indicate a loss in lake volume for that month. **Abbreviations**: WY, water year; Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake; –, not applicable]

Budget component	WY 2011	WY 2012	Two year average	Percentage of total budget	Percentage of inflow or outflow
Flushing Channel	73,300	88,300	80,800	3	6
Burnt Bridge Creek	100,400	83,200	91,800	3	6
Lake River IN	1,436,200	1,124,100	1,280,200	44	88
Groundwater	6,600	6,600	6,600	<1	<1
Precipitation	1,500	1,200	1,300	<1	<1
Lake River OUT	1,310,400	1,286,300	1,298,400	45	98
Sedimentation	94,200	-36,500	28,800	1	2
Residual	195,100	44,400	119,800	4	–
as a percentage of inflow	12	3	8	–	–
as a percentage of outflow	14	3	9	–	–
Change in Storage	17,500	-20,600	-1,500	<1	–
as a percentage of inflow	1	2	<1	–	–
as a percentage of outflow	1	2	<1	–	–

Table 16. Annual total phosphorus budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[All values in pounds of phosphorus per year. Positive values for sedimentation represent a loss of phosphorus. Negative values for storage indicate a loss in lake volume for that month. **Abbreviations**: WY, water year: Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake; –, not applicable]

Budget component	WY 2011	WY 2012	Two year average	Percentage of total budget	Percentage of inflow or outflow
Flushing Channel	5,500	5,600	5,600	2	4
Burnt Bridge Creek	6,500	5,100	5,800	2	4
Lake River IN	133,900	123,400	128,600	45	91
Groundwater	1,500	1,600	1,600	1	1
Precipitation	500	400	450	<1	<1
Lake River OUT	128,900	127,000	127,900	44	95
Sedimentation	12,100	1,900	7,000	2	5
Residual	9,300	9,400	9,300	3	–
as a percentage of inflow	6	7	7	–	–
as a percentage of outflow	7	7	7	–	–
Change in Storage	-760	-4,100	-2,400	1	–
as a percentage of inflow	1	3	2	–	–
as a percentage of outflow	1	3	2	–	–

Table 17. Annual orthophosphate budget components for Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

[All values in pounds of phosphorus per year. Negative values for storage indicate a loss in lake volume for that month. **Abbreviations**: WY, water year: Lake River IN, when the direction of Lake River flow is into the Vancouver Lake; Lake River OUT, when the direction of Lake River flow is out of Vancouver Lake; –, not applicable]

Budget component	WY 2011	WY 2012	Two year average	Percentage of total budget	Percentage of inflow or outflow
Flushing Channel	2,100	1,500	1,800	4	7
Burnt Bridge Creek	3,800	2,900	3,300	7	14
Lake River IN	19,500	17,500	18,500	38	76
Groundwater	430	430	430	1	2
Precipitation	500	400	450	1	2
Lake River OUT	25,500	13,500	19,500	39	100
Residual	360	9,600	5,000	10	–
as a percentage of inflow	1	42	20	–	–
as a percentage of outflow	1	71	25	–	–
Change in Storage	500	-440	30	<1	–
as a percentage of inflow	2	2	<1	–	–
as a percentage of outflow	2	3	<1	–	–

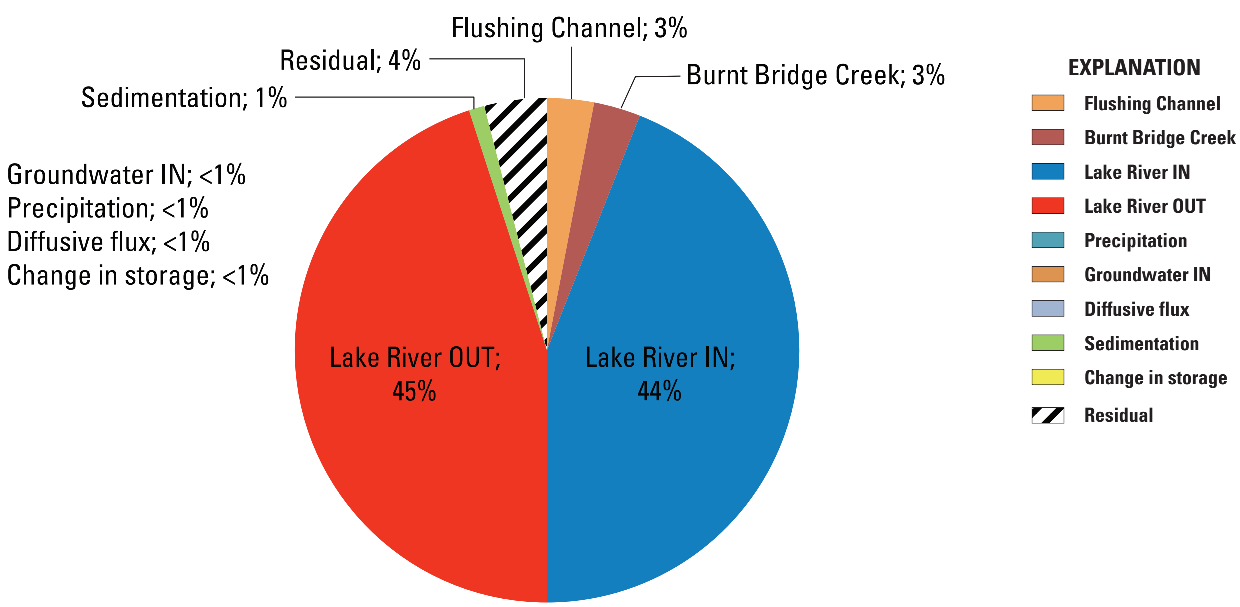


Figure 36. 2-year average of total nitrogen budget for Vancouver Lake, Vancouver, Washington from October 2010–October 2012.

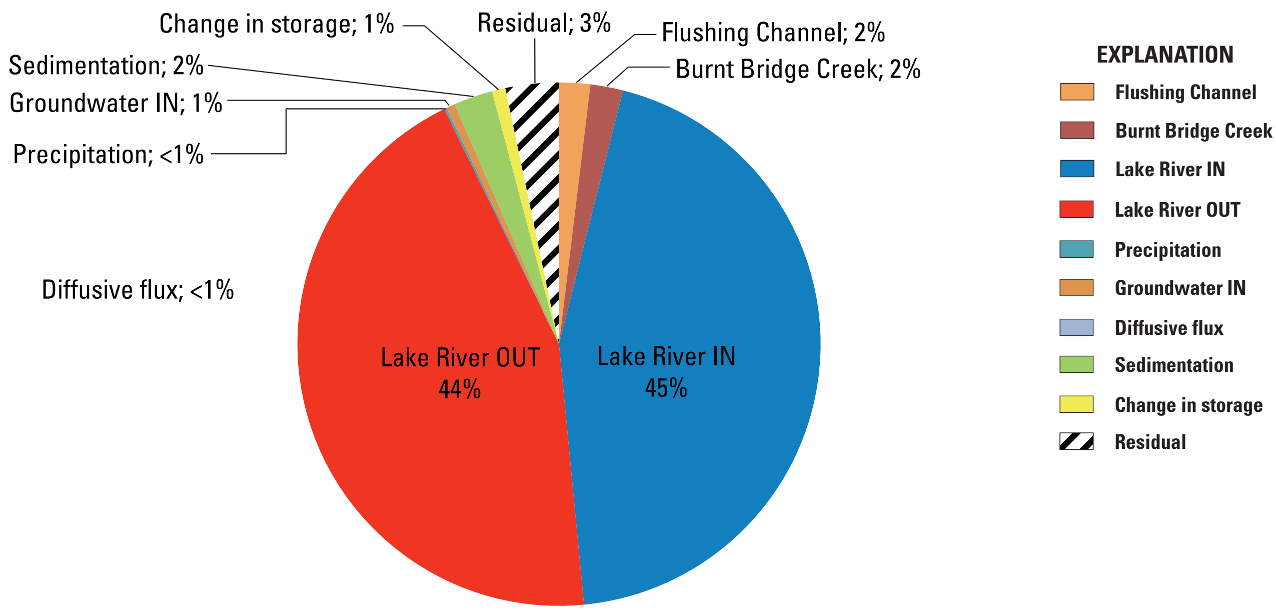


Figure 37. 2-year average of total phosphorus budget for Vancouver Lake, Vancouver, Washington from October 2010–October 2012.

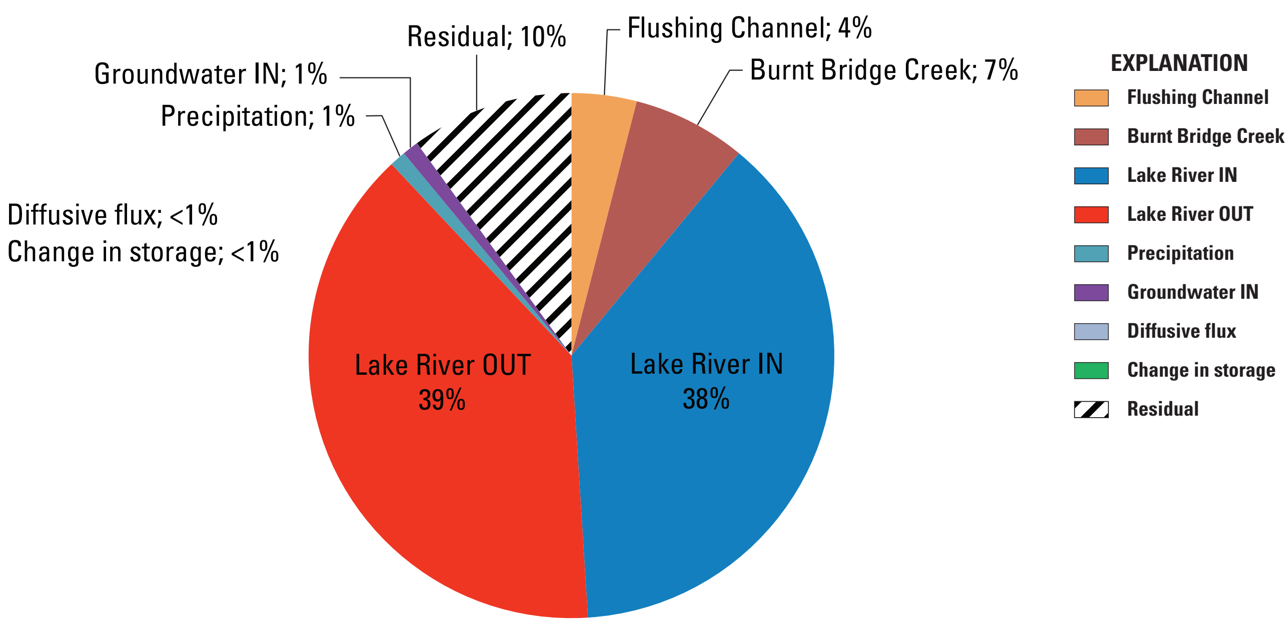


Figure 38. 2-year average of orthophosphate budget for Vancouver Lake, Vancouver, Washington from October 2010–October 2012.

Other Considerations

From the results of the water and nutrient budgets for Vancouver Lake, it is evident that Lake River at Felida is a dominant source of water and solute mass to and from the lake. As a result, reduction of nutrient loads in Lake River at Felida are of major importance for improving the lake quality. However, other factors might be playing important roles for the overall nutrient conditions within the lake and are discussed here.

Influence of Salmon Creek

Salmon Creek drains into Lake River approximately 1.5 mi north of where Lake River joins Vancouver Lake. Salmon Creek is located outside the boundaries of the lake water and nutrient budget (fig. 5), but nitrogen and phosphorus loads were determined at this site to estimate the proportion of nutrient load entering Vancouver Lake from Lake River at Felida that originated from Salmon Creek. This estimate is important because the dominant source of nutrients into Vancouver Lake is from Lake River at Felida. Therefore, to understand the sources of nutrients present in Lake River at Felida, it is important to understand the contribution that Salmon Creek makes to Lake River that can then become input of water and nutrients to the lake.

To estimate the loads from Salmon Creek from October 2010 to October 2012, we used continuous discharge data collected by Clark Public Utilities (Salmon Creek at Northcutt, fig. 5); an estimated flow record constructed for Salmon Creek at Lake River by the USGS during water quality sample collection (appendix A; fig. 5). The estimated flow at Salmon Creek at Lake River and water quality data collected during this study was used to estimate monthly loads using LOADEST following the same approach previously described for the other surface water sources. Discharge in Salmon Creek was highest in winter when storms are common, and decreased in the summer to less than 50 ft^3/s (fig. 39). Mean daily flow ranged from 30 to 1,300 ft^3/s, with an overall daily mean of 250 ft^3/s.

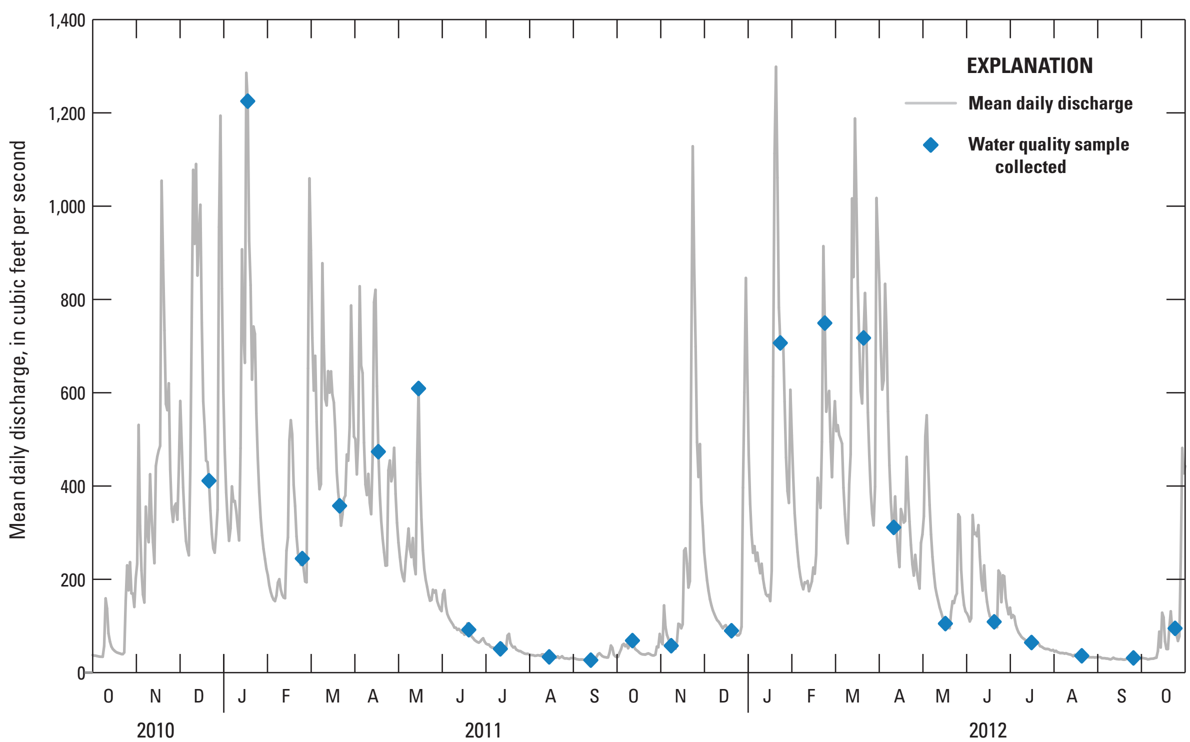


Figure 39. Mean daily flow at Salmon Creek at Lake River, near Vancouver Lake, Vancouver, Washington, October 2010–October 2012.

The water quality data from Salmon Creek (summarized previously), indicated that nitrogen and phosphorus concentrations were some of the highest values measured in surface waters during this study. Loads from Salmon Creek were variable and followed a similar seasonal pattern as measured at Burnt Bridge Creek. Loads were highest in autumn and winter, and decreased in spring and summer (fig. 40) and were largely controlled by changes in flow during the year. Overall, nutrient loads in Salmon Creek were much greater than loads at Flushing Channel and Burnt Bridge Creek, but still much less than loads in Lake River at Felida. As with all the other sites examined, phosphorus loads were about an order of magnitude less than the corresponding nitrogen loads throughout the study.

Monthly loads for TN ranged from 7,100 to 135,300 lb with a 2-year monthly average of 52,000 lb (table 18). Monthly TP loads ranged from 660 to 6,900 lb with a 2-year monthly average of 2,800 lb (table 18). Finally, monthly orthophosphate loads ranged from 190 to 3,300 lb and averaged 1,000 lb/month (table 18). Error estimates were similar to other surface-water sites with monthly average uncertainty in loads of 12, 11, and 17 percent for TN, TP, and orthophosphate, respectively (table F5).

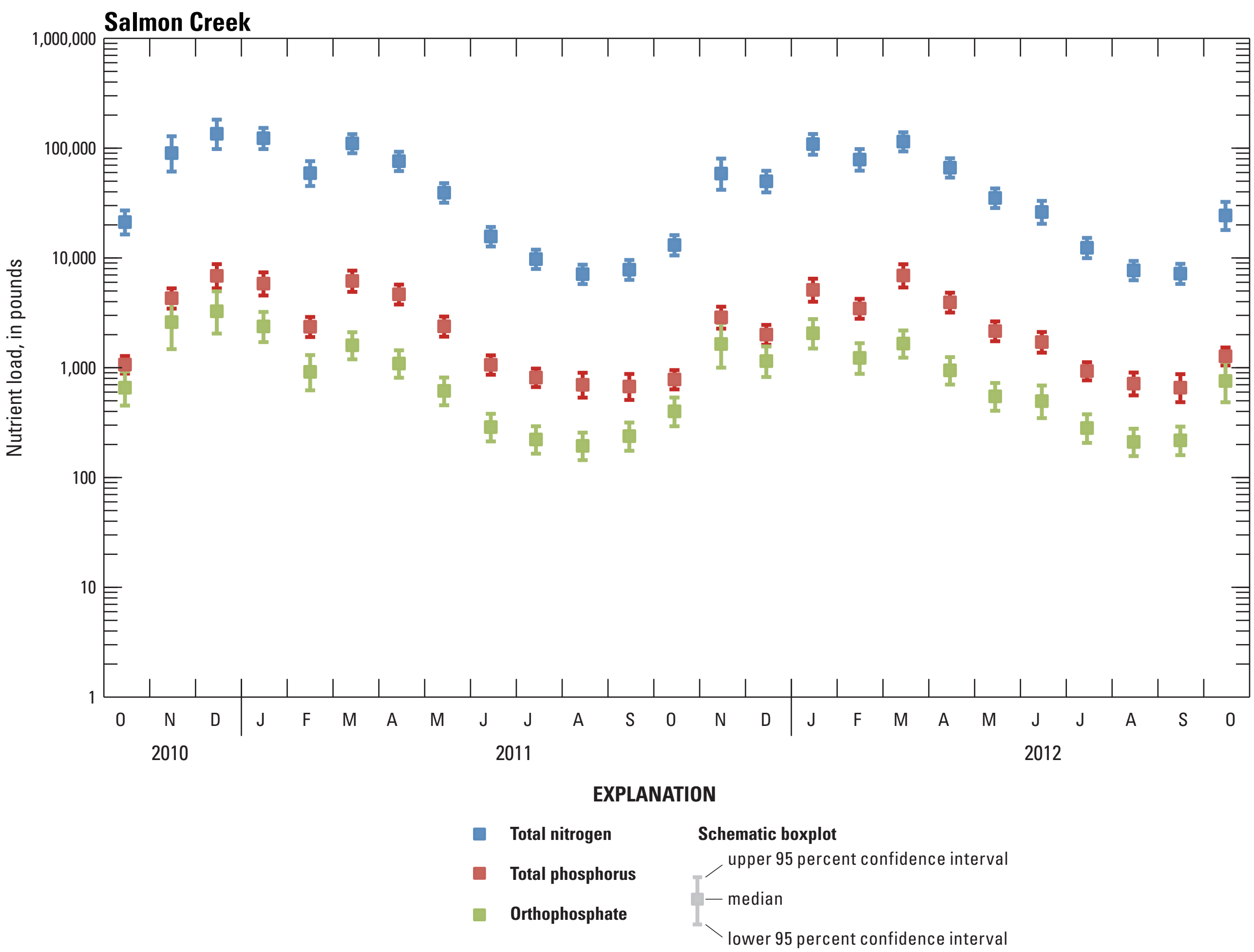


Figure 40. Monthly nitrogen and phosphorus loads from Salmon Creek, near Vancouver Lake, Vancouver, Washington, October 2010–October 2012. Data represent monthly load, determined from LOADEST model, plus or minus the 95 percent confidence interval.

Table 18. Monthly Salmon Creek nutrient loads and potential nutrient loads entering Vancouver Lake originating from Salmon Creek near Vancouver, Washington, October 2010–October 2012.

	Total nitrogen load (pounds)	Total phosphorus load (pounds)	Orthophosphate load (pounds)	Fraction of month Lake River flows into lake	Potential total nitrogen load entering lake (pounds)	Potential total phosphorus load entering lake (pounds)	Potential orthophosphate load entering lake (pounds)
October 2010	21,200	1,100	660	0.47	10,000	500	310
November 2010	90,200	4,300	2,600	0.44	39,700	1,900	1,100
December 2010	135,300	6,900	3,270	0.45	60,900	3,100	1,500
January 2011	123,200	5,800	2,380	0.38	46,800	2,200	900
February 2011	59,200	2,400	920	0.48	28,400	1,100	440
March 2011	110,400	6,200	1,600	0.77	85,000	4,800	1,200
April 2011	76,100	4,700	1,090	0.73	55,600	3,400	800
May 2011	39,300	2,400	620	0.58	22,800	1,400	360
June 2011	15,700	1,100	290	0.36	5,700	380	100
July 2011	9,800	800	220	0.36	3,500	290	80
August 2011	7,100	700	190	0.44	3,100	310	90
September 2011	7,800	700	240	0.44	3,400	300	100
October 2011	13,100	800	400	0.46	6,000	360	180
November 2011	58,700	2,900	1,650	0.46	27,000	1,300	760
December 2011	49,900	2,000	1,150	0.46	23,000	920	530
January 2012	109,000	5,100	2,060	0.39	42,500	2,000	800
February 2012	78,700	3,500	1,230	0.41	32,300	1,400	500
March 2012	114,800	6,900	1,660	0.53	60,800	3,700	880
April 2012	66,400	3,900	950	0.45	29,900	1,800	430
May 2012	35,200	2,200	550	0.36	12,700	780	200
June 2012	26,200	1,700	500	0.47	12,300	810	230
July 2012	12,400	900	280	0.39	4,800	360	110
August 2012	7,700	700	210	0.44	3,400	320	90
September 2012	7,200	700	220	0.45	3,200	300	100
October 2012	24,400	1,300	760	0.49	12,000	620	370
Monthly minimum	7,100	660	190	0.36	3,100	290	80
Monthly maximum	135,300	6,900	3,300	0.77	85,000	4,800	1,500
Monthly average	52,000	2,800	1,000	0.47	25,400	1,400	500
Water year 2011	695,400	36,900	14,100	0.49	341,900	18,200	6,900
Water year 2012	579,400	31,300	10,900	0.44	254,400	13,700	4,800

To estimate the amount of nutrients reaching the lake from Salmon Creek, the monthly loads were multiplied by the fraction of the month when Lake River at Felida was flowing into the lake (fig. 15). This approach assumes that all of the nutrient load from Salmon Creek entering Lake River during times it flows into the lake, also enters the lake, which likely is not the case. For example, loads from Salmon Creek during the end of the inflow period might not enter the lake before flow switches to outflow. In this case, nutrient load from Salmon Creek will be overestimated. Additionally, loads from Salmon Creek during the end of outflow periods may accumulate and flow back into the lake when flow switches to inflow. In this case, loads from Salmon Creek will be underestimated. The combined effect from these two processes is currently unknown, but not unreasonable to think they might cancel each other on a monthly time scale. As a result, the best estimate of the contribution of Salmon Creek loads to Vancouver Lake is to assume that all of the load enters the lake during periods of inflow from Lake River. Travel times from Salmon Creek into the lake are currently unknown and warrant further exploration in order to fine tune the effects that nutrient from Salmon Creek have on the lake. However, as a rough estimate, the median velocity measured at Lake River at Ridgefield streamgage (0.65 ft/s) gives a travel time between Salmon Creek and Felida approximately 3.3 hours, which should be independently verified.

The potential monthly TN load to the lake from Salmon Creek ranged from 3,100 to 85,000 lb, and TP and orthophosphate monthly ranges were 300 –4,800 lb and 80–1,500 lb, respectively. Annual potential TN and TP loads from Salmon Creek are greater than loads from Burnt Bridge Creek and Flushing Channel combined, and the orthophosphate potential loads from Salmon Creek are comparable to the combined loads from Burnt Bridge Creek and Flushing Channel.

Another way to examine the influence of Salmon Creek loads on Vancouver Lake is to represent these inputs as a fraction of the total Lake River IN loads. The proportion of the Lake River IN nutrient load originating from Salmon Creek was highest in late autumn and winter and often less than 5 percent during summer months (fig. 41). This pattern is explained by the fact that Salmon Creek flows peak in winter and decline in summer (fig. 39), whereas Lake River flows are fairly consistent year round (fig. The average proportion to Lake River at Felida loads from Salmon Creek for the 2-year study period were 22, 14, and 29 percent for total nitrogen, total phosphorus, and orthophosphate, respectively. However, in winter months, these proportions can exceed 20–50 percent of the total Lake River IN load. At a maximum (March 2011), the contribution from Salmon Creek exceeded 60 percent to the Lake River IN load for total nitrogen and orthophosphate.

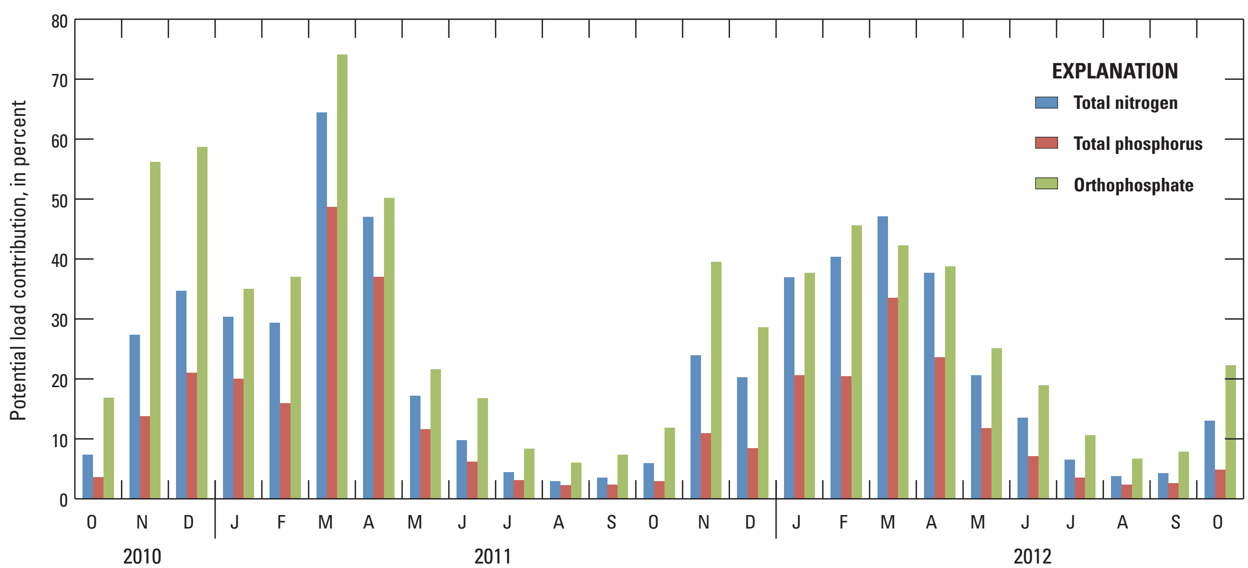


Figure 41. Potential fraction of Lake River (during inflow to Vancouver Lake) nutrient loads that originated from Salmon Creek, Vancouver, Washington, October 2010–2012.

Importance of Lake Sediment Resuspension

Because the lake is relatively large and shallow, wind-induced sediment resuspension may be important in Vancouver Lake, and there is indirect evidence of this process taking place. For example, time series graphs of surface Chl-*a*, particulate N, and particulate P concentrations follow patterns in TSS concentrations in bottom waters at Lake Sites 1 and 2 (fig. 42). These patterns are more pronounced in summer months when the lake at its shallowest and when resuspension of lake sediment may be more important.

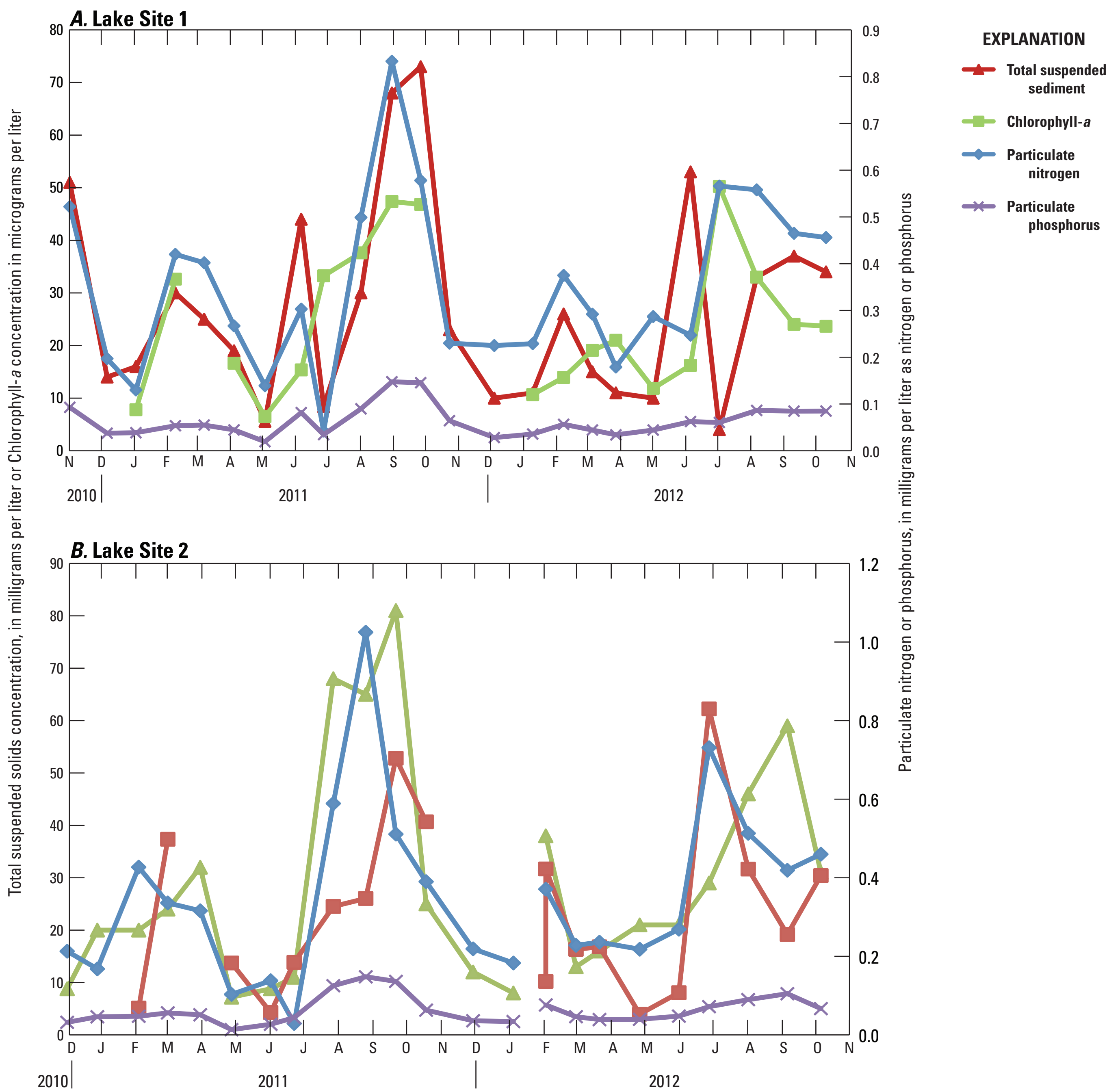


Figure 42. Total suspended sediment, surface Chlorophyll-*a*, particulate nitrogen, and particulate phosphorus for (*A*) Lake Site 1 and (*B*) Lake Site 2 in bottom waters, Vancouver Lake, Vancouver, Washington, November 2010–October 2012.

In addition, the patterns in TSI (fig. 27) imply, when TSI (Chl-*a*) is less than TSI(Secchi) and TSI(TP), that Chl-*a* is not contributing entirely to turbidity of the lake during these times. These deviations may be the result of resuspension with events in August–October 2011, May–June 2012, and July–September 2012. Paired wind and turbidity data were collected for 3 months during summer 2012 to develop relationships between wind velocity and turbidity in the lake; however, the data were highly variable (data not shown) and an empirical relationship could not be clearly developed.

The combined bottom water chemistry and TSI data imply that summer months are important times for possible sediment resuspension events and should be further examined for their effect on internal nutrient cycling.

Phosphorus Content of Sediment

During summer 2012, lake sediment cores were collected at Lake Sites 1 and 2 to determine the amount of phosphorus that was potentially available for biological uptake in the lake. During a resuspension event, sediment-bound phosphorus can be used by the biota and potentially contribute to algal blooms; therefore, it is important to know the nutrient content of the sediment. Sediment cores were collected with a push corer and sectioned into 5 -cm intervals. A series of sequential extractions on the sediment subsections were used to determine the fractions of phosphorus in the sediment (Rydin and others, 2000). Analysis of these samples were performed by Aquatic Research, Inc. in Seattle, Washington.

Loosely bound and readily available inorganic P was 3 percent or less of the total sediment phosphorus, whereas unavailable aluminum and calcium bound P made up 60–90 percent of the total sediment P across all samples analyzed (table 19). The amount of readily available P decreased with depth. From this information, it is possible to calculate a potential release of readily available inorganic P from the sediment using the density of the sediment and area of the lake. Using the average amount of readily available P in the upper 5 cm of sediment from both sites (34 mg P/kg sediment), this converts into approximately 53,300 lb (24,200 kg) of sediment bound phosphorus that can be used for biological uptake within the lake. This is the equivalent of about a one-third of the TP that is delivered to the lake each year from Lake River at Felida; about 10 times the amount that enters from Flushing Channel or Burnt Bridge Creek; and relative to other budget entries, a significant value. However the biggest unknown factor is how quickly this source of phosphorus can be released, and how deep sediments are mixed during resuspension events. Without further information on the duration and extent of sediment resuspension, this estimate of sediment bound P available to in-lake production should be considered an overestimation.

Table 19. Phosphorus fractions of lake sediment collected in August 2012 from Site 1 and Site 2 in Vancouver Lake, Vancouver, Washington.

[**Loosely bound P** and **Iron bound P** are considered inorganic forms of phosphorus available for uptake. **Calcium bound P** and **Aluminum bound P** are considered as the unavailable inorganic fraction. **Organic P** is potentially available for uptake. **Abbreviations**: P, phosphorus; mg P/kg, milligrams of phosphorus per kilogram of sediment; cm, centimeters]

Sample ID	Total P (mg P/kg)	Loosely bound P (mg/kg)	Iron bound P (mg/kg)	Calcium bound P (mg/kg)	Aluminum bound P (mg/kg)	Organic P (mg/kg)	Available inorganic fraction (percent)	Unavailable inorganic fraction (percent)	Potentially available organic fraction (percent)
SITE1 0–5 cm	1,174	<2.00	37	487	224	427	3	60	36
SITE1 10–15 cm	893	<2.00	15	490	156	232	2	72	26
SITE1 25–30 cm	905	<2.00	20	528	142	215	2	74	24
SITE2 0–5 cm	1,010	<2.00	24	569	172	246	2	73	24
SITE2 10–15 cm	674	<2.00	7	433	65	169	1	74	25
SITE2 25–30 cm	886	<2.00	3	779	17	87	0	90	10

Phosphorus Inputs From Waterfowl

Bird populations have been shown to have significant effect on the nutrient loads and overall water quality of a given lake, particularly when that water body is located along a migratory route (Manny and others, 1994; Chaichana and others, 2010). The Ridgefield Wildlife Refuge, in operation since 1965, is located north of Vancouver Lake and home to more than 75 species of birds, many of which use the refuge as winter nesting grounds (U.S. Fish and Wildlife Service, 2010). As a result, an estimate of potential phosphorus inputs from waterfowl is warranted in order to see how it compares with other quantified sources.

Data for waterfowl usage at the lake is sparse at best. In the mid-1980s, an inventory of waterfowl was conducted in an area that covered Vancouver Lake and the Ridgefield Wildlife Refuge (Envirosphere, 1986). In that study, bird counts for Vancouver Lake and the refuge were reported separately which allowed us to determine the ratio of the number of individuals in the lake compared to the number in the refuge for various species, which we define as the species population ratio. More detailed mid-winter inventories have been recorded at the refuge from 1985 to present (U.S. Fish and Wildlife Service, 2010), and represent our best estimates for waterfowl usage in the area. These mid-winter surveys are conducted during a single day in January; average numbers of dominant species from 1998 to 2007 were 8,069 Canada geese, 9,791 dabbling ducks, 1,595 diving ducks, and 1,619 tundra swan (U.S. Fish and Wildlife Service, 2010). The species population ratios for Vancouver Lake derived from Envirosphere (1986) were 0.10 for Canada geese, 0.94 for dabbling ducks, 5.7 for diving ducks, and 0.0 for tundra swan. Therefore, we estimate that mid-wintering population in Vancouver Lake to be 811 Canada geese, 9,185 dabbling ducks, and 9,114 diving ducks.

We developed a simple regression model between body weight and phosphorus content of waterfowl droppings from data presented in Manny and others (1994) and Chaichana and others (2010) for variety of bird species (data not shown, R^2=0.99). This regression was used to calculate daily total phosphorus inputs based on the estimated bird count in the Vancouver Lake and published body weights for various bird species (Manny and others, 1994). These estimates were then summed for each month. Using this approach we estimate that the monthly phosphorus input from waterfowl directly into the lake ranges from 260 to 290 lb, with annual totals of 3,400 lb for both water year 2011 and 2012. This is equivalent to approximately 60 percent of the annual loads from Flushing Channel and Burnt Bridge Creek, and about 2 percent of the annual load from Lake River at Felida. Annual input from waterfowl is about 2 times the amount estimated from groundwater, and 8 times the amount from precipitation. However, estimates of phosphorus loading from waterfowl assumes that daily mid-winter bird populations are maintained every day of the year. Furthermore, these estimates assume there is no attenuation of the nutrient load by lake biota, so loadings from waterfowl should be considered overestimates. Compared to surface water sources, phosphorus inputs from waterfowl are likely minor. If we are overestimating waterfowl load by two to eight times, these inputs are still comparable to groundwater and precipitation loads. However, because groundwater and precipitation loads represent less than 1 percent of the total nutrient budgets, we conclude that waterfowl inputs are a minor factor for the lake. Estimates from waterfowl can be refined in the future by conducting seasonal, lake-specific inventories instead of relying on mid-winter counts at the refuge alone.

Additional Sources

In other studies of nutrient sources to lakes, additional non-point sources of nutrients have been recognized as important components of the nutrient budget including septic systems, pollen and litterfall, vehicle emissions, and the presence of alder stands in the watershed (see Moran and others, [2013] for detailed summaries of these potential sources to lakes). Besides the VLSC and beach park, there are only a handful of residences located near the shoreline of the lake. We had a groundwater well downgradient of the VLSC and potential inputs from their septic system was captured. In fact, the highest groundwater nutrients were measured in this location. Rates of groundwater seepage near the beach park and residential areas were near zero, the current study has accounted for most septic inputs in the nearshore. Additionally, the riparian areas of the lake are not extensive, so inputs from litterfall, pollen, and the lack of alder in the watershed make these sources of nutrient input to the lake minimal. However, it is possible that we are missing some additional N and P inputs from atmospheric deposition resulting from the transportation in the area. The lake is located adjacent to the Port of Vancouver, some roads travel along the shorelines, and there is some industry located nearby. Our estimates from deposition were based on NADP data from the broader region and it is possible that actual N and P concentrations in precipitation are greater around the lake. However, since the load from precipitation is estimated at less than 1 percent of the total budget, even if our estimates are an order of magnitude off of true values, it will not represent a significant portion of the nutrient budget to the lake. Therefore, we conclude that for the case of Vancouver Lake, most of these non-point sources are assumed to be negligible relative to surface water inputs to the lake.

Data Gaps and Future Work

Results from this project provide the Partnership with some fundamental information on the functioning of the lake. This was the first comprehensive study of water flows into and out of the lake, and the associated nutrient loads. The previous water budget (Bhagat and Orsborn, 1971) did not include continuous flow data into and out of the lake, so the budget was based on estimates from a small number of flow measurements. Results from this study will help guide future work at the lake and start to identify the data gaps to address important questions on how to manage nutrient sources to the lake.

First, more information is needed to better understand the influence of Salmon Creek on nutrient loads entering Lake River which eventually reaches Vancouver Lake. We are able to provide information on potential loads, but without understanding the hydrodynamics between Salmon Creek and Lake River, and Lake River and the lake, we can only provide these first-level estimates. Overall, the preliminary analysis shows that in winter months Salmon Creek could be an important input into Lake River and subsequently the lake. Therefore, having a better understanding of the actual volume of Salmon Creek water which contributes to the volume of Lake River that enters the lake is warranted.

In addition, it is currently unknown how much nutrient loading takes place along the length of Lake River between where it connects to the Columbia River and where it enters the lake. Loads in Lake River are orders of magnitude greater than other sources, and the higher flows in Lake River are clearly the reason for this. The load is a product of the flow multiplied by concentration, and because it is not likely that flow rates into and out of the lake can be substantially reduced without the construction of a flow regulation device. Therefore, further identification the factors controlling nutrient inputs (concentrations) within Lake River is needed to lower nutrient loads entering from Lake River.

Lake nutrient data indicate that in-lake processes are important. For example, the production of algae in the summer and subsequent senescence in the autumn may contribute to internal cycling of nutrients. In addition, sediment resuspension may play an important role in increasing in-lake concentrations and loads. However, there is a lack of fundamental understanding on the extent and duration of sediment resuspension and how it relates to nutrient increases in the lake. Therefore, a high priority for future research at the lake should involve quantifying nutrient release from sediments. An aspect of this work could include addressing wind-induced resuspension, specifically using equations from wave theory to estimate the extent and duration of resuspension from wind.

Conclusions

Water and nutrient budgets were determined monthly from October 2010 to October 2012 at Vancouver Lake, Vancouver, Washington. Results showed that Lake River at Felida was the most dominant source of water to the lake, composing 85 percent of total inputs to the lake. Evaporation, groundwater inflow, and precipitation were all less than 1 percent of annual water budgets, demonstrating the importance of surface flows into and out of the lake.

Total nitrogen loads were an order of magnitude greater than total phosphorus loads, and Lake River at Felida was the dominant source of both nutrients to the lake, composing 88–91 percent of all inputs into the lake. Nutrient loads from groundwater inflow and precipitation were minor compared to surface water flows. On an annual basis, changes in nutrients from lake storage and sedimentation were negligible.

Our study shows that reducing nutrient loads from Lake River at Felida will be important for improving the water quality of the lake in the future, although it will be challenging. The hydrological characteristics of the lake are linked to the Columbia River stage which is dictated greatly by the ocean tides and hydropower operations which affect flow in the Columbia River. The construction of a flow control structure on Lake River at Felida would allow for the reduction of nutrient loads into the lake but would need to balance the other needs of the lake at the same time (such as, recreation access to lake and fish migrations). In addition, nutrient loads originating from Salmon Creek can be a substantial proportion of Lake River input loads, particularly in winter months. Thus, reduction of loads in this watershed will help reduce total input loads into Vancouver Lake. Details on the processes of sediment resuspension and internal loading of nutrients remains a data gap at Vancouver Lake.

Acknowledgments

The authors would like to acknowledge the help of many people that provided their valuable time, without their efforts this project would have not been possible. Various personnel that helped in the field include Ken Frasl, Sarah Henneford, Trish Foreman, Irwin Fletcher, Eric Porter, and Matt Bachmann. We thank all the members of the Vancouver Lake Watershed Partnership for their insight during annual progress reviews; Phil Trask and Eileen Stone from PC Trask & Associates, Inc. for project management; Jeff Schnabel from Clark County Environmental Services for valuable input throughout the project; Rob Zisette from Herrera Environmental Consultants for technical help and guidance; members of the Vancouver Lake Sailing Club, especially Ken Gibson, for facilitating boat access to the lake, use of their property for water quality sampling, groundwater sampling and installation of the weather station; the Port of Vancouver for help accessing water quality and flow sites at Flushing Channel; Dan Matlock from Pacific Groundwater Group for providing lake level data and estimates of groundwater discharge into the lake from their groundwater flow model; and Steve Sylvester and Jon Anderson at Washington State University, Vancouver for access to centrifuges for processing porewater samples.

References Cited

Arar, E.J., and Collins G.B., 1997, U. S. Environmental Protection Agency method 445.0, in vitro determination of chlorophyll *a* and pheophytin *a* in marine and freshwater algae by fluorescence, Revision 1.2: Cincinnati, Ohio, U.S. Environmental Protection Agency, National Exposure Research Laboratory, Office of Research and Development, 22 p.

Aspila, I., Agemian, H., and Chau, A.S.Y., 1976, A semi-automated method for the determination of inorganic, organic, and total phosphate in sediments: Analyst, v. 101, p. 187–197.

Belanger, T.V., and Montgomery, M.T., 1992, Seepage meter errors: Limnology and Oceanography, v. 37, no. 8, p. 1787–1795.

Bhagat, S.K., and J.F., Orsborn, 1971, Summary report on water quantity and quality studies of Vancouver Lake, Washington, Pullman, WA: Washington State University college of Engineering Research Division, 59 p.

Boyer, J., Rollwagen-Bollens, G., and Bollens, S.M., 2011, Microzooplankton grazing before, during and after a cyanobacterial bloom in Vancouver Lake, Washington, USA: Aquatic Microbial Ecology, v. 64, p. 163–174.

Buso, D.C., Likens, G.E., LaBaugh, J.W., and Bade, D., 2009, Nutrient dynamics, *in* Winter, T.C., and Liken, G.E., eds., Mirror Lake, interactions among air, land and water: University of California Press, Berkeley, p. 69–204.

Cable, J.E., Burnett, W.C., Chanton, J.P., Corbett, D.R., and Cable, P.H., 1997, Field evaluation of seepage meters in the coastal marine environment: Estuarine, Coastal and Shelf Science, v. 45, p. 367–375.

Cable, J.E., Martin, J.B., and Jaeger, J., 2006, Exonerating Bernouilli? On evaluating the physical and biological processes affecting marine seepage meter measurements: Limnology and Oceanography: Methods 4, 2006, p. 172–183.

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

Caromile, S.J., Meyer, W.R., and Jackson, C.S., 2000, 1998 warmwater fish survey of Vancouver Lake, Clark County: Olympia, Washington, Washington Department of Fish and Wildlife, 38 p.

Chaichana, R., Leah, R., and Moss, B., 2010, Birds as eutrophicating agents–A nutrient budget for a small lake in a protected area: Hydrobiologia, v. 646, p. 111–121. doi:10.1007/s10750-010-0166-2.

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., 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.

Cooke, G.D., Welch, E.B., Peterson, S.A., and Nichols, S.A., 2005, Restoration and management of lakes and reservoirs, third edition: Taylor & Francis, New York, p. 47–85.

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.

Ebbert, J.C., Poole, J.E., and Payne, K.L., 1985, Data collected by the U.S. Geological Survey during a study of urban runoff in Bellevue, Washington, 1979–1982: U.S. Geological Survey Open File Report 84-064, 256 p.

Embrey, S.S., and Inkpen, E.L., 1998, Water-quality assessment of the Puget Sound Basin, Washington, nutrient transport in rivers, 1980–93: U.S. Geological Survey Water Resources Investigations Report 97-4270, 30 p.

Envirosphere, 1986, Habitat inventory and evaluation of the Vancouver Lake/Columbia River lowlands, Final Report: Envirosphere Company, Bellevue, Washington, 68 p.

Farnsworth, R.K., Thompson, E.S., and Peck, E.L., 1982, Evaporation atlas for the contiguous 48 United States: U.S. Department of Commerce, National Oceanic and Atmospheric Administration, June 1982, 27 p.

Fishman, M.J., ed., 1993, Methods of analysis by the U.S. Geological Survey National Water Quality Laboratory—Determination of inorganic and organic constituents in water and fluvial sediments: U.S. Geological Survey Open-File Report 93-125, 217 p., http://pubs.er.usgs.gov/publication/ofr93125.

Flint, L.E., and Flint, A.L., 2002, Porosity, *in* Dane, J.H., and Topp, C., eds., Methods of soil analysis—Part 4-physical methods,: Madison, Wisconsin, Soil Science Society of America, 866 p.

Foreman, J.R., Marshall, C.A., and Sheibley, R.W., 2014, Discharge, water temperature, and selected meteorological data for Vancouver Lake, Vancouver, Washington, water years 2011–13: U.S. Geological Survey Data Series 849, 52 p., http://dx.doi.org.10.3133/ds849.

Gilliom, R.J., 1983, Estimation of nonpoint source loadings of phosphorus for lakes in the Puget Sound region, Washington: U.S. Geological Survey Water-Supply Paper 2240, 28p.

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., http://pubs.er.usgs.gov/publication/pp272E.

Keefe, C.W., 1994, The contribution of inorganic compounds to the particulate carbon, nitrogen, and phosphorus in suspended matter and surface sediments of Chesapeake Bay: Estuaries, v. 17, p.122–130.

Klump, J.V., and Martens, C.S., 1981, Biogeochemical cycling in an organic rich coastal marine basin-II. Nutrient sediment-water exchange processes: Geochimica et Cosmochimica Acta, v. 45, no.1, p. 101–105, 107–121.

Kuwabara, J.S., Topping, B.R., Lynch, D.D., Carter, J.L., and Essaid, H.I., 2009a, Benthic nutrient sources to hypereutrophic Upper Klamath Lake, Oregon, USA: Environmental Toxicology and Chemistry, v. 28, no. 3, p. 516–524.

Kuwabara, J.S., Topping, B.R., Parchasoo, F., Engelstad, A.C., and Greene, V.E., 2009b, Benthic flux of nutrients and trace metals in the northern component of San Francisco Bay, California: U.S. Geological Survey Open-File Report 2009–1286, p. 26.

Kuwabara, J.S., Topping, B.R., Carter, J.L., Wood, T.M., Cameron, J.M., Asbill-Case, J.R., and others, 2012, Changes in benthic nutrient sources within a wetland after hydrologic reconnection: Environmental Toxicology and Chemistry, v. 31, no. 9, 1995–2013.

Lee, D.R., 1977, A device for measuring seepage flux in lakes and estuaries: Limnology and Oceanography, v. 22, no.1, p. 140–147.

Levesque, V.A., and Oberg, K.A., 2012, Computing discharge using the index velocity method: U.S. Geological Survey Techniques and Methods 3–A23, 148 p., http://pubs.usgs.gov/tm/3a23/.

Li, Yuan-Hui, and Gregory, Sandra, 1974, Diffusion of ions in sea water and in deep-sea sediments: Geochimica et Cosmochimica Acta, v. 38, no. 5, p. 703–714.

Manny, B.A., Johnson, W.C., and Wetzel, R.G., 1994, Nutrient additions by waterfowl to lakes and reservoirs: predicting their effects on productivity and water quality: Hydrobiologia, v. 279/208, p. 121–132.

McBride, M.S., and Pfannkuch, H.O., 1975. The distribution of seepage within lakebeds, U.S. Geological Survey Journal of Research, v. 3, no. 5, p. 505–512.

McFarland, W.D., and Morgan, D.S., 1996, Description of the ground-water flow system in the Portland basin, Oregon and Washington: U.S. Geological Survey Water Supply Paper 2470-A, 58 p.

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/.

Morgan, D.S., and McFarland, W.D., 1996, Simulation analysis of the ground-water flow system in the Portland basin, Oregon and Washington: U.S. Geological Survey Water Supply Paper 2470-B, 83 p.

Mueller, D.S., and Wagner, C.R., 2009, Measuring discharge with acoustic Doppler current profilers from a moving boat: U.S. Geological Survey Techniques and Methods 3A-22, 72 p., http://pubs.water.usgs.gov/tm3a22.

Mundorff, J.M., 1964, Geology and ground-water conditions of Clark County Washington, with a description of a major alluvial aquifer along the Columbia River: Water Supply Paper 1600, 267 p., http://pubs.er.usgs.gov/publication/wsp1600.

Murdoch, L.C., and Kelly, S.E., 2003, Factors affecting the performance of conventional seepage meters: Water Resources Research, v. 39, no. 6, 1163 p., doi:10.1029/2002WR001347.

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

Myers, J., 2010, Streamflow summary for Burnt Bridge Creek (Clark County), 2008: Washington State Department of Ecology, December 2010, No. 10-03-072, 38 p.

National Atmospheric Deposition Program, 2013, Precipitation chemistry data for the national trend network: National Atmospheric Deposition Program online database, accessed on August 2, 2013 at: http://nadp.sws.uiuc.edu/data/ntn/.

Parametrix, 2008, Vancouver Lake lowlands groundwater model summary report, February 2008: Parametrix, Incorporated, Auburn, Washington, 171 p.

Patton, C.J., and Kryskalla, J.R., 2013, Analytical properties of some commercially available nitrate reductase enzymes evaluated as replacements for cadmium in automated, semi-automated, and manual colorimetric methods for determination of nitrate plus nitrite in water: U.S. Geological Survey Scientific Investigations Report 2013–5033, 36 p., http://pubs.usgs.gov/sir/2013/5033/.

Patton, C.J., and Kryskalla, J.R., 2011, Colorimetric determination of nitrate plus nitrite in water by enzymatic reduction, automated discrete analyzer methods: U.S. Geological Survey Techniques and Methods Report 5-B8, 34 p., http://pubs.er.usgs.gov/publication/tm5B8/.

Pfannkuch, H.O., 1984, Effect of anisotropy and groundwater system geometry on seepage through lakebeds—1. Analog and dimensional analysis: Journal of Hydrology, v. 75, p. 213–237.

Port of Vancouver, 2009, Vancouver Lake Flushing Channel flow monitoring: Presentation by Port of Vancouver to the Vancouver Lake Watershed Partnership, Vancouver, Washington, February 8, 2009.

Rantz, S.E., 1982a, Measurement and computation of streamflow—Volume 1. measurement of stage and discharge: U.S. Geological Survey Water-Supply Paper 2175, 284 p.

Rantz, S.E., 1982b, Measurement and computation of streamflow—Volume 2. computation of discharge: U.S. Geological Survey Water-Supply Paper 2175, 347 p.

Redfield, A., 1958, The biological control of chemical factors in the environment: American Scientist, v. 46, p. 205–221.

Roberts, M., 2013, Lake Loma phosphorus screening-level assessment: Washington State Department of Ecology, 13-03-031, 39 p.

Rollwagen-Bollens, G., Bollens, S., Gonzalez, A., Zimmerman, J., Lee, T., and Emerson, J., 2013, Feeding dynamics of the copepod Diacyclops thomasi before, during and following filamentous cyanobacteria blooms in a large, shallow temperate lake: Hydrobiologia, v. 705, p. 101-118.

Rosenberry, D.O., and Menheer, M.A., 2006, A system for calibrating seepage meters used to measure flow between ground water and surface water: U.S. Geological Survey Scientific Investigations Report 2006-5053.

Rosenberry, D.O., Winter, T.C., Buso, D.C., and Likens, G.E., 2007, Comparison of 15 evaporation methods applied to a small mountain lake in the northeastern USA: Journal of Hydrology, v. 340, no. 3–4, p. 149–166.

Rosenberry, D.O., and Winter, T.C., 2009, Hydrologic processes and the water budget, *in* Winter, T.C., and Liken, G.E., eds., Mirror Lake, interactions among air, land and water: University of California Press, Berkeley, p. 23–67.

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., http://pubs.er.usgs.gov/publication/tm4A5.

Rus, D.L., Patton, C.J., Mueller, D.K., and Crawford, C.G., 2012, Assessing total nitrogen in surface-water samples—Precision and bias of analytical and computational methods: U.S. Geological Survey Scientific Investigations Report 2012–5281, 38 p.

Rydin, E., Huser, B., and Welch, E.B., 2000, Amount of phosphorus inactivated by alum treatments in Washington lakes: Limnology and Oceanography, v. 45, p. 226–230.

Shaw, R.D., and Prepas, E.E., 1990, Ground water-lake interactions–I. Accuracy of seepage meter estimates of lake seepage: Journal of Hydrology, v. 119, p. 105–120.

Sheibley, R.W., and Paulson, A.J., 2014, Quantifying benthic nitrogen fluxes in Puget Sound, Washington—A review of available data: U.S. Geological Survey Scientific Investigations Report 2014-5033, 44 p., http://dx.doi.org/10.3133/sir20145033.

Shinn, E.A., Reich, C.D., and Hickey, T.D. 2002, Seepage meters and Bernoulli's revenge: Estuaries, v. 25, no. 1, p. 126–132.

Sinclair, K.A., and Kardouni, 2012, Surface water/groundwater interactions and near-stream groundwater quality along Burnt Bridge Creek, Clark County: Washington State Department of Ecology, 12-03-003, 60 p.

Thornthwaite, C.W., 1948, An approach toward a rational classification of climate: Geographical Review, v. 38, no. 1, p. 55–94.

Ullman, W.J., and Aller, R.C., 1982, Diffusion coefficients in nearshore marine sediments: Limnology and Oceanography, v. 27, p. 552–556.

U.S. Environmental Protection Agency, 1993, Determination of phosphorus by semi-automated colorimetry (Method No. 365.1): U.S. Environmental Portection Agency, August, 1993, 17 p., http://water.epa.gov/scitech/methods/cwa/bioindicators/upload2007_07_10_methods_method_365_1.pdf.

U.S. Environmental Protection Agency, 1997, Determination of carbon and nitrogen in sediments and particulates of estuarine/coastal waters using elemental analysis (Method 440.0), revision 1.4: U.S. Environmental Protection Agency, National Exposure Research Laboratory, Office of Research and Development, 10 p., http://www.epa.gov/microbes/documentsm440_0.pdf.

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, http://pubs.water.usgs.gov/twri9A.)

U.S. Fish and Wildlife Service, 2010, Ridgefield National Wildlife Refuge comprehensive conservation plan: U.S. Fish and Wildlife Service, Portland, Oregon, 701 p.

Vancouver Lake Watershed Partnership, 2008, Vancouver Lake technical foundation: Vancouver, Washington, September 2008, 53 p.

Vancouver Lake Watershed Partnership, 2013, Ten year planning and recommendations report: Vancouver, Washington, November 26, 2013, 38 p.

Washington State Department of Ecology, 2013, Water quality assessment tool for Washington— 303(d)/305(b) integrated report viewer: Washington State Department of Ecology database, accessed on January, 1, 2014 at: http://apps.ecy.wa.gov/wats/.

Wierenga, R., 2005, Vancouver Lake and Lake River watersheds—Salmon Creek and lakeshore: Presentation by Clark County Public Works to the Vancouver Lake Watershed Partnership, Vancouver, Washington, March 16, 2005, 32 p.

Appendixes

Appendixes A–G are included as PDFs and can be downloaded from http://pubs.usgs.gov/sir/2014/5201/.

Appendix A. Relating Flow from Continuous Streamgage Stations to Water-Quality Stations for Burnt Bridge Creek at Vancouver Lake (14211920), Salmon Creek at Lake River (14213050), and Lake River at Felida (14211955)

Appendix B. Quality-Assurance and Quality-Control Data

Appendix C. Tables of Water Quality Collected from Surface Waters and Groundwater, October 2010–October 2012

Appendix D. Lake Profiles for Temperature, Specific Conductivity, Dissolved Oxygen, pH, and Turbidity, October 2010–October 2012

Appendix E. LOAD ESTimation Model Results and Comparison to Measured Load Data

Appendix F. Monthly Surface-Water Load Estimates and Error Analysis from LOAD ESTimation Model, October 2010–October 2012

Appendix G. Porewater Nutrient Data from Vancouver Lake, Washington, October 2010–October 2012

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

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Sheibley and others—**Water and Nutrient Budgets for Vancouver Lake, Vancouver, Washington, October 2010–October 2012**—Scientific Investigations Report 2014–5201

ISSN 2328-0328 (online)
http://dx.doi.org/10.3133/sir20145201