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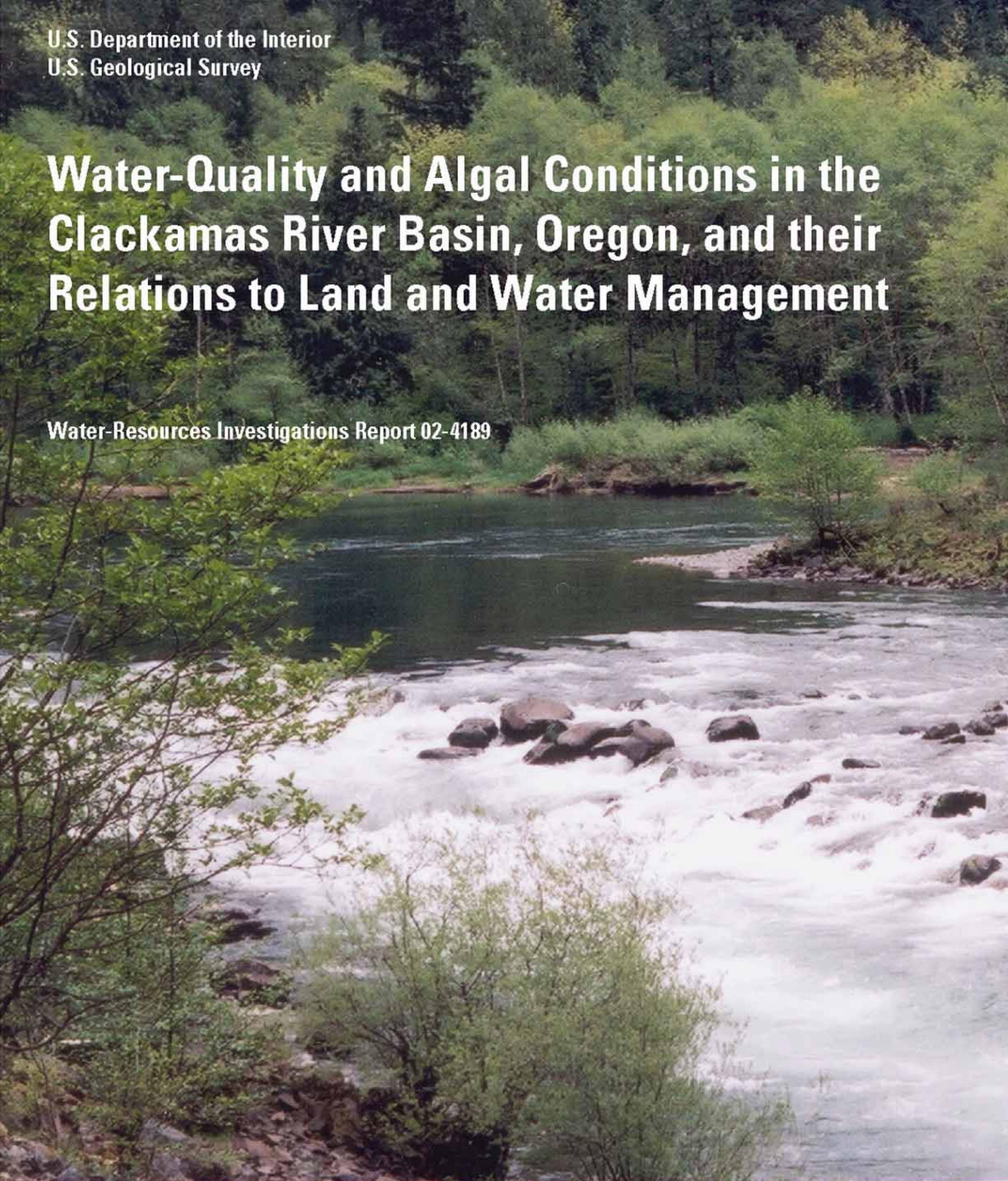
Water-Quality and Algal Conditions in the Clackamas River Basin, Oregon, and their Relations to Land and Water Management

Water-Resources Investigations Report 02-4189



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Cover photograph:

The Wild and Scenic stretch of the upper Clackamas River has deep pools, swift runs, and swirling rapids.

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Water-Quality and Algal Conditions in the Clackamas River Basin, Oregon, and their Relations to Land and Water Management

By KURT D. CARPENTER

Water-Resources Investigations Report 02–4189

Portland, Oregon: 2003

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CONVERSION FACTORS

Multiply	By	To obtain
	Length	
micrometer (µm)	0.00003937	inch (in)
meter (m)	3.281	foot (ft)
mile (mi)	1.61	kilometer (km)
	Volume	
milliliter (mL)	0.001057	quart (qt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	28.317	cubic feet per second (ft^3/s)
cubic feet per second (ft^3/s)	0.02831	cubic meters per second (m^3/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
acre-feet (acre-ft)	1.233×10^3	cubic meters (m^3)
	Mass	
microgram (mg)	0.00000003527	ounce (oz)
milligram (mg)	0.00003527	ounce (oz)
kilogram (kg)	35.27	ounce (oz)
	Area	
square miles (mi^2)	640	acres (ac)
acres (ac)	0.0015625	square miles (mi^2)
square meters (m^2)	10.75	square feet (ft^2)
	Temperature	
degrees Celsius (°C)	1.8 (°C) + 32	degrees Fahrenheit (°F)
	Concentration, in water	
micrograms per liter (µg/L)	0.001	milligrams per liter (mg/L) parts per million (ppm)
milligrams per liter (mg/L)	1000	micrograms per liter (µg/L) parts per billion (ppb)

Vertical coordinates in this report are referenced to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada.

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

MAPPING SOURCES:

Base map modified from various digital data sets from Portland, Oregon, METRO and U.S. Geological Survey (scales vary). Projection: State Plane, Zone 5076, North American Datum 1983.

GLOSSARY

SITE CODES

CLEAR	Clear Creek near the mouth
COLLA	Collawash River near Two Rivers Campground
CR_ABNFK	Clackamas River upstream of North Fork Reservoir
CR_BARTON	Clackamas River at Barton Park
CR_BLNFK	Clackamas River below North Fork Reservoir
CR_CARVER	Clackamas River at Carver
CR_MCIVER	Clackamas River at McIver Park (near Estacada)
CR_UPPER	Upper Clackamas River at Two Rivers Campground
CR_3LYNX	Clackamas River upstream of Three Lynx Creek
CR_99E	Clackamas River upstream of Hwy 99E Bridge
DEEP	Deep Creek upstream of Hwy 224
EAGLE_M	Eagle Creek near the mouth
EAGLE_W	Eagle Creek near the wilderness boundary
FALL	Fall Creek near the confluence with the North Fork Clackamas River
FISH	Fish Creek near the mouth
NFCLACK	North Fork Clackamas River at the mouth
NFK_BUOY1	North Fork Reservoir at buoy 1 (near Promontory Park)
NFK_BUOY2	North Fork Reservoir at buoy 2 (upstream of Promontory Park)
NFK_BUOY3	North Fork Reservoir at buoy 3 (upstream of buoy 2)
NFK_BURN	North Fork Reservoir near burn pile on north shore
NFKRES_1	North Fork Reservoir at log boom (station 1)
NFKRES_2	North Fork Reservoir at powerlines (station 2)
NFKRES_B	North Fork Reservoir at North Fork Bay
OAK_BLTLK	Oak Grove Fork below Timothy Lake
OAK_RAIN	Oak Grove Fork at Rainbow Picnicground
RICHARDSON	Richardson Creek at Hwy 224
ROARING	Roaring River near mouth
ROCK	Rock Creek near mouth
SFCLACK	South Fork Clackamas River near mouth
SIEBEN	Sieben Creek at Hwy 224
WINSLOW	Winslow Creek near mouth

SYMBOLS, ABBREVIATIONS, ACRONYMS, AND TERMS

Algal guilds Groups of algal taxa that have particular preferences or tolerances for water-quality conditions, or that possess some unique physiochemical characteristic such as the ability to fix atmospheric nitrogen.

As Arsenic.

AFDM Ash-free dry mass, a measure of the organic content of a biological sample.

biovolume A volumetric estimation of algal biomass reported in cubic micrometers (microns) per square centimeter.

°C Degrees Celsius.

CCA Canonical Correspondence Analysis, a multivariate statistical technique that allows for evaluation and testing of significance of relations among sites, environmental variables, and species.

cells/cm^2 Cells per square centimeter, a measure of cell density.

$CaCO_3$ Calcium carbonate.

chl *a* Chlorophyll *a*.

Cl- Chloride.

CO_2 Carbon dioxide.

DIN Dissolved inorganic (bioavailable) nitrogen, the sum of nitrite, nitrate, and ammonium nitrogen.

DKN Total dissolved Kjeldahl nitrogen, includes organic nitrogen and ammonium nitrogen (filtered, digested).

DO Dissolved oxygen.

DOC Dissolved organic carbon.

epilimnion The parcel of water in a lake or reservoir extending from the surface to the metalimnion (where the thermocline occurs).

EWI Equal-Width Increment: A sampling method whereby a depth- and width-integrated sample is collected, composited, and homogenized prior to dispensing subsamples for analysis.

ft^3/s Cubic feet per second: A measure of streamflow.

GIRAS Geographic Information Retrieval and Analysis System (USGS data base).

GIS Geographic Information System.

HAAs Haloacetic acids, toxic disinfection by-products that occur when water containing organic carbon is treated with chlorine for drinking.

hypolimnion The parcel of water in a lake or reservoir that extends from just off the bottom to the bottom of the metalimnion, where the thermocline occurs.

kg/d kilograms per day.

MCL Maximum Contaminant Level.

metalimnion The parcel of water in a lake or reservoir where the temperature is changing rapidly with depth, located between the epilimnion and the hypolimnion.

MRL Minimum laboratory reporting level, smallest measured concentration of a constituent that may be reliably reported using a given analytical method.

mg/L Milligrams per liter, or parts-per-million.

mg/m^2 Milligrams per square meter.

mL Milliliter, or 10^{-3} liters.

SYMBOLS, ABBREVIATIONS, ACRONYMS, AND TERMS

μg/L Micrograms per liter, or parts-per-billion.

μm Micrometer, or 10^{-6} meters.

$\mu m^3/cm^2$ Cubic micrometers (microns) per square centimeter: A measure of algal biovolume.

N Nitrogen.

N_2 Nitrogen gas.

NADP National Atmospheric Deposition Program.

NH_3 Ammonia.

NH_4^+ Dissolved ammonium nitrogen. Used in this report to indicate ammonium (NH_4^+) or ammonia (NH_3), regardless of pH.

NPDES National Pollution Discharge Elimination System.

NO_2^- Dissolved nitrite nitrogen.

NO_3^- Dissolved nitrate nitrogen.

NTU Nephelometric turbidity unit.

NWIS National Water Information System (USGS data base).

NWQL USGS National Water-Quality Laboratory in Arvada, Colorado.

P Phosphorus.

pH A measure of the acidity of a solution, calculated as –log (concentration of H^+ ion).

PO_4^{3-} Orthophosphate phosphorus, a form of dissolved phosphorus (filtered).

QC Quality control.

RM River mile.

SC Specific conductance (the electrical conductivity of water at 25°C).

SiO_2 Silicon dioxide, an important nutrient for diatom algae.

SOC Suspended organic carbon.

SRP Soluble reactive phosphorus includes PO_4^{3-}, dissolved polyphosphates, and other forms of dissolved P (filtered, not digested).

TDP Total dissolved phosphorus (filtered, digested).

Thermocline The layer of water in a lake or reservoir between the epilimnion and the hypolimnion, where the rate of decrease in water temperature with depth is greatest.

THMs Trihalomethanes, toxic disinfection by-products that occur when water containing organic carbon is treated with chlorine.

TKN Total Kjeldahl nitrogen includes organic nitrogen and ammonium nitrogen (unfiltered, digested).

TN Total nitrogen (unfiltered, digested), the sum of TKN and nitrite-plus-nitrate.

TP Total phosphorus (unfiltered, digested).

USEPA U.S. Environmental Protection Agency.

USGS U.S. Geological Survey.

WWTP Wastewater treatment plant.

ACKNOWLEDGMENTS

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Water-Quality and Algal Conditions in the Clackamas River Basin, Oregon, and their Relations to Land and Water Management

By Kurt D. Carpenter

EXECUTIVE SUMMARY

This report presents findings from a water-quality assessment conducted in the Clackamas River Basin, northwestern Oregon, from 1996 to 1999, focusing on nutrient and algal conditions. Concerns about the quality of the Clackamas River emerged in 1994, when a bloom of blue-green algae (*Anabaena* spp.) occurred in North Fork Reservoir, concurrent with taste and odor problems in drinking water supplied by the river. Providing clean water for drinking and supporting a cold-water fishery, including several stocks of salmon, steelhead, and trout, are among the beneficial uses designated by the State for the Clackamas River. Supporting these uses requires high-quality cold water that is well-oxygenated and low in chemical contaminants. With regard to those characteristics, the Clackamas River has withstood pressures from human activities in the basin relatively well; with the exception of high water temperatures and *E. coli* bacteria during summer, which currently do not meet water-quality standards, the river's water quality is rated good to excellent compared with other rivers in Oregon. However, recent algal blooms are a sign of eutrophication (nutrient enrichment). Declines in water quality that can result from algal blooms—including taste and odor problems, increased concentrations of toxic disinfection by-products in drinking water, low levels of dissolved oxygen, and high pH—are beginning to appear in the Clackamas River.

The purpose of the study was to determine the extent of eutrophication in the Clackamas River Basin, including the Clackamas River, its major tributaries, and reservoirs, with an emphasis on basic water quality (nutrients, dissolved oxygen, pH, temperature, and conductance), water quantity (water sources within the basin), and algal conditions (biomass and species composition). Sampling sites were located in streams draining areas with a variety of land uses, including forest management, agriculture, and urban development, as well as downstream from the hydroelectric projects in the basin, to examine how these human influences might be affecting water-quality and algal conditions. Most of the data were collected from May to September 1998, with monthly sampling of reservoirs and sampling of streams every other month. Nutrient concentrations in ground water also were examined during a one-time sampling of a few wells and springs to evaluate whether ground water is transporting nutrients to the Clackamas River.

Major Findings

Nuisance algal growths, with accompanying negative effects on water quality, were observed at several locations in the basin during this study, including certain tributaries, reservoirs, and the main-stem Clackamas River. Algal assemblages in well-shaded streams (greater than 90% canopy closure) produced low biomass (11 to 23 mg/m^2 [milligrams per square meter] chlorophyll *a*), probably the result of light limitation. Streams with greater light availability sometimes reached high algal biomass.

In 1998, biomass in the lower Clackamas River reached a maximum of 300 mg/m^2 chlorophyll *a*, which exceeded the threshold range of 100–150 mg/m^2 suggested to prevent the occurrence of nuisance algal conditions, such as fouled stream channels and daily fluctuations in concentrations of dissolved oxygen and pH. Algal biomass at sites immediately downstream from the hydroelectric project's reservoirs and/or powerhouses also exceeded the nuisance threshold, sometimes by a factor of 4 or more, especially in September. Nuisance algal conditions also were observed in some of the tributaries, including the North Fork of the Clackamas River, Clear Creek, Rock Creek, and Sieben Creek.

High algal biomass in the Clackamas River appears to be a recent phenomenon, as biomass was low during a previous study that found 21 mg/m^2 chlorophyll *a* in the lower Clackamas River at river mile 0.4 in late August 1993. High biomass was sometimes observed during 1998 in locations where nutrient concentrations appeared relatively low. Although this finding appears contradictory, growing algae may deplete water column nutrient concentrations, giving the deceptive appearance of low nutrient availability. Hypotheses explored in this report to explain such growths include (1) high water velocities, (2) an apparent symbiotic relationship between nitrogen-fixing algae and green algae, (3) utilization of nutrients from ground-water infusions along stream margins, (4) utilization of dissolved organic nitrogen that is typically not considered in nutrient assessments, (5) reduced grazing on algae by aquatic invertebrates, and (6) highly efficient recycling of nutrients.

Although blue-green algae were consistently observed in both of the major reservoirs during this study, sometimes forming blooms, the foul tastes and odors that occurred in the water supply in 1994 did not occur in 1998. Prolific growths of filamentous green algae (*Cladophora* and *Stigeoclonium*) were, however, observed on streambed substrates in the lower Clackamas River, where the effects of excessive algae on dissolved oxygen, pH, and stream habitat were pronounced. Further, as the algae began to decay, aesthetic and water-quality conditions in the lower Clackamas River also deteriorated as clumps of drifting algae became entangled on docks and fishing lines, clogged drinking water intakes, and increased turbidity levels in the river. Concentrations of disinfection by-products, toxic compounds that form during chlorination, also increased in drinking water during this time, presumably the result of the increased organic matter in the river from the drifting algae.

These are unambiguous signs of nutrient enrichment. Any restoration efforts will require management strategies aimed at reducing the transport of nutrients to the Clackamas River and its tributaries. Nutrient sources can be difficult to identify and quantify, especially in watersheds such as the Clackamas Basin that contain diverse land uses. Evaluating potential nutrient sources in the basin and proposing hypotheses to explain the observed proliferations of algae, one of the goals of this study, was the first step. More detailed follow-up studies at smaller scales will be required to better quantify nutrient sources and to examine cause-and-effect relationships between land and water management and water quality.

Nutrient concentrations in the basin showed considerable variation among sites, and the sources of phosphorus and nitrogen were different, especially with respect to streams draining forested land. There, concentrations of dissolved phosphorus (up to 26 µg/L [micrograms per liter]) were found in streams draining portions of the High Cascades Ecoregion, including the upper Clackamas River (at river mile 57) and the lower Oak Grove Fork, possibly the result of naturally occurring phosphorus from young volcanic rocks in this area. Total phosphorus concentrations at all main-stem sites in the upper basin, and several upper basin tributaries, exceeded 9 µg/L, the reference condition suggested by the U.S. Environmental Protection Agency for streams in the Cascade Range Ecoregion.

Nitrogen concentrations in these and other streams in the upper basin, however, were mostly below laboratory reporting levels (<5 µg/L).In contrast, streams draining the middle Clackamas Basin, including Clear Creek, Eagle Creek, and the North Fork of the Clackamas River, showed the opposite pattern, with relatively high concentrations of nitrogen and relatively low concentrations of phosphorus. The nitrate concentrations in these basins ranged from 43 to 206 µg/L in July, significantly exceeding the 5 µg/L reference condition suggested by the U.S. Environmental Protection Agency for streams in the Cascade Range Ecoregion. Nitrate concentrations in upper Eagle Creek in the Salmon-Huckleberry Wilderness Area and Roaring River (two reference streams) were 9 and <5 µg/L, respectively, in July, which is close to the suggested reference condition.

Inputs of nitrogen from middle-basin watersheds (and from North Fork Reservoir, which appeared to release nitrogen during the spring), combined with inputs of phosphorus from the upper basin, provide the necessary nutrients to support algal growth in the Clackamas River. Therefore, due to the abundance of phosphorus in the main stem, any inputs of nitrogen from tributaries and other sources, including nitrogen fixed by blue-green algae in the reservoirs and streams, may stimulate algal growth in the Clackamas River.

Inputs of nitrogen and phosphorus also occur from the lower basin tributaries, including Deep, Richardson, Rock, and Sieben Creeks, which had much higher nutrient concentrations compared with other sites, likely reflecting anthropogenic activities. Inputs from these tributaries likely contributed to the observed proliferations of algae in the Clackamas River during this study. However, due to the relatively low streamflow in Richardson, Rock, and Sieben Creeks, they contributed smaller loads of nutrients, despite their high nutrient concentrations. Deep Creek, however, with higher flow, did contribute relatively large loads of both nitrogen and phosphorus to the Clackamas River.

Several potential sources of nutrients were identified in the basin, including point-source discharges from wastewater treatment plants and fish hatcheries. Nonpoint sources, including soil erosion, fertilizers, nitrogen-fixing plant species, atmospheric deposition, field burning, and livestock, also may contribute to enriching streams with nutrients. Another potentially important source of nutrients is ground water, which was shown to contain high levels of nitrogen and phosphorus. Although the quantity of ground water entering the Clackamas River was not determined, the streamflow data suggest that it may be significant, especially in the reach between River Mill Dam and Barton.

Most of the **streamflow** in the Clackamas River originated from the upper basin, where large amounts of precipitation and infiltration recharge ground-water aquifers, thus supplying the river with consistent flows into late summer, despite the lack of rain at that time. Water from the Oak Grove Fork of the Clackamas River (via discharges from the Oak Grove Powerhouse) and the Collawash and Roaring Rivers accounted for much of the streamflow in the Clackamas River. Other tributaries, especially those in the lower basin, contributed lesser amounts of summertime streamflow. The basin's largest reservoir, Timothy Lake, which stores snowmelt during the spring, provided a steady supply of water to the Oak Grove Fork and downstream reaches during summer and contributed about one-third of the streamflow in the upper Clackamas River during reservoir drawdown in late September.

Although temperature, dissolved oxygen, and pH data from this study indicate that State **water-quality standards** may have been exceeded at times during this study, the temperature and dissolved oxygen criteria are based on multiple-day averages, not single point "instantaneous" measurements, as were typically collected for this study. The water temperature, for example, is based on the 7-day average of the maximum daily temperature, whereas the dissolved oxygen criterion is based on a 30-day mean minimum concentration. Nevertheless, continuous data (15-minute intervals) collected in late June and mid-July in the lower Clackamas River at river mile 2.7 showed instantaneous exceedances for water temperature, dissolved oxygen, and pH, sometimes for much of the day. These data suggest that water-quality criteria were not being met for a period spanning at least 2 weeks, however, the data were not sufficient to fully characterize compliance with water-quality criteria.

Water-quality criteria for water temperature and dissolved oxygen are more stringent during fish spawning, egg incubation, and fry emergence periods, which, in the Clackamas Basin, occur nearly year round (from August 15 through July 15). The dissolved oxygen standard, however, also depends on the intergravel dissolved oxygen concentration, which, because such measurements may disturb fish spawning areas, has not been measured in the Clackamas River. As a result, it was not possible to determine whether dissolved oxygen standards were being met.

Water temperatures were generally cold (less than 11°C [degrees Celsius]) in the Clackamas River in May, but increased to levels that might have exceeded State water-quality criteria in July. All main-stem Clackamas River sites, from just upstream of the Collawash River to the mouth, and most tributaries potentially exceeded the 7-day average maximum daily temperature criterion of 12.8°C in July. Water temperature in some tributaries, including the upper Oak Grove Fork (downstream of Timothy Lake), Winslow Creek, Fall Creek, and Eagle Creek (at the downstream boundary of the Salmon Huckleberry Wilderness Area) was less than 12.8°C during sampling in July.

The reservoirs appeared to increase water temperatures in downstream reaches, especially in September. Water temperatures in the Oak Grove Fork increased during the drawdown of Timothy Lake by about 2°C in September 1998, whereas a larger temperature increase of about 4°C was observed in the Clackamas River as it flowed through North Fork Reservoir. At this time, water temperatures probably exceeded the criterion within the reservoir, and at all main-stem sites downstream, with the highest value (20.4°C) occurring in the Clackamas River at Barton. However, the inputs of warm tributaries in the lower basin, especially Eagle, Clear, and Deep Creeks, also contributed to high water temperatures in the lower Clackamas River.

Levels of **dissolved oxygen and pH** varied among sites, with substantial fluctuations occurring throughout the day at some sites. Dissolved oxygen concentrations appeared to be controlled in many places by water temperature and reaeration rather than by biological processes, with the highest concentrations coinciding with the coldest temperatures. In some cases, however, patterns in the dissolved oxygen concentrations and pH were consistent with the effects of algal photosynthesis, with highest levels occurring during the day and lowest levels at night or early morning. Such fluctuations resulted in potential exceedances of State water-quality criteria in the lower Clackamas River at river mile 2.7 in late June and mid-July, when the respective minimum dissolved oxygen concentrations were 8.3 and 7.7 mg/L (milligrams per liter [parts-per-million]). In September, a spawning period for spring and fall Chinook salmon, the 30-day 11 mg/L mean minimum dissolved oxygen criterion was probably not met at any of the main-stem sites. The lowest measured dissolved oxygen concentrations for tributary sites occurred in Clear, Eagle, Deep, and Rock Creeks in August, when dissolved oxygen concentrations ranged from 8 to 8.4 mg/L. The Oak Grove Fork downstream from Timothy Lake also probably did not meet the 11 mg/L or the 95% saturation criterion in September, when dissolved oxygen concentrations in Timothy Lake were especially low.

Fluctuations in pH also were observed in the lower Clackamas River (at river mile 2.7) in late June and mid-July, with the highest values occurring in the late afternoon, slightly exceeding the State single-measurement criterion of 8.5 pH units. Similar fluctuations in pH also were observed in the lower Clackamas River (at Carver, river mile 7.9) in August. Exceedances of the pH criterion were observed in only one of the tributaries (Deep Creek), where the afternoon pH was 8.8 units in July.

Timber production, agriculture, and urban development, the major land uses in the basin, may each be contributing to declines in water quality. These activities all have potential to contribute nutrients, either directly through soil erosion and inputs of fertilizers, for example, or through ecosystem or habitat disturbances that can alter nutrient cycling processes. The highest concentrations of nitrogen and phosphorus were found in tributaries draining land having these uses, whereas nutrient concentrations (and algal biomass) in streams in undisturbed watersheds, including upper Eagle Creek and Roaring River, were substantially lower.

Forest management (timber harvesting, roads, and fertilization in some areas) appeared to be a source of nutrients to streams. A positive correlation was found between the amount of nonforest upland (including clear cuts and other areas without vegetation) and concentrations of total phosphorus among streams in the middle and upper Clackamas Basin, where forest management is the dominant land use. This finding, combined with the positive correlation between concentrations of total phosphorus and silica, an important component of most soils, suggests that timber harvesting and associated network of roads in these watersheds may be transporting phosphorus through erosion of phosphate-rich soils. A similar relationship was found between nitrate concentrations and the amount of nonforest upland, although the increase in nitrate was observed only at sites in the middle basin, where most the timberland is privately owned. Nitrogen from these sites may originate from several sources, including tree harvesting (which reduces uptake of N by vegetation), post-harvest burning of slash debris, wildfires, fertilizer applications, atmospheric deposition, and proliferations of N-fixing plants such as red alder and scotchbroom that often colonize disturbed soils.

Sites in basins containing the highest amounts of agricultural and urban land had the highest concentrations of nutrients, and algal assemblages included several taxa that are indicative of nutrient enrichment. The highest concentrations of both nitrogen and phosphorus, and the highest algal biomass for a lower basin tributary, occurred in Sieben Creek, which drains a watershed undergoing rapid urbanization. The excessively high concentration of nitrate in Sieben Creek (>7,000 µg/L) may have resulted from applications of fertilizer on urban or agricultural land in the basin, or from leaky septic systems. Other areas in the lower Clackamas Basin, such as mobile home parks, also may contribute wastewater high in nutrients to the Clackamas River.

The **hydroelectric projects** in the basin produce electricity, provide water storage, and regulate streamflows in much of the basin. As such, water quality in the Oak Grove Fork and Clackamas River is closely related to the quality of the water within Timothy Lake and North Fork Reservoir. Processes within the reservoirs, such as heating of the water, the uptake of dissolved nutrients by growing phytoplankton, and the decomposition of organic material and release of nutrients from reservoir sediments, may alter thermal regimes, nutrient availability, and concentrations of dissolved oxygen in downstream reaches. In September, for example, water released from the reservoirs increased water temperatures in the Oak Grove Fork and in the Clackamas River, as previously indicated. Longitudinal temperature measurements collected in August 1997 showed that warming in North Fork Reservoir largely occurred in the uppermost reaches of the reservoir, where streambed material transported from upstream has created a shallow reach that is ideal for warming.

The reservoirs also provide a favorable habitat for planktonic blue-green algae to develop, sometimes to bloom proportions that occasionally produce taste and odor problems in drinking water supplies. The highest surface chlorophyll *a* concentrations in Timothy Lake and North Fork Reservoir (18 µg/L in July and 24 µg/L in September 1996, respectively) occurred during blooms of blue-green algae (*Anabaena* spp.). Although these instantaneous values indicate a possible exceedance of the State Action Level for nuisance phytoplankton growth (15 µg/L chlorophyll *a*, based on a 3-month average) in 1996, chlorophyll *a* values were much lower in the reservoirs in 1997 and 1998, typically less than 8 µg/L.

At times, algal blooms appeared to affect levels of nutrients, dissolved oxygen, and pH in the reservoirs and in downstream reaches. Phytoplankton growth in North Fork Reservoir and the settling of algal cells appeared to lower phosphorus concentrations downstream from the reservoir. Downstream from Timothy Lake, however, an increase in the phosphorus concentration was observed in September, possibly due to the release of phosphorus from the reservoir's anoxic hypolimnion.

The nitrogen fixed by blue-green algae, and other nutrients from organic materials that collect in the reservoirs, may be transported to the reservoir sediments. Here, they can be recycled into dissolved inorganic nutrients and transported downstream, thus providing a source of nutrients to algae in downstream reaches. As noted earlier, excessive growths of algae were observed immediately downstream from each of the hydroelectric project reservoirs during this study. Other factors, including power peaking, which often produces daily fluctuations in water levels downstream from the projects, also may stimulate algal growth in downstream reaches through mechanisms hypothesized in this report.

Numerous hypotheses to explain the occurrence of **blue-green algae blooms** in the reservoirs were explored in this report. The low concentrations of nitrogen that were typically found in the reservoirs provide an advantage to algae that are capable of fixing nitrogen, such as *Anabaena*. The positive correlation between chlorophyll *a* and total phosphorus suggests that phosphorus availability may regulate blue-green algal growth in the reservoirs. In August 1997, concentrations of chlorophyll *a* and soluble reactive phosphorus were higher in the upstream reaches of North Fork Reservoir compared with those near the dam, indicating that the blooms were forming near the inlet, again suggesting the importance of phosphorus in regulating algal biomass.

Meteorological factors, such as rainstorms or mixing events caused by wind also may contribute to algal blooms. The September 1994 algae bloom in North Fork Reservoir, which coincided with taste and odor problems in drinking water, occurred about 5 days after a 0.85-inch rainstorm in the basin. The September 1996 bloom of *Anabaena* in North Fork Reservoir occurred shortly after fall turnover, when reservoir bottom water mixes to the surface. These events may have transported phosphorus to the surface, where an existing algal population was stimulated into a bloom during subsequent sunny weather.

Potential Management Strategies to Improve Conditions

Nutrient **management strategies** aimed at reducing the effects of eutrophication often target the nutrient that is in shortest supply (relative to demand) and thus limits further algal growth. Multiple lines of evidence presented in this report suggest that algal growth in many of the streams in the Clackamas Basin, including the main-stem Clackamas River, is regulated by nitrogen. If this is the case, reductions in nitrogen through management strategies could ultimately reduce algal growth in the river. Phytoplankton growth in the reservoirs, however, appears to be regulated by phosphorus, both nitrogen and phosphorus, or by the amount of time available for growth, which is dictated by the flushing rate of the reservoirs (particularly North Fork Reservoir). Future studies suggested in this report could more definitively test which nutrient(s) are regulating algal growth in the streams and reservoirs, which could help prioritize future nutrient management strategies and restoration efforts in the basin.

Many of the strategies suggested in this report to reduce the effects of nutrient enrichment, such as restoring riparian vegetation and reducing erosion through storm-water management, also may help alleviate other water-quality problems in the basin, such as high levels of turbidity or high water temperatures. Other strategies specifically aimed at nutrients include fertilizer-use education and removal of invasive nitrogen-fixing plants. Habitat restoration efforts include enhancing the natural functions of riparian zones and wetlands, as well as increasing stream complexity.

Management strategies aimed at reducing the frequency or severity of blue-green algae blooms in the reservoirs include erosion control to lower phosphorus concentrations, which were positively correlated with algal biomass in the reservoirs. The severity and frequency of algal blooms in North Fork Reservoir might be reduced through dilution by releasing water from Timothy Lake, depending on the water quality in Timothy Lake at the time. Management strategies aimed at reducing concentrations of disinfection by-products in drinking water could include watershed restoration efforts that reduce algal growth in the basin (nutrient reduction strategies and stream vegetation enhancements), thereby reducing the amount of organic matter in raw water. Additionally, mechanical modifications to drinking water treatment plants, including prefiltration of raw water to reduce levels of organic material prior to chlorination, also may reduce concentrations of disinfection by-products.

Potential Future Studies

This study documented current baseline water-quality and algal conditions in streams and reservoirs, generated hypotheses to explain the observed patterns in conditions, and evaluated management strategies that might improve conditions. Additional monitoring could further define water-quality and algal conditions in the basin, thereby providing a benchmark against which future studies may be compared. Also, detailed watershed assessments that examine the interactions between land use, habitat, and water quality could help further our understanding of how human activities affect water-quality and algal conditions in areas where water-quality problems were identified in this study. Focused studies could then lead to the development and implementation of management strategies aimed at improving conditions.

Routine monitoring could help detect changes in water quality and provide information on year-to-year variability necessary for identifying trends in water quality over time and for determining compliance with water-quality standards. Although the Oregon Department of Environmental Quality collects water-quality data from four main-stem Clackamas River sites about six times per year, sampling of algal biomass or species composition is not included and no data are collected from tributaries. Other agencies, such as Clackamas County Water Environment Services, have collected some water-quality data from some of the lower basin tributaries, but no comprehensive analysis of all data has been conducted. Routine monitoring of nutrients, contaminants, and streamflow in the lower-basin tributaries is needed to identify how these streams affect water quality in the main-stem Clackamas River. The highest nutrient concentrations were observed in the lower-basin tributaries, and future restoration efforts or changes in land-use practices in these subbasins could be quantified through routine monitoring.

Focused studies aimed at identifying factors that contribute to or limit algal growth, and determining to what extent algal growth is affecting water quality, habitat conditions, and drinking water supplies could lead to the development and implementation of management strategies to improve conditions. Determining which factors (nutrients and/or light availability) are limiting algal growth in the Clackamas River, tributaries, and reservoirs could be accomplished by nutrient-addition experiments. Once limiting nutrients are identified, nutrient-reduction strategies can be prioritized.

Evaluating nutrient sources in the basin, including point sources (wastewater treatment plants, fish hatcheries, and reservoirs) and non-point sources (runoff from land surfaces, phosphate rock deposits, ground water, and atmospheric deposition) could help in the development of management strategies. Identifying nitrogen and phosphorus inputs from land-use activities (agriculture, urban development, and forest management) could benefit from up-to-date, small-scale, and field-verified information on the amount, condition, and distribution of land cover, crop types, and vegetation classes, along with other variables such as population density, road density, and areas or distribution of impervious surfaces.

Additional studies that identify the sources of organic matter, including algae, could help reduce concentrations of toxic disinfection by-products in treated drinking water. Further, testing for the presence of algal toxins, which are sometimes produced by blue-green algae including *Anabaena* and *Microcystis*, which were found in the reservoirs, could identify whether this is an issue in the Clackamas Basin. Also, evaluating whether the tidal effect in the lower Clackamas River causes water from the Willamette River to reach drinking-water treatment plant intakes may help managers ensure that only high-quality raw water is withdrawn from the river. Lastly, evaluating the potential effects of fluctuating water levels on aquatic biota (algae and macroinvertebrates), caused by hydroelectric project operations, also may result in opportunities for improving conditions.

Despite the episodes of poor water quality that were occasionally observed in the Clackamas River, tributaries, and reservoirs during this study, the Clackamas River remains one of the highest quality streams in Oregon, and runs of wild salmon, steelhead, and trout can still be found in its waters. However, if the river is to continue to support other designated beneficial uses, such as providing high-quality drinking water, efforts are needed to reduce nutrient enrichment and restore natural processes in order to reverse the symptoms of eutrophication that are beginning to appear. Restoration efforts and future studies proposed here should result in improvements over time, thus improving habitat and water quality in the Clackamas Basin.

INTRODUCTION

> *"I have been on all rivers and tributaries of the Columbia from the Cascades to Priest's Rapids, to which the Chinook salmon go…and I do not hesitate to say that the Clackamas River, with its clear, cold water, its rapids, and its long, shallow gravel beds, is the most natural and favorite region for salmon spawning (L.T. Barin, 1885 [in Taylor, 1999])."*

The Clackamas River in northwestern Oregon is valued for its scenic beauty, recreational opportunities, salmon and steelhead runs, and for providing a high-quality source of drinking water. From its headwaters in the Cascade Range between Mount Hood and Mount Jefferson, the upper Clackamas River descends 7,200 feet on a northwesterly course, winding through steep canyons and gorges and cutting through prominent basalt outcrops and cliffs. The many falls and rapids, separated by deep, clear pools and expansive cobble bars, make the upper Clackamas River a favorite among whitewater enthusiasts, anglers, and hikers. Downstream from Estacada, the river emerges into gentler terrain, forming a broad floodplain that is confined by steep cliffs that form upland terraces in places. Here, the lower Clackamas River is wider, flowing past volcanic buttes in the lower basin before meeting the Willamette River south of Portland.

From the high mountainous areas to the low valleys, the landscape of the Clackamas Basin is diverse, featuring five ecoregions, each with its own unique combination of climate, geology, soils, and vegetation that shape the various hydrologic and chemical factors that influence water quality. Human activities in the basin, including timber harvesting, construction of roads and urban developments, farming, gravel mining, and hydroelectric power generation also may affect water quality. The largest inputs of contaminants introduced by human development occur in the lower basin, particularly on the north side of the Clackamas River, where agricultural and urban land is concentrated (fig. 1). Water-quality problems, such as high levels of turbidity, also occasionally occur from soil erosion, particularly in the upper basin, where steep topography and geologic instability, combined with abundant winter precipitation, contribute to erosion during periods of heavy runoff.

The Clackamas River Basin encompasses 940 square miles of public and private forestland, agricultural land, rural residential areas, and urban developments. Most (69%) of the land in the basin is managed by the U.S. Forest Service, mostly within the Mount Hood National Forest. Twenty percent of the basin is privately owned, with 5% belonging to private timber companies. The Confederated Tribes of the Warm Springs Indian Reservation, the U.S. Bureau of Land Management, and other agencies own the remaining area (Metro, 1997). Extensive timber harvesting of Douglas fir, Pacific silver fir, and western red cedar has occurred on public and private commercial forestland in the basin, although most (51%) of the basin is mature forest, 22% is regrowth forest, and 19% is nonforested upland (fig. 1).

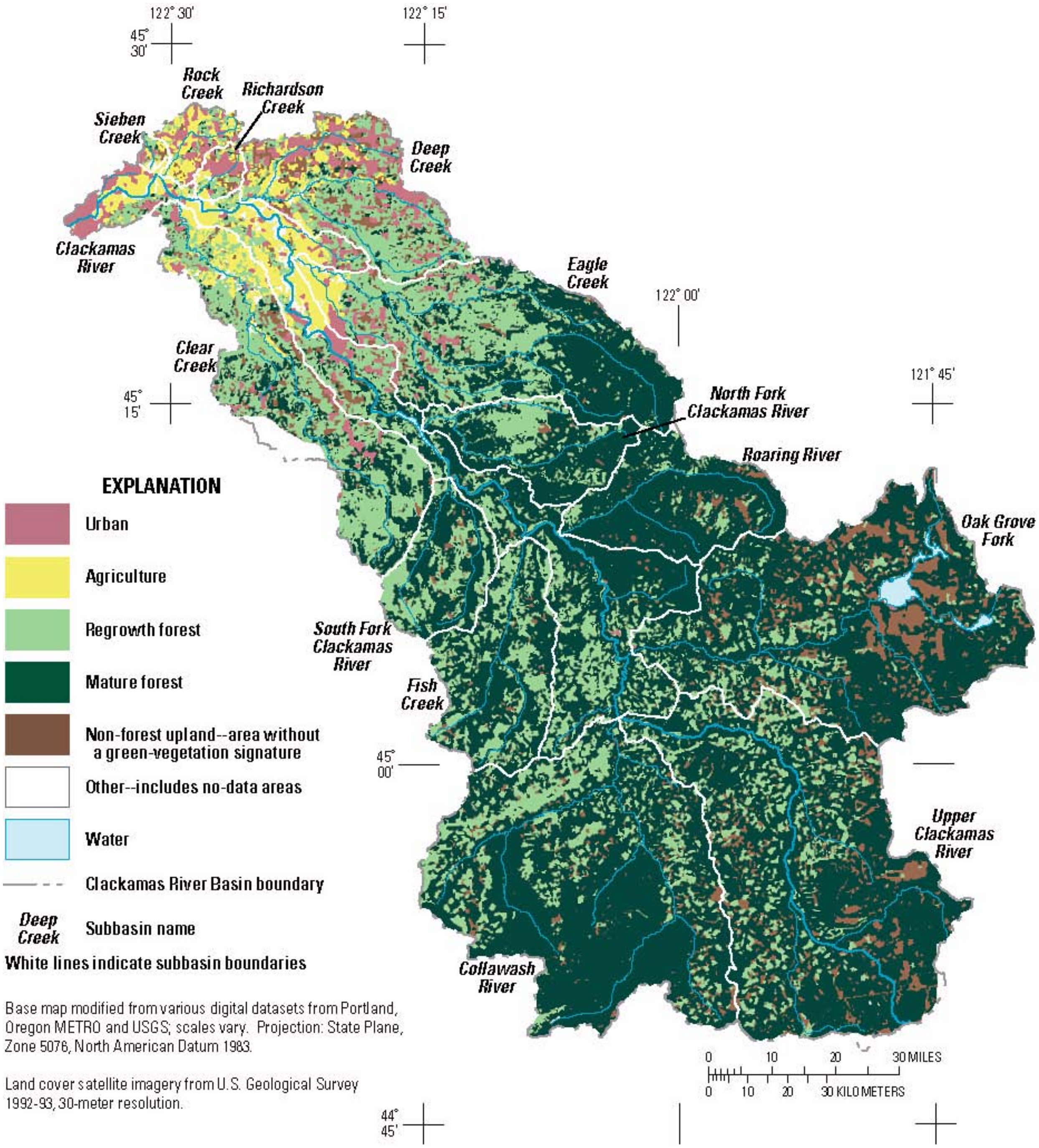

Figure 1. Land-cover map of the Clackamas River Basin, Oregon, 1992–93 (Refer to table 4 for land-cover descriptions).

About one-third of the privately owned land is used for agricultural crops, including Christmas trees, landscaping plants and ornamentals, cane berries, hay, hazelnuts, oats, wheat, vegetables, and fruits (Hassanein and Peters, 1998). Industries in the basin include food processing plants, aggregate gravel mining operations, metal foundry companies, and others, mostly in the lower portion of the basin. Residential developments in the basin range from small rural homes to densely populated urban areas.

Study Background and Objectives

Water quality in the Clackamas River is considered very good to excellent compared to other rivers in the State, based on the Oregon Water Quality Index (Greg Petit, Oregon Department of Environmental Quality, written commun., 1998), and has withstood pressures from human impacts and natural disturbances seemingly well. In September 1994, however, foul tastes and odors appeared in drinking water supplied by the Clackamas River. A survey of the watershed for a potential cause of this problem indicated that an algal bloom had developed in North Fork Reservoir (Bruce Hemenway, South Fork Water Board, oral commun., 1998). Water samples collected from the reservoir contained *Anabaena*, a blue-green alga that is notorious for causing taste and odor problems in drinking-water supplies (Terrell and Perfetti, 1989). Chemical analysis of the raw and treated drinking water identified geosmin (Gordon McGhee, Clackamas River Water, written commun., 1999), a taste and odor compound that is produced by many blue-green algae (Safferman, 1967; Izaguirre and others, 1982) and certain actinomycete bacteria (des Eaux, 1987).

Nuisance blooms of blue-green algae are fueled by excess nutrients, and their presence may be an indication that eutrophication, the process of nutrient enrichment, is occurring. Other signs of eutrophication, such as large growths of algae, also have been observed in the Clackamas River and some of its tributaries. During the spring of 1996, moderate-to-heavy growths of green algae were observed in the upper Clackamas River and some of its tributaries, including Fish Creek and the Oak Grove Fork.

Although algae can be an important food resource for stream invertebrates, contributing to food webs, excessive growths of algae can stress fish and other aquatic life by causing low levels of dissolved oxygen (DO) and high pH and smothering stream channels. Further, when large proliferations of algae senesce and decay, they often lead to episodes of poor water quality, making the water turbid as algae are transported downstream during die-off (sloughing) events.

In addition to nutrient overenrichment, another potential cause of excessive algal growth, particularly in the lower Clackamas River, is high water temperatures. The lower Clackamas River has experienced high water temperatures for at least 15 years, and the Oregon Department of Environmental Quality currently lists the lower 23 miles of the river (from River Mill Dam to the mouth) on the 303 (d) list of water bodies considered water-quality limited because of persistent high water temperatures during summer (Oregon Department of Environmental Quality, 2000). Additionally, the Oregon Department of Environmental Quality has recently listed the lower 15 miles for *E. coli* bacteria (Oregon Department of Environmental Quality, 2002).

Although some water-quality data have been collected in the Clackamas Basin, studies of basic water quality relating tributary conditions to those in the main stem have been lacking. To fill this data gap, the U.S. Geological Survey (USGS), in cooperation with the Clackamas River Water Providers, U.S. Forest Service, Portland General Electric, Clackamas River Basin Council, Clackamas County Department of Water Environment Services, and the Oregon Department of Transportation, began a study to examine and document the current baseline water-quality and algal conditions in the Clackamas Basin. The objectives of the study were to:

1. Characterize spatial and temporal variations in streamflow, water quality (nutrients, DO, pH, water temperature and conductance), and algal conditions (algal biomass and species composition) in the major streams and reservoirs;
2. Monitor for the occurrence of algal blooms in the reservoirs and attempt, if possible, to identify potential triggers for such blooms;
3. Characterize nutrient concentrations in ground water and estimate potential ground-water discharges to the main-stem Clackamas River;
4. Examine relations between water-quality and algal conditions with respect to land and water management (forestry, urbanization, agriculture, hydroelectric power generation, and the drawdown of Timothy Lake), and evaluate possible management scenarios that might improve conditions.

Overview of the Clackamas River Basin

For purposes of this report, the Clackamas River Basin as a whole was partitioned into three regions having different basin characteristics: (1) the mostly forested upper basin, (2) the middle basin, which generally corresponds to the Western Cascades Lowlands and Valleys Ecoregion (Metro, 1997), and (3) the lower basin, where most of the human development is located (figs. 1 and 2).

Upper and Middle Clackamas River Basin—The upper and middle Clackamas Basin hosts several large tributaries, including the Collawash River, Oak Grove Fork, Roaring River, and Fish Creek, whose watersheds are within the Mount Hood National Forest. The U.S. Forest Service manages about two-thirds of this area, primarily for timber production (Metro, 1997), and a dense network of logging roads traverses the upper basin (U.S. Forest Service, 1995c). The North and South Forks of the Clackamas River and the upper portions of Eagle and Clear Creeks are in the middle basin, where much of the private timberland is located (figs. 1 and 2). Streamflow regulation in this area occurs in the main-stem Clackamas River from the Oak Grove Powerhouse (at river mile [RM] 47.8) downstream to North Fork Reservoir (at RM 33.5) and within the 11-mile hydroelectric project on the main stem.

The Clackamas River from Big Springs (near the headwaters at Olallie Butte) to Big Cliff (about 1 mile upstream of North Fork Reservoir) and about 14 miles of the Roaring River were designated Wild and Scenic in 1988. State Scenic Waterways in the basin include 12 miles of the North Fork Clackamas River and 4 miles of the South Fork Clackamas River. There are two federally designated wilderness areas, both within the Mount Hood National Forest: The Bull-of-the-Woods Wilderness Area encompasses 34,900 acres in the Collawash River Basin, and the Salmon-Huckleberry Wilderness Area in the headwaters of Eagle Creek contains 44,600 acres. The Roaring River watershed, another large parcel of land (27,500 acres), also is largely unmanaged compared with nearby watersheds (U.S. Forest Service, 1996c).

Oak Grove Fork Basin and Hydroelectric Project Area—The Oak Grove Fork of the Clackamas River is located in the northeastern, high-elevation portion of the Clackamas River Basin (fig. 2). Most of the land in the basin is managed by the U.S. Forest Service and the Confederated Tribes of the Warm Springs Indians (Metro, 1997). Timothy Lake, a popular recreation destination in the summer, is located near the headwaters of the Oak Grove Fork and is the largest reservoir in the Clackamas River Basin, holding 70,000 acre-feet of water (table 1). Timothy Lake was completed in 1956, when Timothy Meadows, a wetland area once grazed by sheep (Johnson and others, 1985), was flooded to form the reservoir. Grazing allotments for cattle still exist in the Timothy Lake basin, with about 100 cow-calf pairs grazing the area in 1995 (U.S. Forest Service, 1996b).

Water levels in Timothy Lake are typically held constant during the summer and lowered in September during the annual drawdown, which provides enhanced flow for power generation and provides storage capacity for spring snowmelt. Water released from Timothy Lake flows down the Oak Grove Fork to the Stone Creek diversion, where most of the water is diverted out of the channel through a pipe, returning through a downstream powerhouse (fig. 2). Downstream, the Oak Grove Fork is again diverted at Harriet Lake, where, under normal streamflow conditions, all of the streamflow is routed to Frog Lake, a small forebay for the Oak Grove Powerhouse located 925 vertical feet below on the main-stem Clackamas River. The USGS operates a streamflow gage in the Clackamas River upstream of Three Lynx Creek, about 0.2 miles downstream from the Oak Grove Powerhouse (fig. 2).

North Fork, Faraday, and River Mill Hydroelectric Project Area—Near the downstream boundary of the Mount Hood National Forest, the Clackamas River enters North Fork Reservoir (fig. 2), the second largest reservoir in the Clackamas Basin (table 1). High streamflows in the Clackamas River typically flush through North Fork Reservoir quickly, producing a relatively short residence time of about 1 week, on average (table 1). As will be discussed later, longer residence times may result during summer, when solar heating produces a warmer surface layer above the colder and denser bottom water. The deep-water release depth of 130 feet may entrain this colder water, thus reinforcing thermal stratification in the reservoir.

Downstream of North Fork Dam the Clackamas River, minus about 100 ft^3/s (cubic feet per second), is diverted to Faraday Forebay by the Faraday Diversion Dam. After passing through the powerhouses at Faraday, water is routed back to the natural channel and into Estacada Lake, a small reservoir formed by River Mill Dam near the town of Estacada (fig. 2). The USGS operates a streamflow gage in the lower Clackamas River 0.25 miles downstream from the dam at RM 23.3. The Clackamas River is free flowing from River Mill Dam to its confluence with the Willamette River.

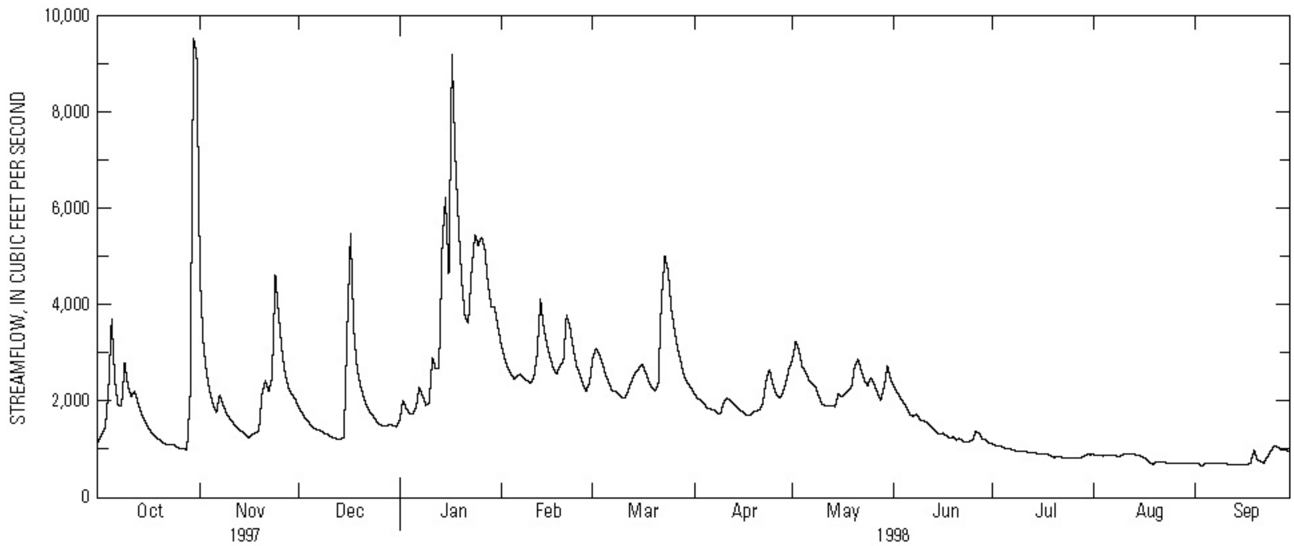

Figure 3. Daily mean streamflow values for the upper Clackamas River above Three Lynx Creek, U.S. Geological Survey gaging station 14209500, water year 1998.

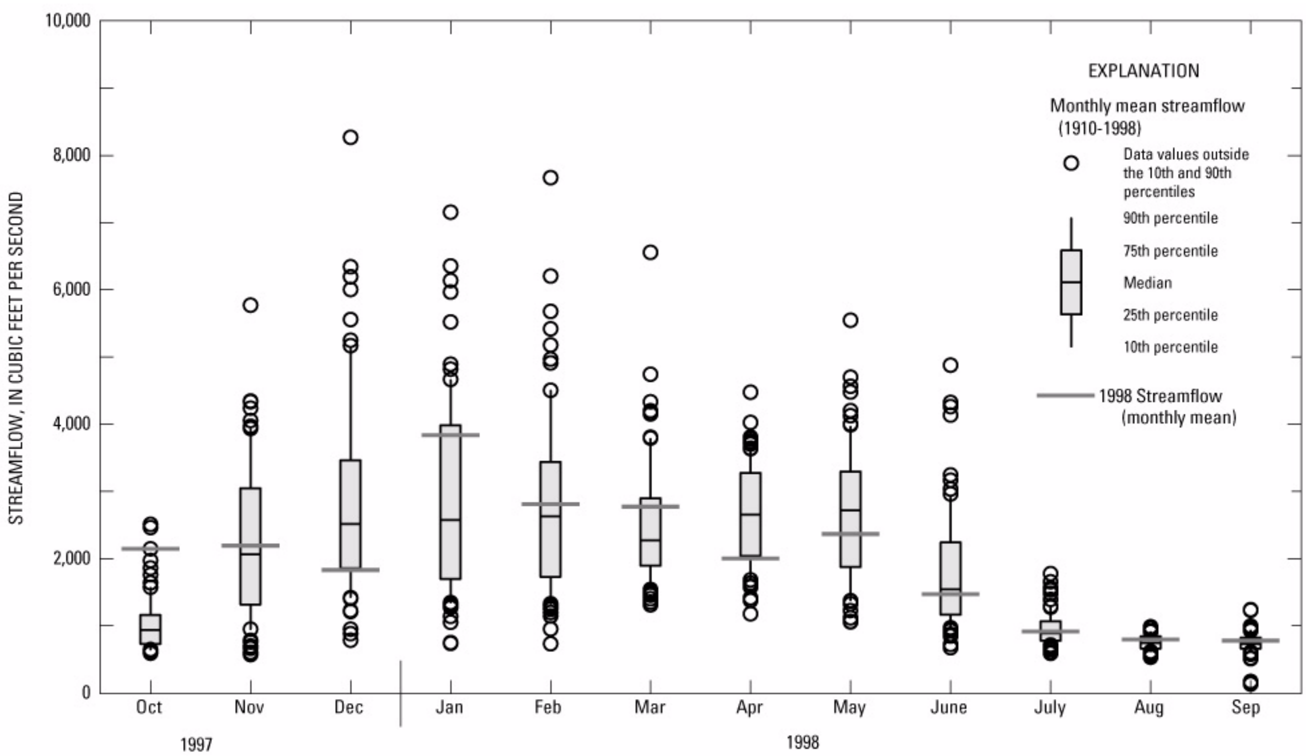

Figure 4. Comparison of water year 1998 streamflow with long-term values in the upper Clackamas River above Three Lynx Creek, U.S. Geological Survey gaging station 14209500.

Table 1. Characteristics of the hydroelectric projects in the Clackamas River Basin, Oregon

[Data source: Bob Steele, Portland General Electric, written commun., 1999; nd, no data; <, less than; mi^2, square miles; >, more than; e, estimated; ft^3/s, cubic feet per second; na, not applicable; ~, approximately]

Characteristic	Hydroelectric Project							
	Oak Grove Fork				Main-stem Clackamas River			
	Timothy Lake	Stone Creek Diversion Dam	Harriet Lake	Frog Lake/ Oak Grove Powerhouse	North Fork Reservoir	Faraday Diversion Dam	Faraday Forebay	River Mill Forebay (Estacada Lake)
Normal pool surface area (acres)	1,430	nd	22	6	375	70	50	150
Normal pool volume (acre-feet)	69,000	nd	400	228	18,630	550	175	2,600
Normal pool elevation (feet)	3,229	nd	2,030	1,981	665	526	520	389
Maximum depth (feet)	100	<10	30	31	140	40	40	80 (25[a])
Water release depth (feet)	70	surface	surface	27	130	surface	37	25
Drainage area (mi^2)	54	>70e	131	131	665	665	665	671
Dam height (feet)	110	10	80	70	206	10	nd	85
Discharge capacity (ft^3/s)	500	250	565	680	5,300	5,500	5,500	4,600
Instream flows downstream (ft^3/s)	10–300	nd	0	na	nd	100	nd	nd
Average residence time[b]	~8.5 months	< 1 hour	0.4 days	nd	7.3 days	5 hours	1.6 hours	1 day

[a] Average depth.
[b] Calculated as normal pool volume/average inflow from USGS (U.S. Geological Survey) flow data (1998).

Lower Clackamas River Basin—Downstream of Estacada, the Clackamas River widens and the channel gradient eases. The lower basin contains a predominantly alluvial valley, where the river flows through a broad floodplain of coarse material, much of which is mined for rock and gravel (Metro, 1997). Steep cliffs constrain the floodplain, and much of the Christmas tree and commercial tree plantations, agriculture, and rural residential areas are located on plateaus and terraces well above the floodplain. With few exceptions, the land in this area is in private ownership. The Clackamas River is designated as a State Scenic Waterway from its headwaters to Carver (excluding the hydroelectric projects on the main stem). Downstream from Carver, the landscape becomes more urban, and industrial development is conspicuous, particularly on the northern side of the river. Thirteen major and 35 minor National Pollution Discharge Elimination System permits have been issued in the Clackamas River Basin, most of which are for direct or indirect discharges to the lower river (Oregon Department of Environmental Quality Web site, http://www.deq.state.or.us/wq/SISData/FacilityHome.asp, accessed 3/20/2000). Permittees include wastewater treatment plants (WWTPs), fish hatcheries, sand and gravel operations, mobile home parks, meat processing plants, golf courses, and metal foundry companies, and there are two permitted toxic release sites in this part of the basin (Metro, 1997). Several major drinking-water intakes, which supply about 225,000 customers with drinking water (Gordon McGhee, Clackamas River Water, written commun., 2000) are located along the lower Clackamas River. The Clackamas River joins the Willamette River near the cities of Gladstone and Oregon City, south of Portland.

The larger tributaries in the northern part of the lower Clackamas Basin include Deep, Rock, Richardson, and Sieben Creeks, which emerge from upland buttes in the geologic formation known as the Boring Lava. These watersheds contain steep slopes in the headwaters, which give way to more gently graded, open valleys, where soils consist of silt loams and hydric clays that have poor-to-moderate drainage. Wetlands occur in many areas, and early settlers drained much of the land for farming with slotted pipes or tile drains (Ecotrust, 2000). Permeable deposits of cobble and gravel occur under the soil layers in some areas (KCM, Inc., 1995), and aquifers are tapped for domestic water supply and irrigation, particularly in the northern portion of the lower Clackamas Basin (Leonard and Collins, 1983).

METHODS

Sampling Activities

Data collection occurred primarily from March through September 1998, although some reconnaissance nutrient and/or algal data were collected from select streams and reservoirs in 1996 and 1997, and ground water was sampled in January 1999 (table 2).

Table 2. Data-collection activities in the Clackamas River Basin, Oregon, 1996–99

[Bullets indicate type, location, month, and year of data collection]

	1996			1997				1998							1999
Basic monitoring	**June**	**July**	**Sep**	**May**	**July**	**Aug**	**Sep**	**Mar**	**April**	**May**	**June**	**July**	**Aug**	**Sep**	**Jan**
North Fork Reservoir sampling		•	•		•	•	•	•	•	•	•	•	•	•	
Timothy Lake sampling		•		•	•	•				•	•	•	•	•	
Stream sampling	•		•			•				•		•		•	
Ground water sampling									•						•
Event sampling															
Periphyton sloughing event											•				
Diurnal surveys of field parameters											•	•	•		
Timothy Lake drawdown sampling														•	

Specific sampling activities are described in the following paragraphs, and sampling site information, along with information about samples collected at each site, is listed in table 3 and shown on plate 1.

Stream sampling—The primary stream sampling sites included eight main-stem sites located from RM 57 to RM 0.3, the Oak Grove Fork below Timothy Lake and the Collawash, Roaring, and North Fork Clackamas Rivers. Primary stream sites were sampled in May, July, and September 1998 (table 2, table 3, and plate 1). Thirteen additional sites were sampled in July 1998, increasing the total number of stream sites to 24, expanding the spatial coverage of sites to include sites in basins draining wilderness areas, private and public forestland, and agricultural and urban land. Sites in the hydroelectric projects included stations immediately downstream from both powerhouses and dams (plate 1 and fig. 2). To obtain a snapshot of conditions in July, the eight main-stem sites were sampled synoptically within 1–2 days, and all sites were sampled within 9 days of each other. Stream discharge and field parameters (water temperature, pH, DO, and specific conductance [SC—the electrical conductivity of water at 25°C {degrees Celsius}]) were measured at each site, and samples were collected for nutrients, algal species composition, and algal biomass (table 3). Algal biomass was estimated using chlorophyll *a* (chl *a*) and ash-free dry mass (AFDM—the amount of organic matter, commonly used as a measure of standing crop [Welch and others, 1988, 1989]).

Additional samplings were conducted to investigate potential nutrient sources or biological processes, such as nutrient uptake. These are described in the results section with their associated data. In April 1998, one effluent sample was collected from the Eagle Creek National Fish Hatchery, and samples were collected from Eagle Creek upstream and downstream of the fish hatchery for soluble reactive phosphorus (SRP) and nitrite-plus-nitrate ($NO_2^- + NO_3^-$) analyses. In September 1998, three nutrient samples were collected from the upper Clackamas River at Highway 224 milepost 37 (RM 38.3) to examine whether higher nearshore nutrient concentrations might be stimulating algal growth along the stream margins where abundant green algae was observed. Samples were collected at the water's edge, 15 feet from shore in deeper water, and 30 feet from shore in the main current.

Periphyton sloughing event—In June 1998, a synoptic sampling for drifting algae and nutrients was conducted in the lower Clackamas River after decaying clumps of filamentous green algae (*Cladophora* and *Stigeoclonium*) became detached from the riverbed downstream of Barton. The drifting algae clogged drinking-water intakes (Gordon McGhee, Clackamas River Water, oral commun., 1998), made the river turbid, and prompted complaints from anglers, boaters, and residents that live on the river (Robert Baumgartner, Oregon Department of Environmental Quality, oral commun., 1998).

Diurnal field parameters—In July and August 1998, diel measurements of DO and pH were made during the morning (5–8 a.m.) and late afternoon (3–6 p.m.) at selected sites to determine whether cycles in algal productivity were affecting DO and pH levels.

Timothy Lake drawdown—To examine potential changes in downstream water quality resulting from the annual September drawdown of Timothy Lake, water samples were collected before and during reservoir drawdown. Samples were collected from two sites on the Oak Grove Fork (near Government Camp [RM 15.5] and upstream of the powerplant intake [RM 6.1]), and one site on the main-stem Clackamas River (at the USGS gage above Three Lynx Creek [RM 47.8]) and analyzed for nutrients, organic carbon, and algal abundance and species composition. Of particular interest was determining whether *Anabaena* cells are transported from Timothy Lake to downstream reservoirs.

Reservoir sampling—Reservoir sampling began in July 1996 and continued each summer through 1998 (table 2). Depth profiles of field parameters (water temperature, DO, pH, and SC) and light were measured in the water column at discrete intervals from the deepest accessible location in each reservoir along the log boom. Two additional sites were sampled in North Fork Reservoir: approximately 1.8 miles upstream from North Fork Dam (station 2) and in North Fork Bay north of Highway 224 (table 3 and plate 1). Water samples were collected for dissolved and total nutrients, chl *a*, phytoplankton abundance, and phytoplankton species composition from the epilimnion (about 1 foot depth), the metalimnion (in the thermocline), and the hypolimnion (3 feet off the bottom). An additional sample was collected from the log boom from the depth of water release.

Ground-water sampling—Three ground-water wells (depths ranging from 80 to 103 feet) and three springs located between Estacada and Carver along cliffs within 1 mile of the Clackamas River were sampled in January 1999 for nutrients, major ions, arsenic (only in wells used for drinking water), and field parameters. Two springs located in the Eagle Creek Basin upstream of the fish hatchery also were sampled for nutrients in April 1998.

Data Collection

Water

Stream and reservoir water sample collection and processing—Clean techniques described by Horowitz and others (1994) were used for collection and processing of nutrients and major ion samples. Water samples were collected from stream sites (table 3) using the Equal-Width Increment method, where the entire cross section is sampled using a depth-integrating sampler (Edwards and Glysson, 1999). Grab samples were collected in the tailwaters of North Fork Dam, where the river was well-mixed. Water samples collected from streams were composited and homogenized in a churn splitter before dispensing total phosphorus (TP) and total Kjeldahl nitrogen (TKN—the sum of ammonia plus digested organic N) samples. Samples for dissolved nutrients were pumped from the churn using a peristaltic pump and filtered through Gelman 0.45-µm (micrometer) pore-size filtration capsules.

Water samples were collected from the reservoirs using a 2.5-liter Van Dorn sampler. Unfiltered samples were collected directly from the Van Dorn sampler, whereas samples for dissolved nutrients were processed using the same methods as for stream samples. Water samples for dissolved and total nutrients were chilled on ice (unpreserved) and shipped within 24 hours to the USGS National Water Quality Laboratory (NWQL) in Arvada, Colorado, where they were kept at 4°C until analysis.

Samples for suspended organic carbon (SOC) and dissolved organic carbon (DOC) were collected into 1-quart, baked glass jars using a USGS DH-76 bronze sampler (Edwards and Glysson, 1999) with a 1/4-inch-diameter plastic nozzle. SOC samples were processed by filtering 50 mL (milliliters) of sample through a 0.45-µm pore-size silver filter in a stainless-steel column pressurized with nitrogen gas (N_2). DOC samples were collected from the same column into 125-mL baked amber glass bottles.

Ground-water sampling—Samples were collected from domestic wells for dissolved and total nutrients, major ions, and arsenic following standard protocols (Wilde and others, 1998). Water samples collected from springs were analyzed for dissolved and total nutrients and major ions only.

Field-parameter measurements—Instantaneous measures of water temperature, DO, pH, and SC were made at stream sites using a Hydrolab Datasonde 3 multiparameter probe adapted for low ionic-strength waters. Depth profiles of field parameters were measured in the reservoirs from the surface to the bottom.

Hydrolab calibrations were performed according to the manufacturer's specifications and included daily morning calibrations for DO, pH, and SC, plus additional DO calibrations at each site. Continuous measurements (15-minute intervals) of field parameters were made in the Clackamas River at RM 2.7 downstream from Cow Creek for a period of approximately 24 hours on four occasions. Field parameters in ground water were measured using individual DO, pH, and SC probes housed in a flow-through chamber.

Streamflow measurements—The USGS operates five continuous-record gaging stations in the basin (plate 1 and fig. 2). Discharge records for these stations were compiled according to methods described by Buchanan and Somers (1984) and Kennedy (1983) and are published in Hubbard and others (1999). Streamflow was measured at all ungaged sites using standard USGS methods (Rantz and others, 1982).

Table 3. Sampling sites and data-collection activities in the Clackamas River Basin, Oregon 1996–99

[no., number; RM, river mile; USGS site ID, site identification number permanently assigned by the USGS (U.S. Geological Survey) and recorded in the National Water Information System (NWIS); --, not applicable; X, field parameters or streamflow measured; N, nutrients; na, not analyzed; Hwy, highway; E, east; P, periphyton; G, gaged; S, suspended algae; C, organic carbon; M, major ions]

Site data, in upstream order							Data collection			
Map no. on plate	Clackamas RM	Tributary RM	Elevation (feet[a])	Site codes	Name	USGS site ID	Field parameters	Water samples	Stream-flow	Algae
1	0.1	--	5	--	Clackamas River at Clackamette Park	452221122361200	X	N	na	na
2	0.3	--	5	CR_99E	Clackamas River at Hwy 99E bridge	452223122360100	X	N	X	P
3	1.2	--	15	--	Clackamas River at walking bridge above Hwy 99E bridge	452243122345800	X	na	na	na
4	2.7	--	33	CR_COW	Clackamas River below Cow Creek	452331122340600	X[b]	N	na	na
5	5.8	0.5	155	SIEBEN	Sieben Creek at Hwy 224	452438122311500	X	N	X	P
6	6.4	0.2	95	ROCK	Rock Creek near mouth	452431122303200	X	N	X	P
7	7.9	--	75	CR_CARVER	Clackamas River at Carver	452335122294500	X	N	X	P
8	8.0	0.1	80	CLEAR	Clear Creek near Carver	14210750	X	N	X	P
9	9.1	0.5	125	RICHARDSON	Richardson Creek at Hwy 224	452352122281500	X	N	X	P
10	12.1	0.7	165	DEEP	Deep Creek at Hwy 224	452340122251000	X	N	X	P
11	13.4	--	149	CR_BARTON	Clackamas River near Barton	452255122244500	X	N	X	P
12	16.7	0.4	205	EAGLE_M	Eagle Creek at Bonnie Lure State Park	452105122223200	X	N	X	P
13	--	6.2	505	--	Eagle Creek at Eagle Fern State Park	451928122171600	X	N	na	na
14	--	0.1	505	--	North Fork Eagle Creek near Eagle Fern State Park	451932122171400	X	N	na	na
15	--	17.9	1,500	EAGLE_W	Eagle Creek near wilderness boundary	451755122064300	X	N	X	P
16	18.9	--	220	--	Clackamas River at Feldheimer Ferry	451941122224800	X	N	na	na
17	20.2	--	255	--	Clackamas River at lower McIver Park	451844122224400	X	N	na	na
18	23.1	--	287	CR_MCIVER	Clackamas River at Estacada (upper McIver Park)	14210000	X	N	G	P
19	26.9	--	525	--	Canal above Faraday Lake	451546122182000	X	na	na	na
20	27.1	--	525	--	Canal above Faraday Lake Bridge	451542122180700	X	na	na	na
21	27.7	--	485	--	Fish Ladder below Faraday Diversion Dam	451514122174400	X	na	na	na
22	29.9	--	645	CR_BLNFK	Clackamas River below North Fork Reservoir	451435122164600	X	N	X	P
23	31.2	--	663	NFKRES_1	North Fork Reservoir station 1 at log boom	451438122164000	X	N	--	S
24	31.7	--	663	NFKRES_2	North Fork Reservoir station 2 at powerlines	451345122151100	X	N	--	S
25	31.0	0.1	663	NFKRES_B	North Fork Reservoir at North Fork Bay	451329122150400	X	N	--	S
26	31.5	0.4	660	NFCLACK	North Fork Clackamas River at mouth	451414122144900	X	N	X	P
27	--	0.2	1,240	FALL	Fall Creek near confluence with North Fork Clackamas River	451432122130500	X	N	X	P
28	--	0.3	2,100	WINSLOW	Winslow Creek at U.S. Forest Service Road 4610	451215122085500	X	N	X	P
29	32.6	0.0	660	--	Fry Lake outfall	451318122143300	X	N	na	na

Table 3. Sampling sites and data-collection activities in the Clackamas River Basin, Oregon 1996–99—Continued

[no., number; RM, river mile; USGS site ID, site identification number permanently assigned by the USGS (U.S. Geological Survey) and recorded in the National Water Information System (NWIS); --, not applicable; X, field parameters or streamflow measured; N, nutrients; na, not analyzed; Hwy, highway; E, east; P, periphyton; G, gaged; S, suspended algae; C, organic carbon; M, major ions]

Site data, in upstream order							Data collection			
Map no. on plate	Clackamas RM	Tributary RM	Elevation (feet[a])	Site codes	Name	USGS site ID	Field parameters	Water samples	Stream-flow	Algae
30	33.4	--	663	--	Clackamas River at North Fork Reservoir inflow	451349122135600	X	N	na	na
31	34.5	--	660	--	Clackamas River at Big Cliff	451159122133000	X	na	na	na
32	34.6	0.1	660	SFCLACK	South Fork Clackamas River near mouth	451156122132500	X	N	X	P
33	34.7	--	660	CR_ABNFK	Clackamas River above North Fork Reservoir at powerlines	451151122130200	X	N	X	P
34	35.6	--	700	--	Clackamas River at Memaloose Bridge	451133122123900	X	na	X	na
35	38.3	--	780	--	Clackamas River at mile post 37	451128122101300	X	N	na	na
36	39.4	--	800	--	Clackamas River at Big Eddy	451052122100600	X	N	na	na
37	41.8	--	860	--	Clackamas River at Fish Creek Bridge	450931122110000	X	na	na	na
38	41.7	1.2	940	FISH	Fish Creek near Three Lynx	14209700	X	N	X	P
39	44.0	0.1	980	ROARING	Roaring River near Estacada	14209600	X	N	X	P
40	46.5	0.1	1,340	--	Dinner Creek at Hwy 224	450455122082000	X	N	na	na
41	47.8	--	1,090	CR_3LYNX	Clackamas River above Three Lynx Creek	14209500	X	N/C	G	P/S
42	53.0	0.5	1,380	OAK_RAIN	Oak Grove Fork at Rainbow Picnicground	450448122023000	X	N	X	P
43	--	6.1	2,050	OAK_PP	Oak Grove Fork above powerplant intake	14209000	X	N/C	G	P/S
44	--	15.5	3,040	OAK_BLTLK	Oak Grove Fork near Government Camp	14208700	X	N/C	G	P/S
45	--	15.9	3,227	--	Timothy Lake at log boom	450653121481000	X	N	--	S
46	57.0	--	1,460	CR_UPPER	Upper Clackamas River at Two Rivers Campground	450156122033100	X	N	X	P
47	57.0	1.1	1,500	COLLA	Collawash River near Two Rivers Campground	450119122034800	X	N	X	P
48	9.5	--	--	WELL_1	Well number 1—02S/03E-20BAB2	452319122280701	X	N, M	--	--
49	10.7	--	255	SPRING_1	Spring number 1—02S/03E-21BBB	452317122271101	X	N, M	--	--
50	17.3	--	--	WELL_2	Well number 2—03S/03E-01BAB	452042122230801	X	N, M	--	--
51	17.3	--	265	SPRING_2	Spring number 2—03S/03E-01BAC	452037122231201	X	N, M	--	--
52	20.2	--	--	WELL_3	Well number 3—03S/03E-13AAC	451850122223601	X	N, M	--	--
53	20.2	--	280	SPRING_3	Spring number 3—03S/04E-18BBB	451859122221501	X	N, M	--	--

[a] Elevation is in feet above the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

[b] Continuous data collected on four occasions.

Laboratory analysis—All chemical analyses were performed at the NWQL, with the exception of alkalinity and chl *a*, which were analyzed at the USGS Oregon District Laboratory in Portland, Oregon. Nutrient analyses were performed within 7 days of delivery to the NWQL. Unfiltered water samples were analyzed for TKN and TP using a Jirka modification (Patton and Truitt, 1992). Analysis of organic carbon was performed by the NWQL using the method of Wershaw and others (1987).

Dissolved inorganic nutrients included nitrite-plus-nitrate ($NO_2^- + NO_3^-$), ammonia plus ammonium ($NH_3 + NH_4^+$), soluble reactive phosphorus (SRP), and dissolved silica (SiO_2). Dissolved organic nutrients (filtered, then digested) included total dissolved phosphorus (TDP) and total dissolved Kjeldahl nitrogen (DKN). All nutrient concentrations in this report are reported on an atomic basis (as nitrogen [N] or phosphorus [P]). Nitrite-plus-nitrate ($NO_2^- + NO_3^-$) is referred to simply as NO_3^- because all or nearly all was in the form of nitrate. Ammonia-plus-ammonium ($NH_3 + NH_4^+$) is referred to as NH_4^+ because all or nearly all was present as ammonium. Chemical data were stored in the USGS National Water Information System (NWIS) database and can be accessed at http://waterdata.usgs.gov/or/nwis/qwdata. The minimum laboratory reporting levels (MRL—the smallest measured concentration of a substance that can be reliably measured using a given analytical method) in effect during 1998 are listed in appendix 1.

Algae

Periphyton sampling—Algae samples were collected at 24 stream sites from rock or cobble substrates in wadeable portions of each stream (table 3). For partially wadeable sites, rocks were sampled from stream margins. Representative rocks were removed and sampled using round plastic pipe ends (scribes) with outside diameters of 4, 5.6, 7.9, and 10.4 cm (centimeters). Scribes were placed on each rock, and the algae located outside the scribe was removed with a plastic-bristle brush and/or scraped off with a knife and discarded. The circular patch of algae remaining on the rock was then scraped into a basin, and the sample was rinsed into a sample bottle using stream water. Approximately 1–2 L (liters) of algal material was composited from 5 to 10 rocks from each site. This technique samples a larger area than many published methods (for example, Porter and others, 1993) and thus reduces the variation associated with sampling smaller areas when algal growth is patchy as was often the case. The large variation in the size of the substrate sampled, however, resulted in a large range of total area sampled per site (140 to 2,700 cm^2). The algal slurry was placed on ice and transported to the laboratory, where it was homogenized in an electric blender and transferred to a churn splitter. Subsamples for algal biomass (chl *a* and AFDM) were removed from the churn using a large-orifice pipettor and transferred to a 47-mm (millimeter) glass fiber filter under vacuum pressure using a filtration apparatus. Subsamples for species identification and enumeration (abundance) were dispensed into sample bottles and preserved with a relatively high concentration of buffered formalin (10% final concentration) to aid in preserving the dense collections of periphyton that were sometimes encountered.

Phytoplankton sampling—Phytoplankton samples were collected from multiple depths within the reservoirs using a 2.5-liter Van Dorn sampler, transferred into sample bottles, and preserved with Lugol's solution at a final concentration of 1%. Suspended-algae samples (from stream sites) were processed the same way, but were collected using a USGS DH-76 bronze sampler with a 1/4-inch-diameter nozzle.

Algal biomass—Chl *a* was determined at the Oregon District Laboratory. Glass-fiber filters containing algal material were hand ground using an electric tissue-grinding apparatus with a Teflon pestle and glass mortar containing 10 mL of 90% acetone. This slurry was filtered through 25-mm glass fiber filters and the extracted pigments were analyzed fluorometrically, correcting for the presence of phaeopigments.

AFDM was analyzed gravimetrically according to methods described by the American Public Health Association (1989). Filters for AFDM were dried at 105°C for 24 hours and burned at 500°C for 2 hours. The AFDM was calculated as the difference in filter weights before and after burning (i.e., the weight of the burned [ashless] material).

Algal identification and enumeration—Algal species identifications, numbers, and biovolumes were determined at Bowling Green State University (BGSU), Ohio. Cell density, in number of cells per square centimeter, and cell biovolume, in cubic microns per square centimeter, were determined for each taxon by measuring the cell dimensions of 10 randomly selected individuals for each taxon in each sample. Five hundred algal units (diatoms or soft algae) were counted in a Palmer-Maloney counting chamber and identified to the lowest possible taxonomic level.

A subsample was processed with fuming concentrated nitric acid to create a permanent (Naphrax-mounted) slide of diatoms. Counting chamber diatom identifications were verified by viewing the permanent slide preparations at 1,000× magnification.

Light/Canopy Closure

The potential sunlight availability was measured at stream sites using a Solar Pathfinder. This device measures the panoramic shading at a site, and therefore estimates the potential amount of light (as a percentage of the average total radiation that will fall on a location for a given month and latitude) from the southern sky during cloudless conditions (Platts and others, 1987). Percent canopy closure was obtained by subtracting the percent sunlight available from 100. Light penetration into the reservoirs was measured using a spherical quantum sensor light meter, and water transparency was measured using a 210-mm Secchi disk when water column conditions permitted adequate viewing.

Land Cover

Basin boundaries for each site were digitized from 1:24,000 USGS topographic maps and processed using Arc/Info (ESRI, copyright 1982–2002) geographic information system (GIS). Land cover for each basin was estimated from 30-meter resolution satellite images (Landsat thematic mapper [TM] data) collected for the entire Willamette Basin in June and August 1992 and 1993. The spectrum signatures were interpreted by the USGS EROS Data Center using a clustering statistical program and ancillary data, including slope and elevation. The major land-cover classifications were mature forest, regrowth forest, nonforest upland, agriculture, and urban (table 4).

The nonforest-upland classification (table 4) included areas in mid-to-high elevation areas that did not produce a green vegetation signature. Because most of the watershed is not above timberline, the amount of exposed rock is probably limited. Thus, nonforest-upland areas were interpreted mostly as being previously forested (recently harvested).

Urban areas were defined by a combination of USGS GIRAS (Geographic Information Retrieval and Analysis System) data and 1990 census population data, defined by areas containing 1,000 or more persons per square mile. Based on field observations and discussions with Clackamas County personnel, the amount of urban land in the Sieben Creek watershed, which according to the land-cover data was determined to be about 10% in 1990, was probably higher in 1998. To determine how much higher, a more detailed urban land-cover analysis of the Sieben Creek watershed was performed in 2001 using WES Works, Clackamas County Department of Water Environment Service's GIS analysis system. Urban developments were identified from aerial photographs taken in 2000, and the individual areas were digitized and summed to obtain the percentage of urban land.

Data Quality Control

Quality control (QC) samples consisted of blank water samples to check for nutrient contamination or bias during collection, processing, and/or analysis; standard reference nutrient samples to check laboratory accuracy; replicate nutrient samples to check laboratory precision; triplicate chl *a* and AFDM samples to check laboratory precision; replicate chl *a* and AFDM samples to check field and laboratory variability; triplicate chl *a* samples to check laboratory accuracy by

Table 4. Description of land-cover categories used in the 1992–93 Thematic Mapper (TM) classification system (after Uhrich and Wentz,1999) [see fig. 1]

[GIRAS, Geographic Information Retrieval and Analysis System]

Land-cover category	Description
Mature forest	Represented by the darkest shades of green in the spectral mosaic.
Regrowth forest	Forested areas with open spaces and trees of smaller size than mature forest.
Nonforested upland	Spectral class without a green vegetation signature. Distinguished from valley areas by elevation and slope differences. Includes recent clearcuts, open grassland, nonforested alpine areas, rock outcrops, and barren land.
Agriculture	Fields that were bare ground (nonvegetated) in June and vegetated in August (irrigated agriculture), plus grass seed, hay, and small grain fields, and pastures.
Urban	Area of urban development. Defined by a combination of GIRAS and 1990 Census of Population data. Represents a population density of 1,000 or more persons per square mile.

an independent analyst; replicate algal cell counts to check for laboratory precision; and replicate algal cell counts by an independent analyst to check laboratory variation. Results of the QC data are summarized next. Tables of the QC data for nutrients and algae are in appendix 2 and appendix 3, respectively.

Nutrients in water—Eleven nutrient blank samples were submitted to the NWQL for analysis. Nutrient blank samples were collected and processed similar to the environmental samples: blank water was used to rinse and fill the sample collection equipment (bottle, cap, and nozzle for stream samples, or Van Dorn sampler for reservoir samples), and then passed into a churn splitter, pumped through tubing and filter capsule, collected in a sample bottle, and shipped to the NWQL.

Phosphorus was detected in blank samples more frequently than nitrogen, with four SRP detections at the MRL of 1 µg/L (microgram per liter), four detections of TDP (ranging from 1 to 14 µg/L), and six detections of TP ranging from 1 to 8 µg/L. Blank samples contained no detectable NH_4^+, TKN, or DKN, but one blank contained 8 µg/L of NO_3^- (appendix 2). This sample also contained 14 µg/L TDP, which may indicate a common source of contamination for that sample.

Five standard reference nutrient samples containing known concentrations of NH_4^+, NO_3^-, SRP, TDP, and TP were submitted to the NWQL for analysis at concentrations that were low but reflected ambient concentrations in the river (appendix 2). Results for the TDP and TP samples were all within the method variance, and the SRP values were within the method variance for all but one sample, for which 26 µg/L was reported for a reference sample with an expected concentration of 36 µg/L. Concentrations of dissolved inorganic nitrogen (DIN) in standard reference samples were lower than expected, with a periodic low bias for NH_4^+ and a consistent low bias for NO_3^- of 16–66% (appendix 2).

Eight replicate nutrient samples were submitted to the NWQL to determine laboratory analytical precision. All NO_3^-, DKN, TKN, SRP, TP, and SiO_2 replicate values showed good agreement, and all were within the method variance. TDP concentrations, however, showed occasionally high variability (up to about 100%) in two of the replicate samples (appendix 2). In this report TDP data are not interpreted so this variability does not affect any conclusions. Although most replicate samples had similar NH_4^+ concentrations, one set of samples collected from North Fork Reservoir had replicate NH_4^+ concentrations of 5 and <2 µg/L (appendix 2).

The nutrient quality-assurance data show that, for most constituents, sample processing and analytical variations were small, and instances of sample contamination, when indicated, appeared to be isolated cases. Further, interpretations or conclusions drawn from the nutrient data, with few exceptions, were made when overall patterns in spatial or temporal variation supported those conclusions or when larger differences among sites were found. Exceptions to this are addressed in the results section on a case-by-case basis.

Algal biomass—The mean relative standard deviation (MRSD), the average of all the individual relative standard deviation (RSD) (the standard deviation [SD] for a set of three measurements, normalized by dividing by the mean) for 53 AFDM and 159 chl *a* samples was 4.3% and 3.5%, respectively. Samples containing filamentous green algae had higher MRSDs for chl *a* (maximum of 7.8%) and AFDM (maximum of 8.9%) compared with samples dominated by other algae. The MRSD for phytoplankton chl *a* samples was 8.1% for 49 samples, although the SDs were low, averaging 0.1 µg/L.

To investigate variability in chl *a* and AFDM due to sampling technique, replicate samples were collected in July from two sites dominated by filamentous green algae (the Clackamas River upstream and downstream from North Fork Reservoir) and two sites dominated by diatoms (the Clackamas River at Highway 99E and the South Fork Clackamas River near the mouth). Replicate biomass samples were in general agreement, with the largest differences occurring at sites having greater biomass (appendix 3). The differences may have been caused by the patchy growth of algae or from uneven subsampling from the churn splitter, particularly for samples dominated by filamentous algae.

Algal species composition—To evaluate variation in the identification and enumeration of algal species, five samples were each split into replicate samples with a churn splitter. Replicate algae samples were analyzed at the BGSU Laboratory for both diatoms and soft algae. The percent similarity of replicate samples ranged from 67 to 86% for all species (using relative abundance). Similarities were slightly higher when restricted to diatoms, which ranged from 77 to 85% using relative abundance and 70 to 87% using relative biovolume (appendix 3).

To evaluate interlaboratory variation in algal sample processing, identification, and counting, preserved sample material and permanent slides of diatoms were shipped to an independent laboratory (University of Louisville, Kentucky [ULK]), where soft algae samples were prepared using the same methods as BGSU. Observed differences between the two laboratories could have resulted from inconsistencies in sample processing, species identifications, and/or enumeration (species counts). Analysis of identical diatom slide preparations, which eliminates the sample-processing step, by both laboratories showed differences in both identification and enumeration. The percent similarity between laboratories for these samples ranged from 61 to 71% using relative abundance (appendix 3).

Some of the differences in species identifications were reconciled by consulting the different taxonomic keys used by the two taxonomists. The BGSU Laboratory uses the taxonomy adopted by the Philadelphia Academy of Natural Sciences (Patrick and Reimer, 1966, 1975), whereas the ULK Laboratory uses more recent European classification that tends toward "splitting" genera or species into lower taxonomic groups. In the case of *Anabaena* and *Nostoc*, which may appear similar under a microscope, field data were used to correctly classify these algae. This is a relatively easy task because *Nostoc* has an identifiable macroscopic structure (a mucilaginous sheath) that is absent in *Anabaena*.

Data Analysis

Environmental data analysis—Correlation and principle components analyses (PCA [SAS Institute, 1989]), correspondence analysis, and canonical correspondence analysis (CANOCO [ter Braak, 1986]) were performed on land-cover, water-chemistry, canopy-density, algal-biomass, and algal-species-composition data to test for any site or species associations with the environmental variables and to identify possible groupings among sites. Four major groups were identified: main-stem sites, upper-basin tributary sites, middle-basin tributary sites, and lower-basin tributary sites. Additional analyses were performed on these site groups, and among sites sampled during each time period (May, July, and September). The sampling site in Clear Creek, which was technically located in the lower basin near the confluence with the Clackamas River, was included with the middle-basin tributary sites in some of the analyses because water chemistry and overall stream conditions were more similar to middle-basin sites than to the other lower-basin tributary sites, probably because much of the streamflow originates from the higher elevation areas in the middle basin (plate 1 and fig. 2).

Nutrient loads and streamflow balances—A mass balance was constructed for streamflow and nutrient loads (in kilograms per day) with the July 1998 data, to identify nutrient or streamflow sources (gains) in the main stem that were not accounted for, such as inputs from ground water or unmeasured tributaries. If negative changes in nutrient loads (losses) were observed, then some unmeasured sink, such as algal uptake, might be suspected. Nutrient loads were calculated as the product of the instantaneous stream discharge and corresponding nutrient concentration. Nutrient loads from the fish hatcheries and WWTPs were estimated using July 1998 effluent discharge rates and estimated nutrient concentrations provided by facility managers. The NO_3^- and SRP content of the Eagle Creek fish hatchery effluent was estimated from a one-time sampling by the USGS in April 1998. The nutrient content of effluent from the WWTPs (NH_3 and TP) were highly variable and warranted calculating a load range using minimum and maximum concentration values. TP and NH_3 data were available from the Sandy WWTP, whereas only NH_3 data were available from the Boring WWTP. Minimum and maximum values (considering both treatment plants) were used to estimate the loads from the Estacada WWTP. It is important to consider, however, that these load estimates do not include NO_3^-, which could be significant as at least one plant (Estacada WWTP) uses a trickling filter to oxidize the NH_3 into NO_3^-.

Nutrient ratios—Nutrient ratios, such as the N:P ratio and the SRP:TP ratio, were calculated to further characterize the nutrient status of the streams and reservoirs. The ratio of dissolved, biologically available forms of N and P (DIN:SRP), indicates the relative availability of the two primary nutrients that algae require for growth. This is important because management strategies aimed at reducing algal growth often target the nutrient that is in shortest supply. During growth, approximately 16 atoms of N are used for every atom of P (or 7:1 by weight), and this ratio, the Redfield Ratio, can be used as a benchmark to evaluate which nutrient would become depleted first if algae continue to deplete existing nutrient pools (Wetzel, 1983).

Another ratio, the portion of TP that is composed of SRP (SRP:TP), also was used to infer whether P in streams was predominantly from a particulate source, such as algal material or sediment, or a dissolved source, such as soluble fertilizers, septic tank wastewater, or ground-water discharges.

Indicator algal taxa—Information on the environmental preferences and tolerances for the algal taxa was obtained from van Dam and others (1994) and Lowe (1974). Because stream algae integrate environmental conditions over time, they can be used as indicators of current or changing ecological conditions (Carrick and others, 1988; Lowe and Pan, 1996). Some algae grow best under a particular set of environmental conditions, and their proliferation or absence may be used to infer water quality. Diatoms, in particular, are especially useful and have been used as indicators of water quality for years (Kolkwitz and Marsson, 1908).

Several indicator algal groups were represented, including those indicative of high nutrient concentrations, alkaline pH, and low concentrations of N. Only diatoms and N-fixing blue-green algae were included in this analysis because of the complexities associated with quantifying filamentous algae. The relative biovolume (the biovolume of each indicator group as a percentage of the total biovolume) was calculated for each sample. The relative biovolume of each group was summed instead of cell numbers because of the large variations in cell sizes commonly observed among different algae. Biovolume values correct for potential bias in cell numbers for small-celled taxa, which might have high numbers but low volume relative to other algae.

Comparisons to water-quality standards—Water-quality standards (numeric criteria) for water temperature, pH, and DO for the Clackamas Basin are listed in table 5. The timing of fish spawning/egg incubation/fry emergence for resident and anadromous fish determines the temperature and DO criteria in effect for a particular place at a particular time. Fish spawning, egg incubation, and/or fry emergence occurs in the Clackamas Basin nearly year-round (table 6), but proposed standards are less stringent for a 4-week period during summer, from mid-July to mid-August (Manette Simpson, Oregon Department of Environmental Quality, oral commun., 2002).

With few exceptions, the field parameter data (water temperature, pH, and DO) collected during this study were single-point, instantaneous measurements, and the frequency and duration of observations required to establish compliance with State standards were beyond the scope of this study. The numeric criterion for water temperature, for example, is based on the 7-day average of the maximum daily temperatures, whereas the DO criterion is based on a 30-day average of the minimum daily values. Instantaneous exceedances of the numeric criteria, therefore, do not constitute violations of State water-quality standards.

Table 5. State of Oregon water-quality criteria for pH, water temperature, and dissolved oxygen for the Clackamas River Basin, Oregon

[Source: Oregon Administrative Rules, Attachment A to Chapter 340, Division 41, 1996. °C, degrees Celsius; °F, degrees Fahrenheit; mg/L, milligrams per liter; DO, dissolved oxygen; %, percent]

Field parameter	State of Oregon Water-Quality Criteria	
	During fish spawning and egg incubation through fry emergence periods (August 15–July 15)	During nonspawning periods, when fish are rearing, migrating, or holding (July 15–August 15)
pH, in standard units	6.5–8.5[a]	6.5–8.5[a]
Water temperature, °C (°F)	12.8°C (55°F)[b]	17.8°C (64°F)[b]
Dissolved oxygen, in mg/L	11.0[c,d], 9.0[e]	8.0[f,g], 6.5[h], 6.0[i]

[a] Reservoirs may be exempted by the Oregon Department of Environmental Quality (ODEQ) if it is determined that the exceedance would occur even without the impoundment and that all practical measures have been taken to bring the pH in the impounded water into compliance.

[b] Based on the 7-day average of the daily maximum temperatures.

[c] Absolute minimum, if intergravel DO is less than 8.0 mg/L

[d] If conditions of barometric pressure, elevation, and temperature preclude achievement of the indicated concentration, then the 95% saturation criteria applies.

[e] If the intergravel DO (spatial median) is greater than or equal to 8.0 mg/L.

[f] Based on a 30-day mean minimum concentration.

[g] If conditions of barometric pressure, elevation, and temperature preclude achievement of the indicated concentration, then the 90% saturation criteria applies.

[h] Based on a 7-day minimum mean concentration.

[i] Absolute minimum.

Table 6. Periodicity chart outlining timing of spawning, egg incubation, and fry emergence for fish in the Clackamas River Basin, Oregon

[Source: Michael Hogansen, Oregon Department of Fish and Wildlife, written commun., 2002. The peak use for summer steelhead was not determined. Source: Oregon Administrative Rules, Attachment A to Chapter 340, Division 41, 1996. GRAY area (G) represents lesser levels of use, based on professional opinion. BLACK area (B) represents 90% of the periods of peak use, based on professional opinion. (1) Use defined by Olsen and others (1992). (2) Use defined by the Oregon Department of Fish and Wildlife (1990).]

	Adult spawning																							
	Month																							
Life stage/activity/species	Jan		Feb		March		April		May		June		July		Aug		Sep		Oct		Nov		Dec	
Winter Steelhead	1	1	G	B	B	B	B	B	B	B	G	G												2
Summer Steelhead (hatchery)	2	2	2	2	2	2																		
Spring Chinook	2	2	2											1	1	B	B	B	G	1	2	2	2	2
Fall Chinook															2	B	B	B	B	B	B	B	G	G
Coho (early hatchery)	B	B	G	G												2	1	1	B	B	B	B	B	B
Coho (late wild)	B	B	B	B	B	G	G															G	G	B
Cutthroat Trout	G	B	B	B	B	G	G																	

	Egg incubation through fry emergence																							
	Month																							
Life stage/activity/species	Jan		Feb		March		April		May		June		July		Aug		Sep		Oct		Nov		Dec	
Winter Steelhead		G	G	B	B	B	B	B	B	B	B	B	G	1	2									
Summer Steelhead (hatchery)	2	2	2	2	2	2	2	2	2															
Spring Chinook	B	B	B	B	B	B	B	B	2	2	2	2	2				B	B	B	B	B	B	B	B
Fall Chinook	B	B	B	B	G	G	G									2	2	2	G	B	B	B	B	B
Coho (early hatchery)	B	B	B	B	G	G	G									2	2	1	G	B	B	B	B	B
Coho (late wild)	B	B	B	B	G	G	G	G	G	G									G	B	B	B	B	B
Cutthroat Trout		B	B	B	B	B	B	B	B	G	G	G												

Nonetheless, instantaneous exceedances were occasionally observed, particularly during the late afternoon or early morning hours, and point to the need for further study to establish compliance with standards.

There were possible exceedances of the State water-quality criterion for water temperature and DO in North Fork Reservoir, and for water temperature, DO, and pH in Timothy Lake. The Oregon Department of Environmental Quality is currently in the process of reviewing water-quality standards for reservoirs (Greg McMurray, Oregon Department of Environmental Quality, oral commun., 2002). There is, however, a recognized Action Limit of 15 µg/L chl *a* for reservoirs that was exceeded once in both North Fork Reservoir and Timothy Lake in 1996. Although these one-time measurements do not qualify as exceedances of the Action Limit which are based on a minimum of three measurements collected over 3 consecutive months, they do indicate the need for additional monitoring.

RESULTS

Stream Conditions

Streamflow

1998 Water year—Streamflows in the Clackamas River were near average during the 1998 water year, with several fall and winter storms producing high streamflow conditions into May (fig. 3). Winter base flows at the Three Lynx gage were about 2,000 ft^3/s from mid-January until May, when streamflows began to decline in response to a decline in the frequency and magnitude of rainfall events. Steady declines in streamflow started in June and continued through the summer, reaching a minimum streamflow of 680 ft^3/s in mid-September (fig. 3). Compared with long-term records, the monthly average streamflow values at the Three Lynx gage were between the 25th and 75th percentile during most months in the 1998 water year and close to the median (50th percentile) during summer (fig. 4).

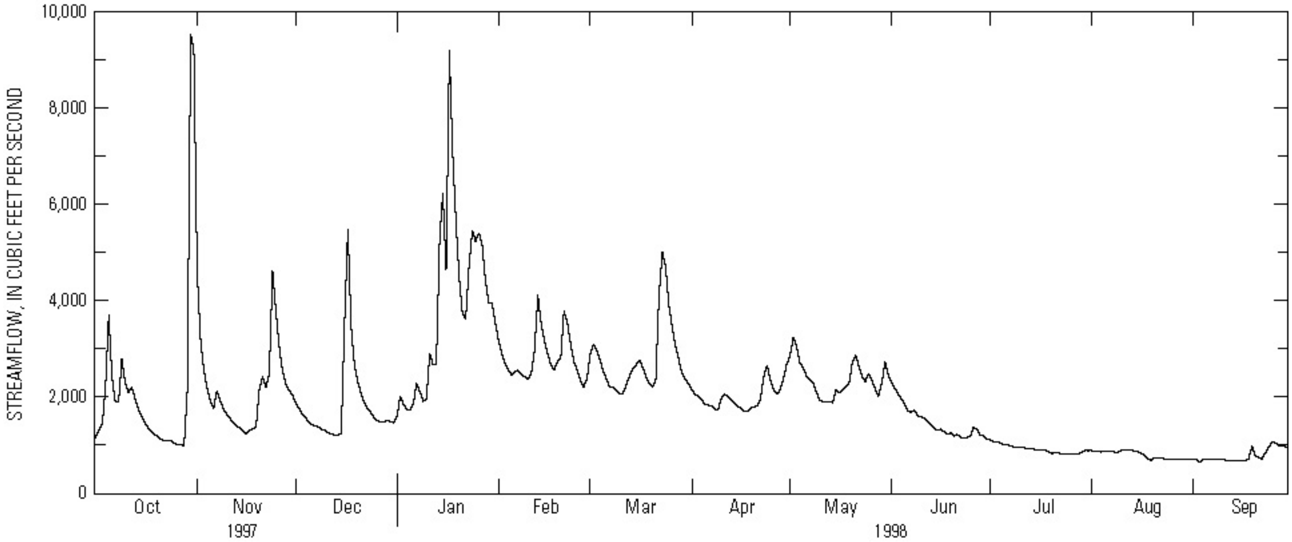

Figure 3. Daily mean streamflow values for the upper Clackamas River above Three Lynx Creek, U.S. Geological Survey gaging station 14209500, water year 1998.

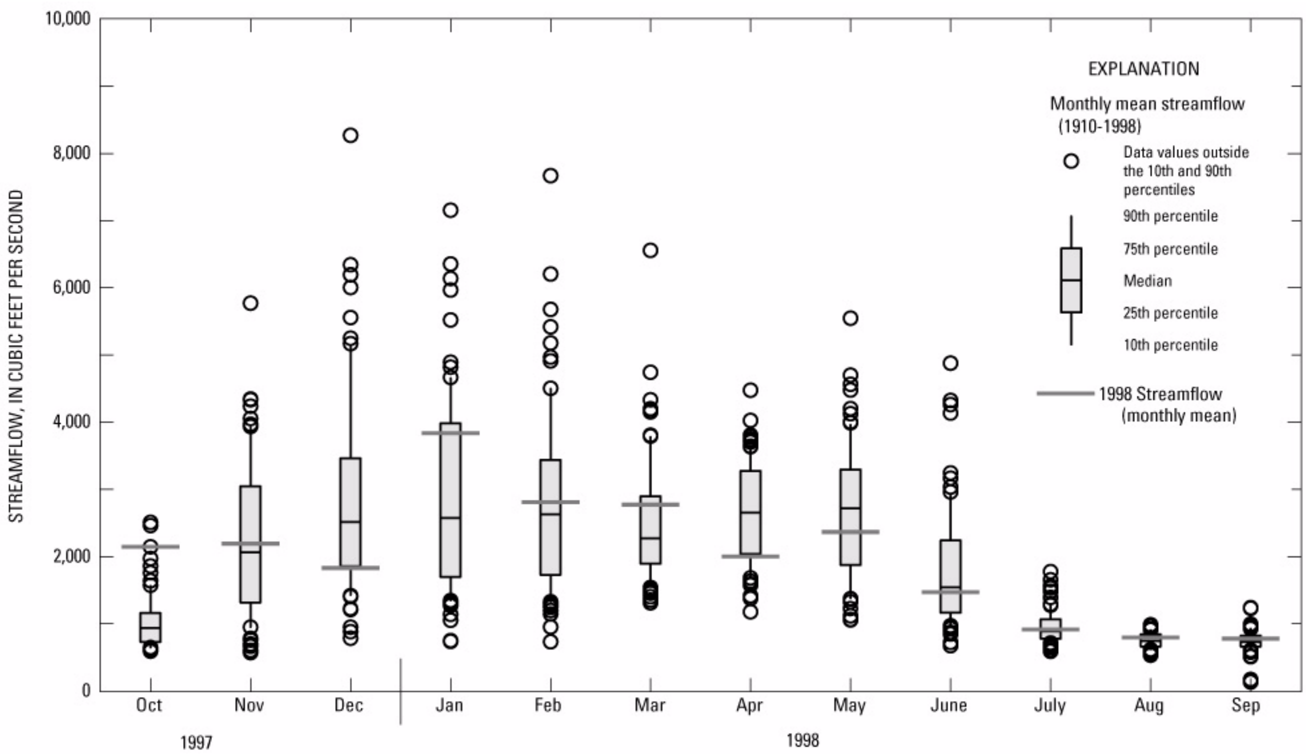

Figure 4. Comparison of water year 1998 streamflow with long-term values in the upper Clackamas River above Three Lynx Creek, U.S. Geological Survey gaging station 14209500.

Streamflows during sampling—During the first stream sampling in May, about 85% of the water near the mouth of the Clackamas River at the Highway 99E bridge (CR_99E—see glossary or table 3 for an explanation of site codes) originated from the upper basin (fig. 5). By July, flows were lower, and discharge from the Oak Grove Powerhouse accounted for much of the streamflow in the upper Clackamas River (figs. 3 and 6). Tributary sites with the highest streamflows in July included the Collawash River (COLLA), Roaring River (ROARING), the Oak Grove Fork below Timothy Lake (OAK_BLTLK), and Eagle Creek near the mouth (EAGLE_M) (fig. 5). Streamflows from the lower-basin tributaries, including Clear Creek (CLEAR), Deep Creek (DEEP), Rock Creek (ROCK), Richardson Creek (RICHARDSON), and Sieben Creek (SIEBEN), contributed a combined 4.5% of the total main-stem streamflow (table 7).

Streamflow balance—July streamflows between CR_UPPER (the upper Clackamas River at Two Rivers Campground) and CR_ABNFK (the Clackamas River just upstream of North Fork Reservoir)—Reach 1 in fig. 6—were nearly balanced, meaning they were within the limits of compounded streamflow measurement errors, indicating no significant unmeasured inputs (such as ground water).

In the lower Clackamas River, however, an unaccounted-for increase in streamflow was observed between McIver Park (CR_MCIVER) and Barton Park (CR_BARTON, Reach 2 in fig. 6), possibly from ground-water inputs. However, because the discharge at CR_MCIVER was not steady on the day of sampling, fluctuating from 1,350 to 998 ft^3/s in the morning to 1,460 ft^3/s in the late afternoon due to variable power generation at River Mill Dam (fig. 7), the amount of ground water is difficult to quantify. The streamflow balance in this reach required estimating the amount of time it takes for a parcel of water to travel from River Mill Dam to Barton Park, because that determined the instantaneous discharge rate for the comparison. In May 1992, Lee (1995) conducted a dye study in this reach when the streamflow was 1,350 ft^3/s, similar to that in July 1998. At that flow, the water velocity was estimated to be between 1.3 and 1.8 miles per hour. This produced a range in discharge from the dam of between 1,056 and 1,360 ft^3/s, for a net unexplained gain of between 140 and 440 ft^3/s (8.5–27%) between CR_MCIVER and CR_BARTON (fig. 6) that might be attributable to ground-water inputs.

Tidal influence in the lower Clackamas River—The pattern of gradually increasing streamflow from CR_BARTON to CR_99E that was apparent in May and July did not occur in September (fig. 5). The discharge at CR_99E in September was about 700 ft^3/s, or about 50% greater than expected, given the discharge relationships previously observed among sites in the lower Clackamas River (fig. 5). This discrepancy in flows might be attributable to the influence of tides. Tides cause reverse flows in the Columbia and Willamette Rivers during low flow periods, an effect that is observed at the streamflow gage in the Willamette River downstream of the Oregon City Falls (Hubbard and others, 1999), where a tidal fluctuation of 3 feet occurred in September 1998. During certain times, backwater conditions may develop in the Clackamas River, a result of such tides. Greater streamflow in the Clackamas River probably resulted from storage and release of water from Clackamette Cove (plate 1) adjacent to the lower river upstream from CR_99E during this tidal cycle.

Data on river stage, SC, and TP in the lower Clackamas and Willamette Rivers support the assertion that backwater conditions cause water from the Willamette River to travel at least 0.3 miles up the Clackamas River to the Highway 99E bridge. A mass-balance analysis indicated that about one-third of the volume of water sampled at CR_99E was water from the Willamette River. Several riffles, however, occur in the lower Clackamas River between CR_99E and the most downstream drinking-water intake, which likely prevents water from the Willamette River from reaching the intake during low flow periods. During high flow periods, however, and particularly following large storms, when the Clackamas River is receding and the Willamette River is rising (as is often observed), backwater conditions may develop far enough upstream for the Willamette River to reach drinking water intakes. Additional studies of this phenomenon, discussed later in this report, are necessary to verify or refute this possibility.

Field Parameters

Water Temperature—Water temperatures in the upper Clackamas River were between 8.3 and 9.2°C in early May (fig. 5 and table 8), which is less than the State of Oregon water temperature criterion of 12.8°C in effect (table 5) due to spawning of winter steelhead and resident cutthroat trout (table 6). Water temperatures in the lower Clackamas River were higher in June and mid-July, reaching levels well above the water-quality criterion (fig. 8).

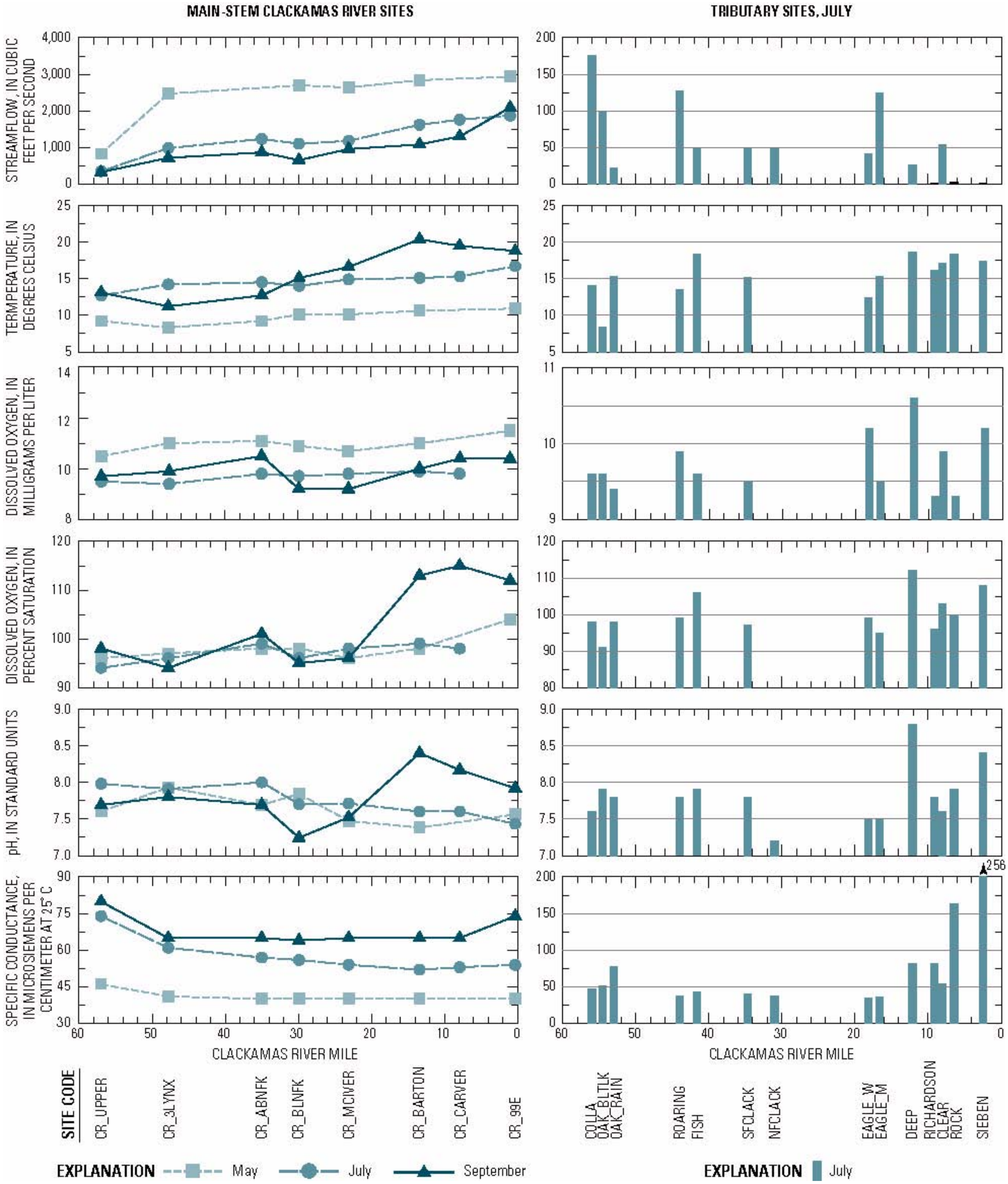

Figure 5. Seasonal variation in streamflow and water-quality variables for main-stem sites in May, July, and September, and values for tributary sites in July 1998. (Lines connecting main-stem values indicate trends only, and do not imply that values between sites were measured. EAGLE_W is a reference site located upstream of EAGLE_M and is included only for comparison.)

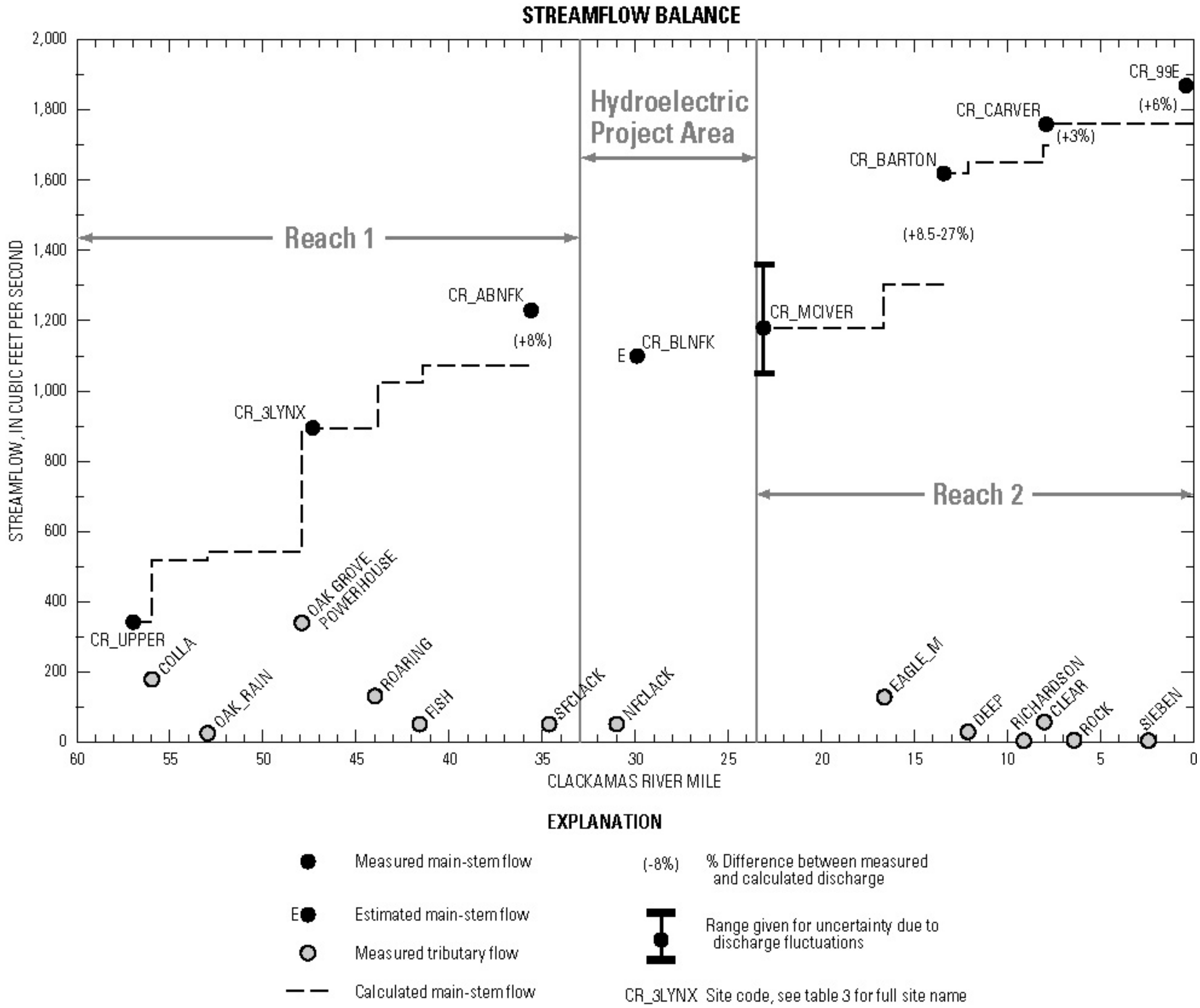

Figure 6. Streamflow balance for the main-stem Clackamas River, Oregon, July 7–15, 1998.

As discussed previously, the water-temperature criterion is based on the 7-day average of the maximum daily temperature; although the data shown in figure 8 do not include 7 consecutive days, they do suggest that high water temperatures occurred for more than 7 days. The highest measured water temperature in the Clackamas River (21.8°C at RM 2.7) was measured on July 16, exceeding the 17.8°C criterion in effect during nonspawning periods (fig. 8).

Water temperatures in the Clackamas River generally increased in a downstream direction, from warming in the main stem and from the inputs of warmer tributaries. Temperatures in the main stem and most tributaries probably exceeded the State 7-day temperature criterion of 12.8°C in early-to-mid July (table 7), when the warmest tributaries included Fish Creek in the upper basin and most all of the tributaries in the lower basin (fig. 5). Most of the highest temperatures were measured in August, when temperatures at FISH (21.1°C), in the fish ladder below Faraday Diversion Dam (20.1°C), EAGLE (22.9°C), CLEAR (20.7°C), DEEP (18.8°C), and ROCK (18.3°C) probably exceeded the 17.8°C criterion in effect during nonspawning periods (table 5). Recall, however, that instantaneous exceedances of the numeric criteria do not necessarily constitute violations in the standard or qualify a stream for listing on the 303(d) list as water-quality limited.

Table 7. Basin characteristics and environmental conditions at sites sampled in the Clackamas River Basin, Oregon, July 1998

[Site codes and nutrient abbreviations are listed in the glossary, and site locations are shown on plate 1; mi^2, square miles; mi/mi^2, miles per square mile; %, percent; ft^3/s, cubic feet per second; °C, degrees Celsius; na, not analyzed; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; <, less than minimum reporting levels (see appendix 1); µg/L, micrograms per liter; kg/d, kilograms per day; mg/m^2, milligrams per meter squared; g/m^2, grams per meter squared]

	Main-stem Clackamas River sites								Upper- and middle-basin tributary sites											Lower-basin tributary sites				
	CR_UPPER	CR_3LYNX	CR_ABNFK	CR_BLNFK	CR_MCIVER	CR_BARTON	CR_CARVER	CR_99E	COLLA	OAK_BLTLK	OAK_RAIN	ROARING	FISH	SFCLACK	WINSLOW	FALL	NFCLACK	EAGLE_W	EAGLE_M	CLEAR	DEEP	RICHARDSON	ROCK	SIEBEN
BASIN CHARACTERISTICS																								
Basin area (mi^2)	157	489	602	668	680	785	920	942	150	55	141	43	45	28	7	3	32	15	90	72	49	4	9	1.8
Stream density (mi/mi^2)	3.1	3.5	3.8	3.9	3.9	4.0	4.0	3.9	4.4	1.6	2.5	5.1	5.4	4.0	4.8	3.0	4.7	6.6	5.5	4.3	3.3	2.9	3.1	2.3
Road density (mi/mi^2)	3.6	3.5	3.4	3.5	3.6	3.6	3.7	3.8	3.1	3.5	3.9	1.4	4.0	4.3	5.3	8.3	4.5	1.4	4.1	4.5	4.3	7.4	6.4	9.5
Urban land (%)	0	0	0	0	1	1	2	3	0	1	1	0	0	0	0	1	0	0	4	4	17	35	24	10
Agricultural land (%)	0	0	0	0	0	1	3	3	0	0	0	0	0	0	0	0	0	0	3	8	11	22	38	27
Mature forest (%)	61	62	63	62	61	59	52	51	67	53	57	77	56	54	80	40	65	91	47	22	6	2	2	3
Nonforest upland (%)	26	23	21	20	20	19	19	19	15	39	32	14	11	11	3	8	5	2	11	18	30	23	17	28
Regrowth forest (%)	13	14	16	17	18	19	22	22	17	3	9	8	32	34	16	51	30	7	34	45	31	11	12	15
WATER QUALITY																								
Streamflow (ft^3/s)	342	900	1,230	1,100	1,180	1,620	1,760	1,870	176	100	22	128	48	48	9	7	48	41	125	54	26	1	2	1
Streamflow yield (ft^3/s per mi^2)	2.2	1.8	2.0	1.6	1.7	2.1	1.9	2.0	1.2	1.8	0.2	3.0	1.1	1.7	1.3	2.3	1.5	2.7	1.4	0.8	0.5	0.3	0.2	0.6
Water temperature (°C)	12.7	14.2	14.5	14	14.9	15.1	15.3	16.7	14.1	8.4	15.3	13.5	18.3	15.2	11.8	12.8	na	12.4	15.3	17.1	18.7	16.2	18.3	17.4
Specific conductance (µS/cm)	74	61	57	56	54	52	53	54	47	52	77	37	44	40	31	26	37	35	36	54	81	82	164	256
Dissolved oxygen (mg/L)	9.5	9.4	9.8	9.7	9.8	10.3	9.8	na	9.6	9.6	9.4	9.9	9.6	9.5	9.8	9.5	na	10.2	9.5	9.9	10.1	9.3	9.3	10.2
Dissolved oxygen (% saturation)	94	96	99	96	98	103	98	na	98	91	98	99	106	97	97	94	na	99	95	103	109	96	100	108
pH (standard units)	8	7.9	8	7.7	7.7	7.7	7.6	7.4	7.6	7.9	7.8	7.8	7.9	7.8	7	7.3	7.2	7.5	7.5	7.6	8.8	7.8	7.9	8.4
NH_4^+ (µg/L)	<2	<2	2	<2	<2	<2	2	<2	<2	<2	<2	<2	<2	<2	7	<2	4	<2	6	6	3	9	12	433
NO_3^- (µg/L)	<5	<5	<5	6	<5	8	32	20	<5	<5	5	<5	7	8	43	116	81	9	142	206	1,045	849	810	7,077
SRP (µg/L)	22	11	10	8	7	7	8	7	7	2	24	8	7	7	3	<1	3	<1	2	6	68	26	65	121
TP (µg/L)	21	18	17	13	15	16	20	41	10	13	26	12	12	8	7	6	9	4	10	15	78	32	75	144
DIN:SRP	<0.3	<0.6	<0.7	<1.0	<1.0	1.1	4.3	2.9	<1	3.5	0.3	0.9	1	1	17	>116	28	>9	74	35	15	33	13	62
SiO_2 (mg/L)	25.3	20.0	19.9	19.4	18.8	17.6	18.0	18.7	15.3	na	24.3	17.8	17.6	18.3	18.2	15.2	18.4	14.7	17.5	22.2	18.7	24.3	31.7	32.0
DIN load (kg/d)[a]	<(6)	<(15.4)	6.0	16.2	<(20.2)	31.7	146.4	91.5	<(3.0)	<(1.7)	0.3	<(2.2)	0.8	0.9	1.1	1.9	10	0.9	45.3	28.1	65.4	1.4	4	13.7
SRP load (kg/d)[a]	18.4	24.1	30.1	21.5	20.2	27.7	34.5	32	3	0.5	1.3	2.5	0.8	0.8	0.1	<(.01)	0.4	<(0.1)	0.6	0.8	4.2	0.1	0.3	0.2
TP load (kg/d)	17.6	39.6	51.2	35	43.3	63.4	86.1	187.6	4.3	3.2	1.4	3.8	1.4	0.9	0.2	0.1	1.1	0.4	3.1	2	4.9	0.1	0.4	0.3
ALGAL BIOMASS / CANOPY CONDITIONS																								
Chlorophyll *a* (mg/m^2)	72	226	24	332	276	60	194	55	54	130	95	20	98	137	14	23	48	11	62	235	143	51	186	371
AFDM (g/m^2)	25	218	7	127	65	38	70	25	11	61	20	10	21	23	3	8	18	4	13	27	18	8	29	41
Canopy closure (%)	15	10	16	11	10	2	15	2	16	10	71	81	32	62	97	92	44	98	61	55	74	43	60	85

[a] Values in parentheses represent the nutrient load with concentrations set to the minimum laboratory reporting levels, and therefore represent theoretical maximum values.

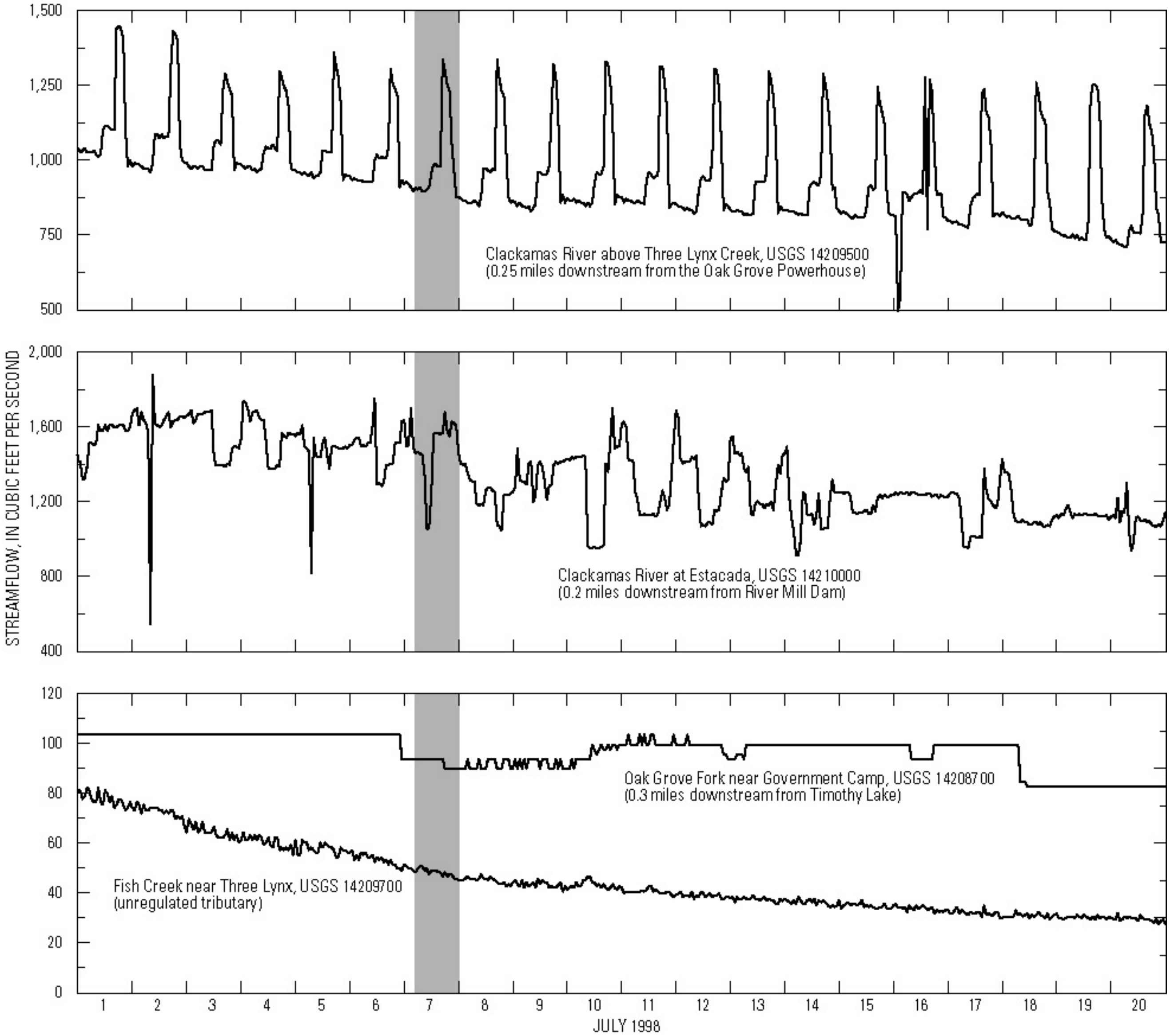

Figure 7. Streamflows in the Clackamas River Basin, Oregon, during sampling in July 1998. (Sampling occurred in the main stem on July 7–8; all other sites were sampled on or before July 15. Shaded areas denote streamflows used for the flow balance.)

Water temperatures were lower in the upper Clackamas River in September compared with July, despite the lower streamflows, probably due to the increasing contribution that ground water makes to streamflow during low-flow periods. Cold-water discharges from the Oak Grove Powerhouse, combined with cooler September nights at higher elevations, also contributed to lower water temperatures in the upper Clackamas River. The temperature at CR_3LYNX was 11.2°C during the September measurement, slightly less than the 12.8°C criterion in effect due to spawning by spring and fall Chinook salmon (table 6). The temperature was 13.1°C, slightly higher than the 12.8°C criterion, at CR_ UPPER on the same date (table 8).

Downstream, the temperature in the Clackamas River increased nearly 4°C through the main-stem hydroelectric project (fig. 5), based on instantaneous temperature measurements taken upstream of North Fork Reservoir (at CR_ABNFK) and downstream of River Mill Dam (at CR_MCIVER) between 9 and 10 a.m. Downstream from North Fork Reservoir (at CR_BLNFK), the water temperature was 15.1°C on the September measurement date. Here, and at all main-stem sites downstream, the 7-day 12.8°C criterion probably was exceeded, with the highest temperature (20.4°C) occurring at CR_BARTON (table 8).

Table 8. Seasonal patterns in streamflow, field parameters, nutrients, and algal conditions at main-stem and tributary sites in the Clackamas River Basin, Oregon, May–September 1998

[Site codes and nutrient abbreviations are listed in the glossary, and site locations are shown on plate 1; ft^3/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; %, percent; µg/L, micrograms per liter; kg/d, kilograms per day; mg/m^2, milligrams per meter squared; g/m^2, grams per meter squared; na, not analyzed; <, less than minimum reporting levels (see appendix 1)]

	Main-stem sites											
	CR_UPPER			CR_3LYNX			CR_ABNFK			CR_BLNFK		
Parameter	May	July	Sep	May	July	Sep	May	July	Sep	May	July	Sep
Streamflow (ft^3/s)	826	342	318	2,470	900	713	na	1,230	863	2,700	1,100	650
Water temperature (°C)	9.2	12.7	13.1	8.3	14.2	11.2	9.2	14.5	12.7	10.1	14.0	15.1
Specific conductance (µS/cm)	46	74	80	41	61	65	40	57	64	40	56	64
Dissolved oxygen (mg/L)	10.5	9.5	9.7	11.0	9.4	9.9	11.1	9.8	10.5	10.9	9.7	9.2
Dissolved oxygen (% saturation)	96	94	98	97	96	94	98	99	101	98	96	95
pH (standard units)	7.6	8.0	7.7	7.9	7.9	7.8	7.7	8.0	7.7	7.8	7.7	7.2
NH_4^+ (µg/L)	<2	<2	<2	<2	<2	4	<2	2	<2	19	<2	<2
NO_3^- (µg/L)	<5	<5	<5	<5	<5	<5	<5	<5	<5	<5	6	<5
SRP (µg/L)	10	22	23	7	11	17	8	10	15	9	8	9
TP (µg/L)	17	21	26	16	18	19	9	17	19	12	13	14
SiO_2 (mg/L)	na	25.3	25.4	na	20.0	21.3	14.7	19.9	21.0	na	19.4	20.5
DIN load (kg/d)[a]	<(14)	<(6)	<(5)	<(42)	<(15.4)	7.0	na	6.0	<(15)	125.5	16.2	<(11)
SRP load (kg/d)	20.2	18.4	17.9	42.3	24.1	29.7	na	30.1	31.7	59.5	21.5	14.3
TP load (kg/d)	34.8	17.6	20.5	96.7	39.6	33.1	na	51.2	40.1	79.3	35.0	22.3
Chlorophyll *a* (mg/m^2)	51.0	71.6	80.3	51.7	226	690	40.8	24.4	61.4	193	332	138
AFDM (g/m^2)	15	25	23	17	218	126	23	8	16	68	127	73

	Main-stem sites											
	CR_MCIVER			CR_BARTON			CR_CARVER			CR_99E		
Parameter	May	July	Sep	May	July	Sep	May	July	Sep	May	July	Sep
Streamflow (ft^3/s)	2,640	1,180	951	2,840	1,620	1,080	na	1,760	1,300	2,940	1,870	2,090
Water temperature (°C)	10.1	14.9	16.6	10.6	15.1	20.4	na	15.3	19.5	10.9	16.7	17.3
Specific conductance (µS/cm)	40	54	65	40	52	65	na	53	65	40	54	74
Dissolved oxygen (mg/L)	10.7	9.8	9.2	11.0	10.3	10.0	na	9.8	10.4	11.5	na	10.4
Dissolved oxygen (% saturation)	96	98	96	98	103	113	na	98	115	104	na	112
pH (standard units)	7.5	7.7	7.5	7.4	7.7	8.4	na	7.6	8.2	7.6	7.4	7.9
NH_4^+ (µg/L)	<2	<2	<2	<2	<2	<2	na	2	<2	<2	<2	<2
NO_3^- (µg/L)	<5	<5	<5	81	8	<5	na	32	5	28	20	<5
SRP (µg/L)	6	7	10	6	7	9	na	8	8	5	7	6
TP (µg/L)	12	15	16	14	16	15	na	20	16	13	41	27
SiO_2 (mg/L)	14.6	18.8	20.1	na	17.6	19.7	na	18.0	19.8	14.9	18.7	19.5
DIN load (kg/d)[a]	<(45)	<(20.2)	<(16)	562.9	31.7	<(18)	na	146.4	15.9	201.4	91.5	<(36)
SRP load (kg/d)	38.8	20.2	23.3	41.7	27.7	23.8	na	34.5	25.4	36.0	32.0	30.7
TP load (kg/d)	77.5	43.3	37.2	97.3	63.4	39.6	na	86.1	50.9	93.5	187.6	138.1
Chlorophyll *a* (mg/m^2)	63.4	276	182	64.0	59.7	88.7	na	194	147	301	54.5	161
AFDM (g/m^2)	42	65	48	14	38	27	na	70	44	128	25	51

Table 8. Seasonal patterns in streamflow, field parameters, nutrients, and algal conditions at main-stem and tributary sites in the Clackamas River Basin, Oregon, May–September 1998—Continued

[Site codes and nutrient abbreviations are listed in the glossary, and site locations are shown on plate 1; ft^3/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; %, percent; µg/L, micrograms per liter; kg/d, kilograms per day; mg/m^2, milligrams per meter squared; g/m^2, grams per meter squared; na, not analyzed; <, less than minimum reporting levels (see appendix 1)]

	Tributary sites											
	COLLA			OAK_BLTLK			ROARING			NFCLACK		
Parameter	May	July	Sep	May	July	Sep	May	July	Sep	May	July	Sep
Streamflow (ft^3/s)	943	176	70	103	100	75	193	128	56	54	48	11
Water temperature (°C)	8.4	14.1	18.0	6.6	8.4	8.0	8.6	13.5	12.4	10.9	na	17.3
Specific conductance (µS/cm)	29	47	59	47	52	47	30	37	39	30	37	39
Dissolved oxygen (mg/L)	10.7	9.6	9.3	10.3	9.6	9.6	10.7	9.9	10.3	10.1	na	9.1
Dissolved oxygen (% saturation)	97	98	105	94	91	91	95	99	101	93	na	98
pH (standard units)	7.5	7.6	8.2	7.6	7.9	7.2	7.6	7.8	7.5	7.3	7.2	7.4
NH_4^+ (µg/L)	<2	<2	<2	<2	<2	<2	<2	<2	<2	<2	4	<2
NO_3^- (µg/L)	<5	<5	<5	<5	<5	6	<5	<5	21	44	81	98
SRP (µg/L)	3	7	9	3	2	8	5	8	12	2	3	6
TP (µg/L)	16	10	13	10	13	13	10	12	14	10	9	9
SiO_2 (mg/L)	na	15.3	15.6	na	na	19.0	na	17.8	18.7	15.8	18.4	22.1
DIN load (kg/d)[a]	<(16)	<(3.0)	<(1.2)	<(1.8)	<(1.7)	<(1.2)	<(3.3)	<2.2	2.9	5.8	10	2.6
SRP load (kg/d)	6.9	3.0	1.5	0.8	0.5	1.5	2.4	2.5	1.6	0.3	0.4	0.2
TP load (kg/d)	37.4	4.4	2.3	2.6	3.2	2.4	4.8	3.8	1.9	1.3	1.1	0.2
Chlorophyll *a* (mg/m^2)	24.3	53.5	55.6	183	130	545	33.0	20.4	51.7	53.2	48.1	187
AFDM (g/m^2)	15	11	12	66	61	115	20	10	16	23	18	22

[a] Values in parentheses represent the DIN load assuming concentrations were at the reporting level, and therefore represent theoretical maximum values.

Dissolved oxygen—Concentrations of DO in the Clackamas River and some of its tributaries were, at times, closely associated with water temperature, with colder temperatures supporting higher levels of DO than warmer temperatures. Biological processes, such as algal photosynthesis, also appeared to exert some control on DO at sites with high algal biomass, especially during summer.

The DO concentrations in the upper Clackamas River were at or slightly above 11 mg/L (milligrams per liter [parts-per-million]) on measurement dates in May (a spawning period for native winter steelhead and resident trout); for reference, the State standard requires an average minimum of 11 mg/L for 30 days. DO concentrations were boosted due to the cold water temperatures in May and relatively low algal biomass (table 8). Immediately downstream of both North Fork and River Mill Dams, however, the DO concentrations were less than 11 mg/L (table 8).

Measurements taken in the early morning and late afternoon showed that DO levels in the upper Clackamas River and some tributaries, including Fish Creek and Roaring River, were inversely related to water temperature, demonstrating the effect of temperature on DO. The general decline in DO concentrations in the upper Clackamas River from May to July, following the increase in water temperature (table 8 and fig. 5), further demonstrates the close association between water temperature and DO. Temperature control on DO also was indicated by the fairly consistent percent-saturation values in the upper Clackamas River, which were within 5% of each other in May and July (fig. 5).

In contrast, DO concentrations at some sites (FISH, DEEP, SIEBEN, and several sites in the lower Clackamas River, especially those downstream of Barton) increased through the day during the summer, even as the water temperature increased (fig. 8).

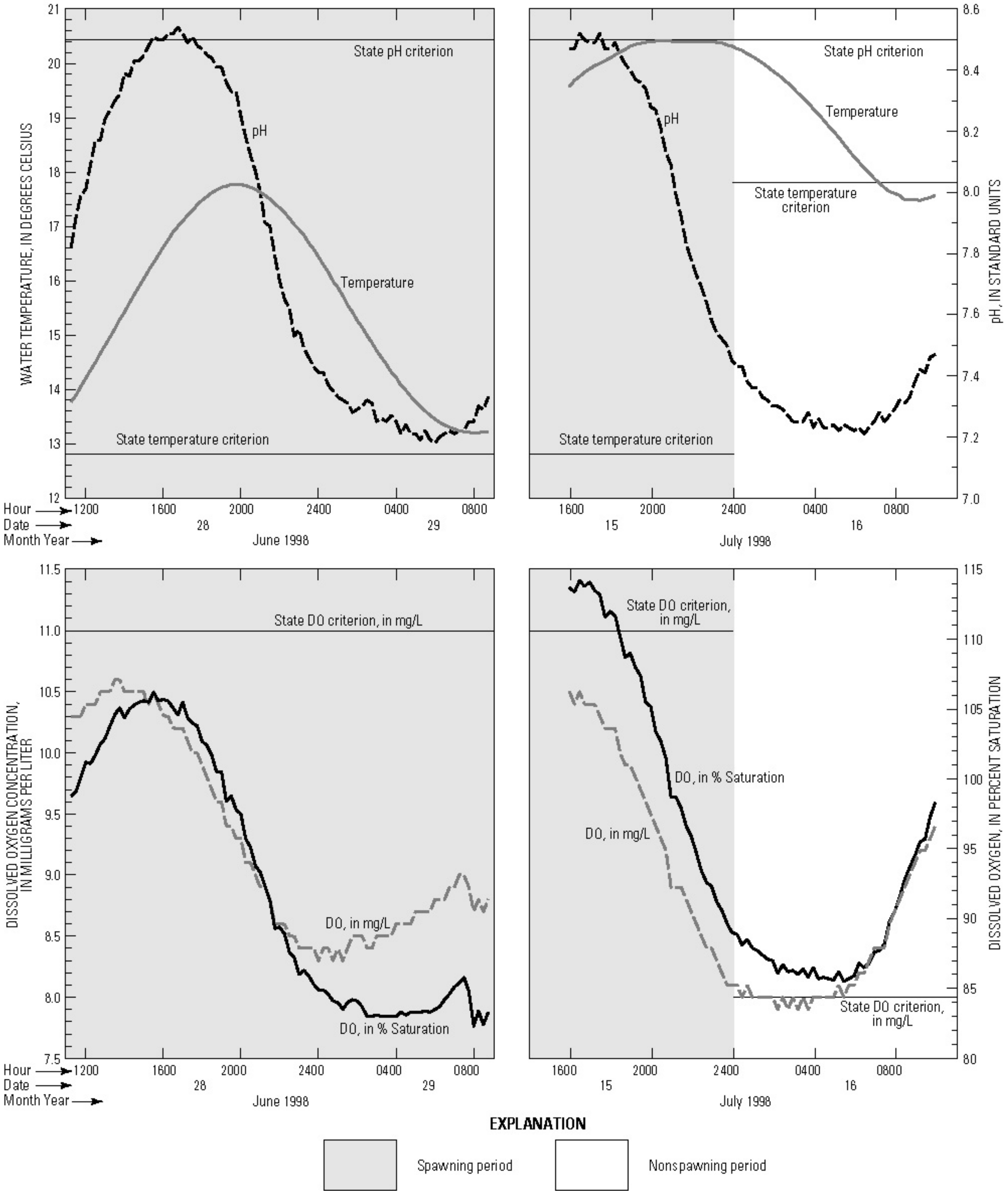

Figure 8. Diel fluctuations in water temperature, pH, and dissolved oxygen in the lower Clackamas River (at CR_COW, RM 2.7), June 28–29, 1998, and July 15–16, 1998. (Spawning periods include spawning and egg incubation through fry emergence. Nonspawning periods include periods when fish are holding, rearing, or outmigrating [see tables 5 and 6].)

The percent saturation values at CR_BARTON, CR_CARVER, and CR_99E, for example, were 113%, 115%, and 112%, respectively, in September (fig. 5). This is an indication that some other process, probably algal photosynthesis, was affecting DO concentrations.

DO concentration in the lower Clackamas River at RM 2.7 (at CR_COW) showed a distinct diel pattern during summer, indicative of algal metabolism, with minimum DO concentrations occurring at night and in the early morning, when water temperatures were lowest. In late June, for example, the DO fluctuated from 10.6 mg/L (105% saturation) in the afternoon to 8.3 mg/L (83.5% saturation) in the morning (fig. 8). At this time, the DO concentration probably did not meet the 30-day 11 mg/L criterion in effect to protect emerging winter steelhead fry (tables 5 and 6). DO concentrations were even lower in mid-July, when the daily minimum concentration was 7.9 mg/L (85.7% saturation) at 2 a.m. (fig. 8). In September, a spawning period for spring and fall Chinook salmon (table 6), a concentration of 11 mg/L was not attained at any of the main-stem sites on measurement dates (table 8).

The lowest measured DO concentrations for tributary sites occurred in Clear, Eagle, Deep, and Rock Creeks in August, when DO concentrations ranged from 8 to 8.4 mg/L. The DO in the Oak Grove Fork downstream from Timothy Lake was 9.6 mg/L (91% saturation in September (table 8), when the DO was depleted (about 5 mg/L [50% saturation]) at the water release depth in Timothy Lake (data presented later in this report).

pH—All of the pH values in the tributaries were greater than 7 and most were between 7 and 8 (fig. 5 and table 7). The highest tributary pH values (8.4 and 8.8) occurred at SIEBEN and DEEP, respectively, with the latter value exceeding the State pH criterion of 8.5, which applies to single measurements (table 5).

Instantaneous afternoon pH measurements taken in the lower Clackamas River at CR_BARTON and CR_COW slightly exceeded the State criterion for some portion of the late afternoon on several occasions during summer. Continuous data collected at CR_COW in late June (and again in mid-July) showed that pH fluctuated roughly 1.4 units through the day, slightly exceeding the 8.5 criterion in the afternoon (fig. 8). Pronounced diel fluctuations in pH and DO, indicative of high rates of algal metabolism, have been found to occur on a daily basis for weeks at a time in other Cascade streams (e.g., Tanner and Anderson, 1996; Herrett and others, 2001).

Several sites had somewhat elevated pH values (equal to or greater than 8.0 units) during the summer, including CR_UPPER, COLLA, CR_ABNFK, and in the fish ladder near the Faraday Diversion Dam (fig. 2). Notably lower pH values, ranging from 7.0 to 7.2 pH units, characteristic of more heterotrophic systems, occurred at sites in the North Fork Clackamas River Basin, including the North Fork Clackamas River at the mouth (NFCLACK), Fall Creek (FALL), and Winslow Creek (WINSLOW) (table 7).

Specific conductance—SC values in the Clackamas River were relatively low (table 8). SC generally declined in a downstream direction (along with P concentrations) between CR_UPPER and CR_ 3LYNX in July, as inputs from more dilute tributaries entered the main stem (fig. 5). A seasonal increase in SC was observed from May to September at most sites (table 8 and fig. 5), presumably caused by the lower streamflows, which cause less dilution. The highest SC values were measured at ROCK and SIEBEN in July, when the respective SC values were 164 and 256 µS/cm (table 7). The large increase in the SC between CR_CARVER and CR_99E in September (fig. 5) was likely an artifact of tidal interaction with the Willamette River (refer to Tidal influence in the lower Clackamas River, p. 25).

Nutrients

Nitrogen and phosphorus values (concentrations and loads) and ratios differed among main-stem and tributary sites and exhibited spatial and longitudinal (downstream) variations that may be attributable to differences in the geology, hydrology, biological processing, and/or land use in the basin. Seasonal increases in SC and P levels in the Clackamas River were observed that were probably related to the decline in streamflow, which resulted in less dilution, and the increasing dominance of ground water. Due to the differing implications of concentrations versus loads, results for each of these are presented separately for N and P.

Nitrogen concentrations—In most streams, NO_3^- was the dominant form of N, although NH_4^+ also was occasionally detected at low concentrations. A spatial pattern in stream N concentrations was observed, with the lowest concentrations (often less than 5 µg/L) occurring at upper-basin sites and moderate-to-high values at middle-basin sites. Nitrate concentrations at tributary sites in the middle basin, including the North Fork Clackamas River, Eagle Creek, and Clear Creek, for example, were 10–20 times higher and NH_4^+ concentrations 3 times higher than at sites in the upper basin (tables 7 and 9).

Table 9. Average values for environmental conditions for groups of sites sampled in the Clackamas River Basin, Oregon, July 1998

[Sites in each group are given in table 7. Site codes and nutrient abbreviations are listed in the glossary, and site locations are shown on plate 1; ft^3/s, cubic feet per second; %, percent; µS/cm, microsiemens per centimeter at 25°C (degrees Celsius); µg/L, micrograms per liter; mg/m2, milligrams per square meter; <, less than minimum laboratory reporting levels (see appendix 1)]

Parameter	Main-stem sites			Tributary sites			
	Hydropower sites	Upper-basin sites	Lower-basin sites	Upper-basin sites	SFCLACK and FISH	Middle-basin sites	Lower-basin sites
Number of sites	4	3	4	4	2	6	4
Streamflow (ft^3/s)	820	825	1,752	107	48	47	8
Agricultural and urban land (%)	2	0	4	1	0	3	46
Mature forest (%)	59	62	56	64	55	58	3
Nonforest upland (%)	22	23	19	25	11	8	25
Regrowth forest (%)	16	14	20	9	33	31	17
Specific conductance (µS/cm)	56	64	53	53	42	37	146
NH_4^+ (µg/L)	<2	2	<2	<2	<2	6	114
NO_3^- (µg/L)	<5	<5	20	5	8	100	2,445
SRP (µg/L)	7	14	7	10	7	4	70
DIN:SRP (range)	<0.6–3.5	<0.7	<1–4.3	<1–3.5	1	9–116	13–62
TP (µg/L)	15	19	26	15	10	9	82
Chlorophyll *a* (mg/m^2)	241	107	103	75	118	66	188
Canopy closure (%)	10	14	6	45	47	75	66

The highest N concentrations, however, ranging from roughly 800 to 7,500 µg/L, were found at sites in the lower basin, where agriculture and urban land is concentrated. N concentrations in the Clackamas River reflected the pattern observed in the tributaries, with the lowest concentrations occurring in the upper basin (upstream from North Fork Reservoir) and higher concentrations generally occurring downstream (fig. 9). In May 1998, N concentrations in the Clackamas River were below detection levels in the upper basin and increased downstream from North Fork Reservoir (at CR_BLNFK), where 19 µg/L of NH_4^+ was detected (fig. 9). Downstream (at CR_MCIVER), however, all forms of N were below detection, possibly from algal uptake of N within the hydroelectric project.

Declines in N concentrations also were observed in the lower Clackamas River between CR_BARTON and CR_99E (in May) and between CR_CARVER and CR_99E (in July). This also suggests algal uptake, because N concentrations in the main stem (especially NO_3^-) were anticipated to increase, not decrease, in response to inputs from the lower-basin tributaries (table 7 and fig. 9) and ground water, as will be discussed later.

A slight increase in N concentrations, possibly due to slowing algal growth (and reduced nutrient uptake) was observed at some sites in late September (table 8). Whereas N concentrations were low at all main-stem sites in early September, NO_3^- was detected later that month at sites in the upper Clackamas River (at CR_3LYNX, CR_ABNFK, and CR_BLNFK) at concentrations ranging from 7 µg/L to 9 µg/L (data not shown). The small increase in streamflow that occurred in late September (fig. 3) also may have contributed to the observed increase in N as previously dry riverbeds were again inundated by the higher flows.

Nitrogen loads and yields—Tributary sites with the highest N loads in July included DEEP, which had a NO_3^- concentration exceeding 1,000 µg/L with moderate streamflow, and sites in the middle basin having much lower N concentrations but relatively higher streamflows (fig. 10 and table 7). Sieben Creek, with its exceptionally high NO_3^- concentration (7,500 µg/L) contributed 4 times as much N as Rock Creek, even though the Sieben Creek Basin is 4 times smaller (table 7).

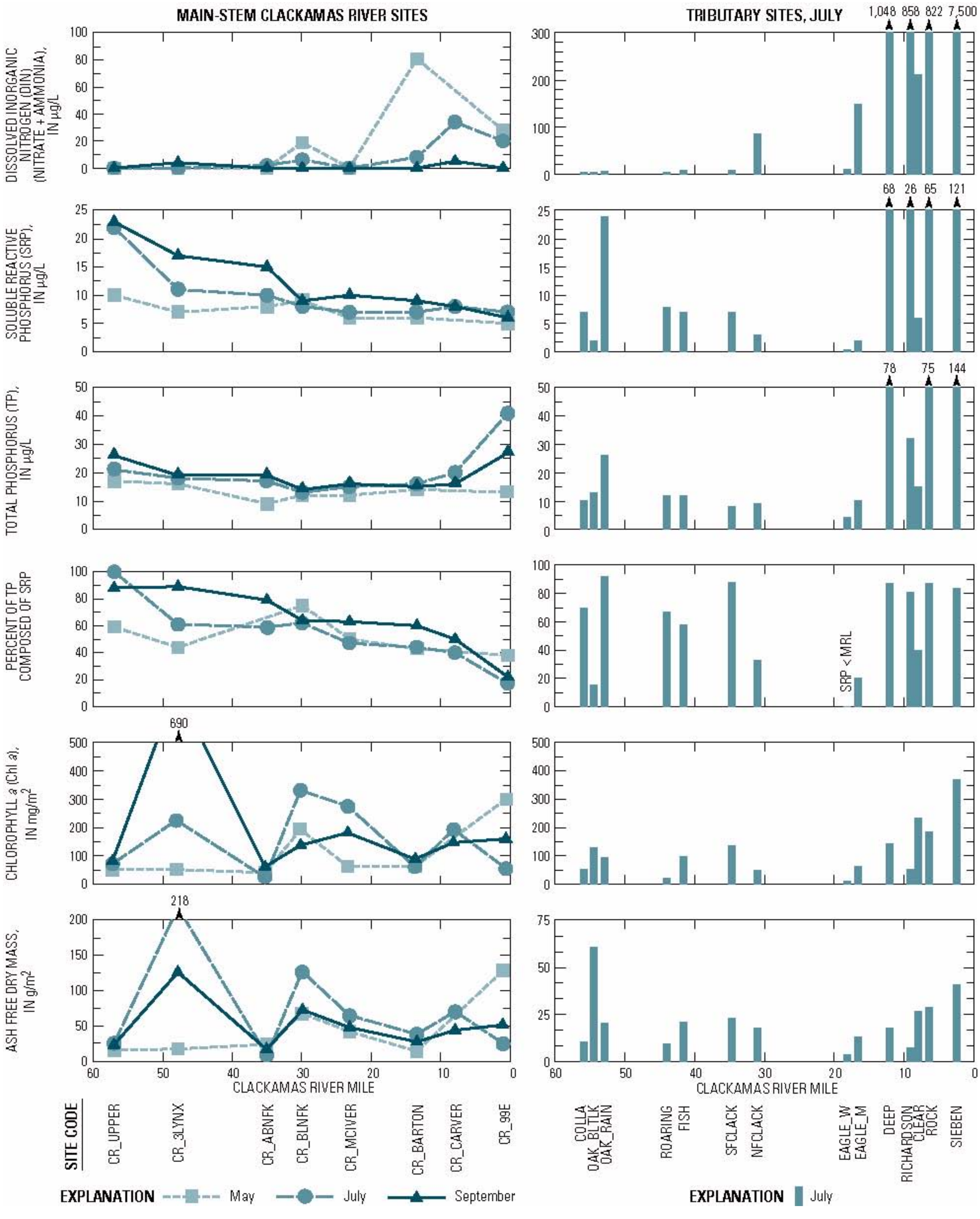

Figure 9. Seasonal variation in nutrient concentrations, nutrient ratios, and algal biomass at main-stem sites in May, July, and September, and values for tributary sites in July 1998. (Zero values for nitrogen and phosphorus compounds indicate that the concentration was less than the minimum laboratory reporting level [appendix 1]. Full site names and locations are listed in table 3 and abbreviations for nutrient and algal biomass units of measure are listed in the glossary.)

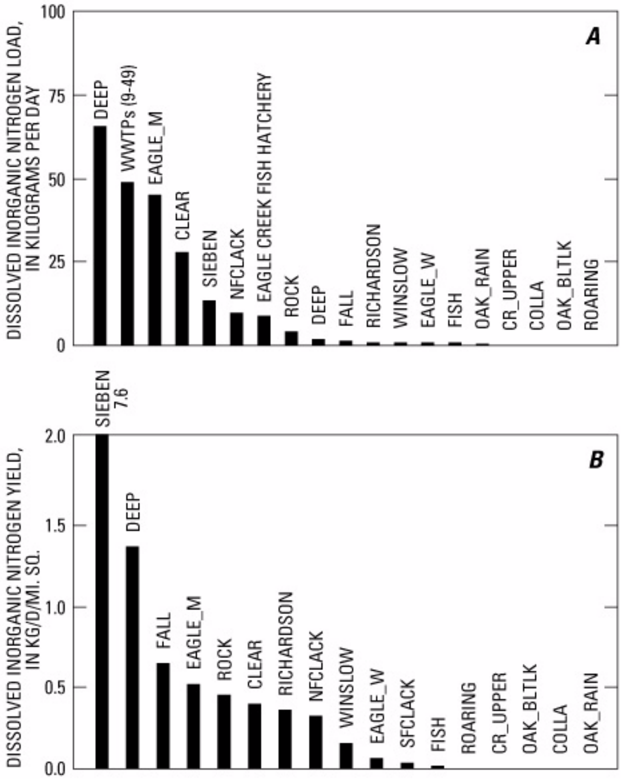

Figure 10. Estimated contributions of dissolved inorganic nitrogen (DIN; NO_3^- + NH_4^+) loads (A) and yields (B) from the tributaries, wastewater treatment plants, and fish hatcheries in the Clackamas River Basin, Oregon, July 1998. (Contributions from point sources were estimated from available data. Site codes and abbreviations for nutrients and algal biomass are listed in the glossary.)

In July, N loads in the upper Clackamas River (upstream from North Fork Reservoir) were low (fig. 11). The measured load of N entering the reservoir (16 kg/d [kilograms per day]) was accounted for by inputs from the main-stem Clackamas River (CR_ ABNFK, 6 kg/d) and the North Fork Clackamas River (NFCLACK, 10 kg/d). This load was matched at the downstream site (CR_BLNFK), despite the slightly lower discharge downstream from the reservoir (fig. 6).

The three WWTPs in the basin, which discharged an estimated 1.3 ft^3/s in July, contributed between 9 and 49 kg/d of NH_4^+ based on available data (NH_4^+ concentrations in effluent ranged from 1,700 to 16,000 µg/L during summer, and NO_3^- data were not available). Eagle Creek National Fish Hatchery, which typically discharges about 35 ft^3/s, contributed an estimated 9 kg/d of N (fig. 10). No nutrient data were available from the State fish hatchery at McIver Park, although contributions were likely minor in July because most of the fish were released in March.

The highest DIN yields (loads per unit basin area) were observed from lower-basin tributary sites (SIEBEN, DEEP, ROCK, and RICHARDSON) and from tributary sites in the middle basin (EAGLE_M, CLEAR, and NFCLACK) (fig. 10). DIN yields from upper Eagle Creek (EAGLE_W, in the Salmon-Huckleberry Wilderness Area) and at sites in the upper basin were much lower (fig. 10).

The longitudinal pattern of N loads in the lower Clackamas River (fig. 11) suggests that algal uptake might be occurring in some reaches. For example, the N load in the lower Clackamas River increased from <20 kg/d downstream from River Mill Dam (at CR_MCIVER) to only 32 kg/d at CR_BARTON in July, despite the large input by Eagle Creek (45 kg/d of N, table 7). At this time, the N load at CR_BARTON was 13 kg/d less than the contribution made by Eagle Creek alone, which might be attributable to N utilization by algae in this reach. Downstream of Barton, the N load increased to 147 kg/d at CR_CARVER, with about 85% of that increase being attributable to inputs from measured tributaries, with unmeasured sources, including Goose Creek and ground-water inputs, making up the difference. Despite inputs of N from lower-basin tributaries and other sources, the N load decreased to 92 kg/d at CR_99E in July (fig. 11), again suggestive of algal uptake. An even more pronounced longitudinal decrease in the main-stem N load, from 563 to 200 kg/d, also was observed between CR_BARTON and CR_99E in May (fig. 11).

To summarize, the scarcity of N in the Clackamas River, combined with sharp declines in N loads, suggests a high demand for N, and that N concentrations may be strongly affected by algal uptake. The major sources of measured N included tributaries in the middle basin, North Fork Reservoir (which appeared to release NH_4^+ in May), tributaries in the lower basin (where agricultural and urban land use is concentrated), and point sources, including WWTPs and fish hatcheries.

Phosphorus concentrations—Concentrations of P in the Clackamas River also showed longitudinal variations that can be attributed to the inputs of tributaries, effects of the reservoirs, and possibly algal uptake. A general downstream decline in the concentration of SRP was observed in the main stem (fig. 9). Relatively high concentrations of P were found at some sites in the upper basin (table 7), especially the high-elevation sites (CR_ UPPER and the Oak Grove Fork at Rainbow Picnicground [OAK_RAIN]), possibly due to naturally occurring phosphate rock in these watersheds.

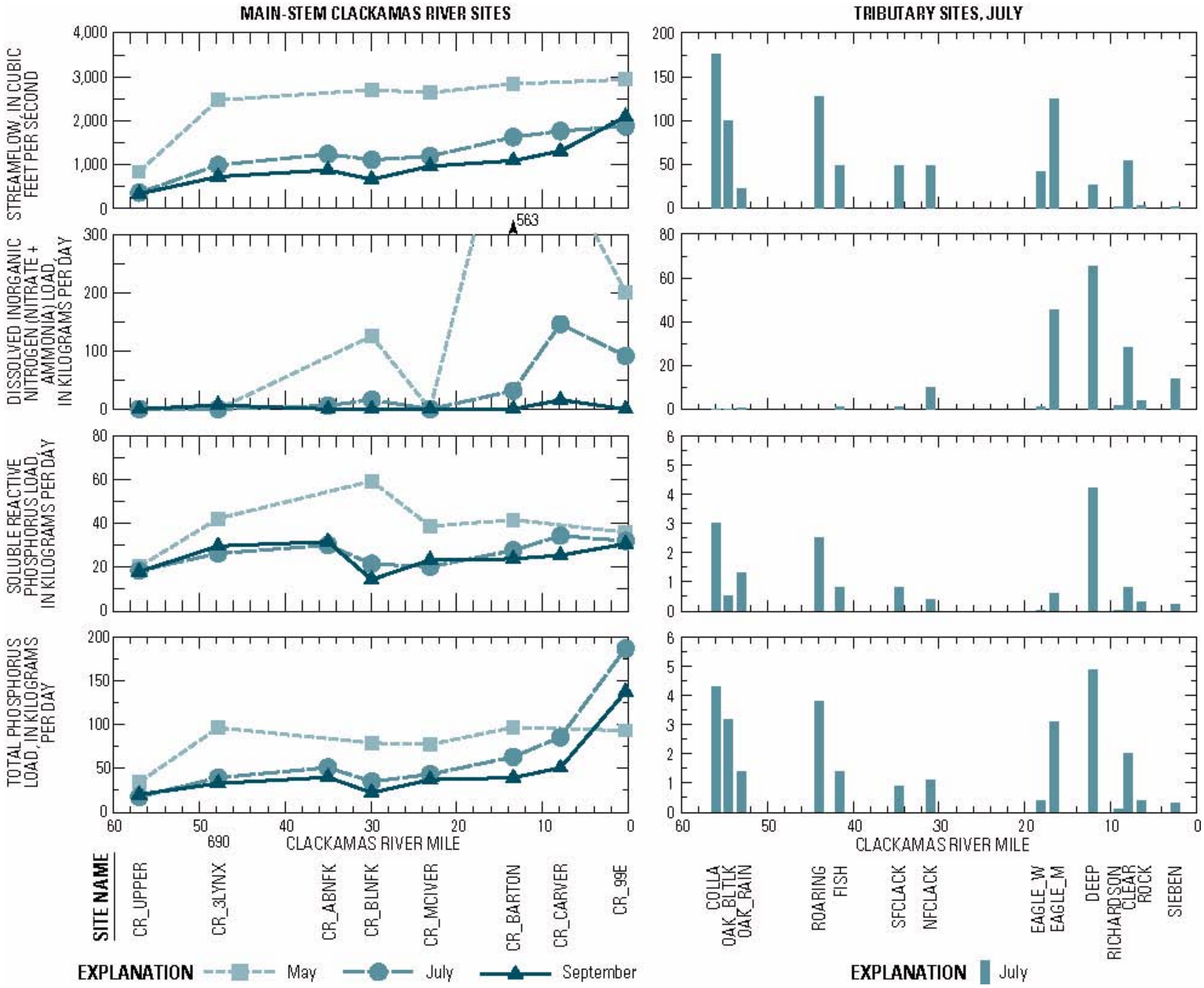

Figure 11. Seasonal variation in nutrient loads at main-stem sites in May, July, and September, and values for tributary sites in July 1998. (Zero values for nitrogen and phosphorus compounds indicate that the concentration was less than the minimum laboratory reporting level [appendix 1]. Site codes and abbreviations for nutrients and algal biomass are listed in the glossary.)

Concentrations of TP at forested sites were positively correlated with both dissolved SiO_2 and SC (fig. 12), a finding that is consistent with a geological source of P in the upper basin. The seasonal increase in P concentrations (and SC values) from July to September (figs. 5 and 9) also suggests that phosphorus-rich ground water was contributing a larger proportion to streamflows during low-flow periods.

The downstream decline in P (fig. 9) was due to the combination of low-phosphorus water inputs from tributaries, including Roaring River, Fish Creek, and the North and South Forks of the Clackamas River, and possibly algal uptake. Concentrations of P downstream of North Fork Reservoir (at CR_BLNFK) also were slightly less compared with those at the upstream site (fig. 9), indicating that the reservoir was a sink for P.

Concentrations of SRP in the lower Clackamas River were steady or declined in downstream direction, despite the inputs of phosphorus-rich water from lower basin tributaries (DEEP, ROCK, RICHARDSON, and SIEBEN) affected by agriculture and urban land uses (table 7). The highest concentration of P (144 µg/L TP at SIEBEN) exceeded the USEPA's suggested goal of 100 µg/L to prevent nuisance algal growth for streams that do not drain into lakes or reservoirs (U.S. Environmental Protection Agency, 1986).

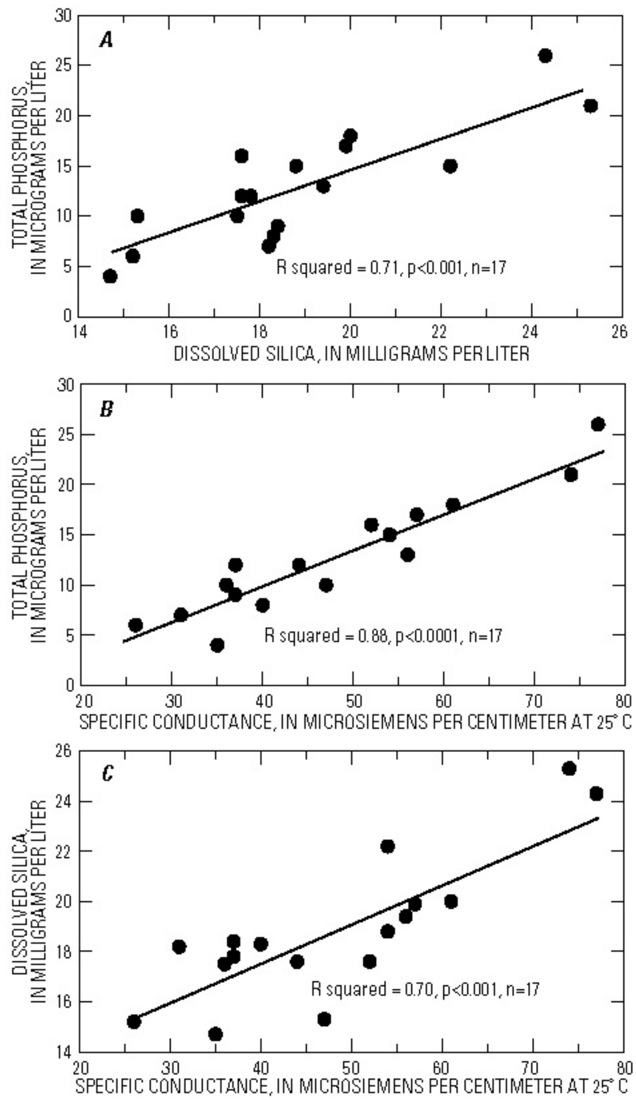

Figure 12. Relations between total phosphorus and dissolved silica concentrations (A), total phosphorus concentrations and specific conductance (B), and dissolved silica and specific conductance (C). (Lower-basin tributary sites and lowermost main-stem sites were outliers because of high nutrient concentrations and were not plotted.)

A slight, but steady longitudinal decrease in the SRP concentration occurred in the lower Clackamas River in September (fig. 9), concurrent with an increase in the TP concentrations, possibly caused by sloughed algal material. The highest TP concentrations in the Clackamas River were observed downstream of Barton, especially in July, when the TP increased sharply, reaching about 40 µg/L at CR_99E.

The longitudinal declines in SRP concentrations might also have been due to uptake by algae. One measure of the relative amount of P available for algal growth is the ratio of dissolved P to total P (SRP:TP), expressed as a percentage. As algae grow, concentrations of SRP in the water column decline, thereby reducing the SRP:TP ratio (in the absence of inputs of particulate P). In the Clackamas River, SRP was the dominant form of P at most sites in the upper basin, making up greater than 90% of the TP (fig. 9). The SRP:TP ratio in the main stem declined from CR_UPPER to CR_99E in July and September (fig. 9), a consequence of uptake and incorporation of SRP into algal biomass. At the same time there was an increase in TP in the lower Clackamas River, probably due to increased amounts of algal material suspended in the water column, which also resulted in lower SRP:TP ratios.

Phosphorus loads and yields—The highest loads of TP came from the upper Clackamas River (at CR_UPPER), Deep and Eagle Creeks, the Collawash and Roaring Rivers, and the Oak Grove Fork (fig. 13). Other lower-basin tributaries, while having relatively high TP concentrations, contributed smaller TP loads because of their smaller streamflows (fig. 11). The three WWTPs in the basin, which discharged about 1.3 ft^3/s in July, contributed significant amounts of TP (between 9 and 16 kg/d, fig. 13), based on available nutrient data: TP concentrations from the WWTPs ranged from 2,900 to 5,400 µg/L during summer.

Relatively high TP yields, the load per unit area, were found at sites in the upper basin (at OAK_RAIN and CR_UPPER, fig. 13), possibly due to the presence of phosphate-containing rock in those watersheds. Other basins with relatively high TP yields included Sieben Creek (SIEBEN) and Rock Creek (ROCK), which likely reflects the influence of agricultural and urban land uses on water quality in those basins.

Phosphorus loads in the Clackamas River were higher in May compared with other months, partly because of higher streamflows (fig. 11). The SRP load in the upper Clackamas River about doubled from CR_UPPER to CR_3LYNX due to inputs from tributaries and the Oak Grove Powerhouse. Downstream of North Fork Reservoir, the SRP load increased to 60 kg/d, due to increased streamflow downstream of the reservoir. Downstream, at CR_MCIVER, the SRP load declined to levels found in the upper Clackamas River. In contrast, lower SRP loads were observed downstream of North Fork Reservoir in July and September compared with the upstream site (CR_ABNFK, fig. 11).

TP loads increased in the Clackamas River from CR_UPPER to CR_99E, particularly in July and September, and mirrored the downstream increase in streamflow (fig. 11). The TP load in the upper Clackamas River in May was about equally shared by contributions from the upper Clackamas River (CR_ UPPER), the Collawash River (COLLA), and the Oak Grove Powerhouse. TP loads in the lowermost reaches of the Clackamas River between CR_CARVER and CR_99E increased sharply in July and September (fig. 11). Relatively low streamflows from the lower-basin tributaries resulted in small P loads in July despite their relatively higher P concentrations (fig. 9).

Seasonal declines in TP loads were observed at most main-stem sites from May to September (fig. 11), reflecting the seasonal declines in streamflow. The TP load at CR_99E, however, increased sharply from May to July, following an algal sloughing (die-off) event in June (refer to Algal Biomass, p. 40.)

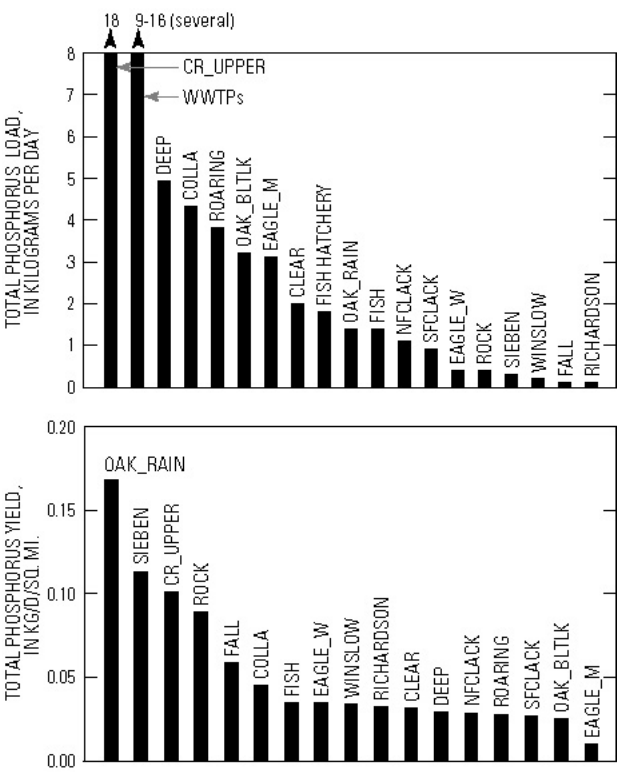

Figure 13. Estimated contributions of total phosphorus loads (A) and yields (B) from the tributaries, wastewater treatment plants, and fish hatcheries in the Clackamas River Basin, Oregon, July 1998. (Contributions from point sources were estimated from available data.)

Soluble reactive phosphorus load balance—In July, the SRP load in the upper Clackamas River increased steadily between CR_UPPER and CR_ ABNFK (fig. 14). The SRP loads in the main stem were boosted from the inputs of tributaries, including the Collawash River, Oak Grove Fork (via the Oak Grove Powerhouse), and Roaring River. A 28% decline in the SRP load was observed downstream of North Fork Reservoir (at CR_BLNFK), due to slightly lower concentrations of SRP and reduced streamflow downstream from the reservoir in July (fig. 14 and table 8). In July and September, the SRP load steadily increased in a downstream direction from CR_MCIVER to CR_CARVER, in response to inputs from the larger tributaries, particularly Eagle, Clear, and Deep Creeks (figs. 11 and 14).

A 9–32% increase in the SRP load that was not accounted for in the SRP balance was observed between CR_MCIVER and CR_BARTON, although fluctuating discharges from River Mill Dam in July (presented in the streamflow results) increased uncertainty in mass-balance calculations. An unaccounted-for increase of 5% in SRP load was observed between CR_BARTON and CR_CARVER, whereas a 9% loss in SRP load, possibly indicative of algal uptake, was observed between CR_CARVER and CR_99E, despite inputs from Rock and Sieben Creeks (fig. 14 and table 7).

Nitrogen-to-phosphorus ratios—The DIN:SRP ratio, the relative availability of dissolved inorganic forms of N and P, is often used to indicate which nutrient might be regulating algal growth. A ratio of roughly 7 indicates balanced nutrient availability, whereas higher ratios may indicate P limitation, and lower ratios may indicate N limitation. DIN:SRP ratios were less than 7 at all main-stem sites in July (table 7), owing to the low N concentrations at sites in the upper basin, suggesting limitation by N. In contrast, DIN:SRP ratios were greater than 7 at all tributary sites in the middle and lower Clackamas Basin (table 7), owing to the relative abundance of NO_3^- at both middle- and lower-basin sites and lack of SRP at middle-basin sites. This suggests that P could potentially be limiting algal growth at middle-basin tributary sites. The high P concentrations at lower-basin tributary sites suggests that P is probably not limiting algal growth, despite the high DIN:SRP ratios.

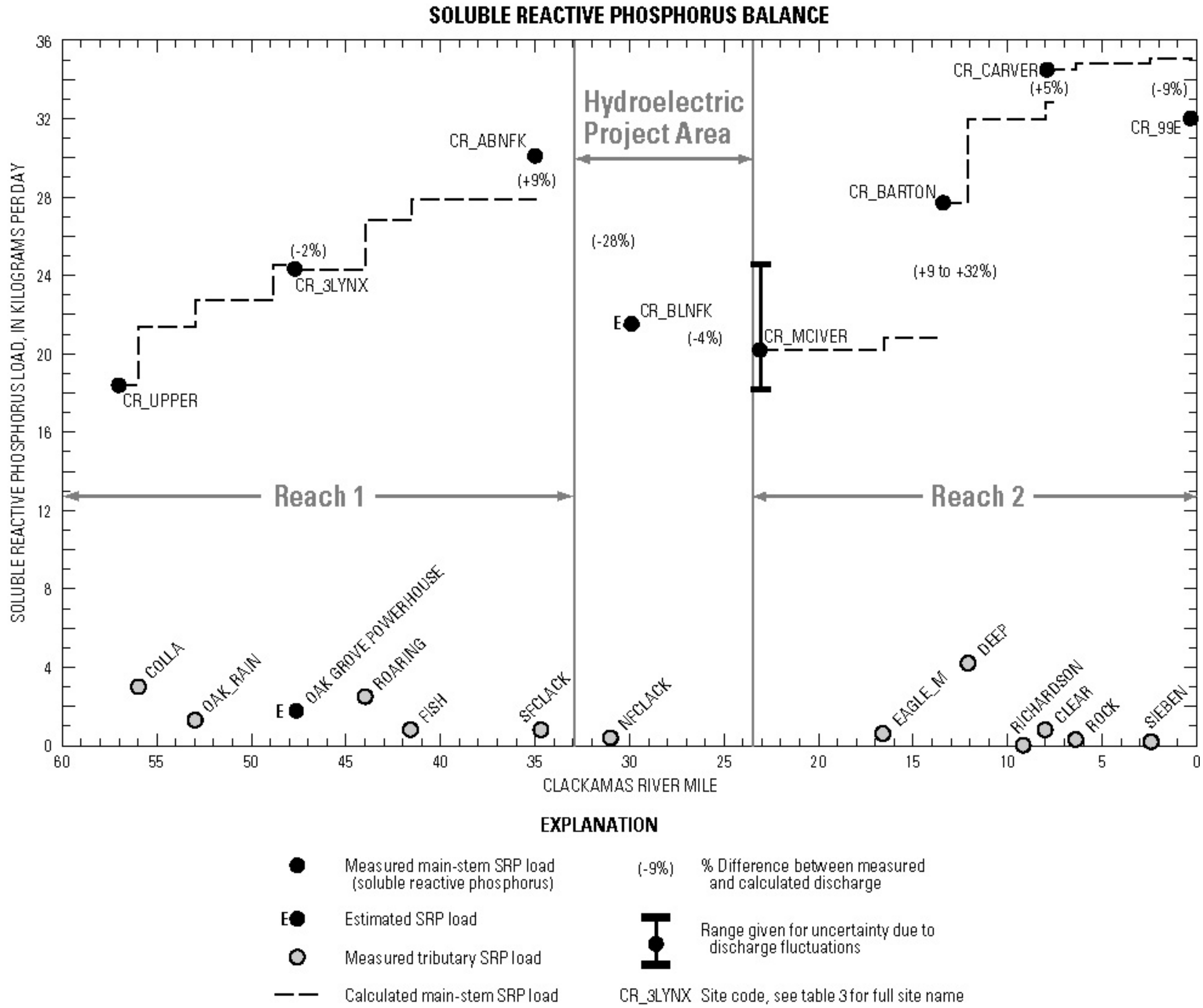

Figure 14. Soluble reactive phosphorus (SRP) load balance in the main-stem Clackamas River, Oregon, July 7–15, 1998. (Discharge values for the Oak Grove Powerhouse and CR_BLNFK were estimated from power-generation records. The SRP load from the Oak Grove Powerhouse assumed an SRP concentration of 2 µg/L [the concentration at OAK_BLTLK].)

Algal Conditions

Algal Biomass (Chlorophyll *a*)

In 1998, accumulations of periphyton (algae attached to the streambed) were first observed in the lower Clackamas River in April, when streamflows were beginning to stabilize and day lengths were increasing. The heaviest algal growths were observed on cobble bars along stream margins and on large rocks in moderate water velocities. By May, thick growths of macroalgae, mostly *Cladophora* sp. (a filamentous green alga) and *Gomphoneis herculeana* (a stalked diatom) produced high biomass (~300 mg/m^2 [milligrams per square meter] chl *a*) in the lower Clackamas River at CR_99E (fig. 9), fouling stream margins. At this time, algal biomass was 2–3 times higher than the range (100–150 mg/m^2 chl *a*) considered indicative of nuisance conditions (Horner and others, 1983; Welch and others, 1988, 1989; Biggs, 1996; Dodds and others, 1997, 1998). The water-quality effects of such high algal biomass (large fluctuations in pH and DO levels) were pronounced in the lower Clackamas River in June (fig. 8).

As the summer progressed, algal biomass declined precipitously in the lower Clackamas River (at CR_99E, fig. 9) following an algal sloughing event (losses of algal material from the streambed into the water column) in June. Chlorophyll *a* values declined nearly 80% in the Clackamas River at CR_99E, from 300 to 50 mg/m^2, between May and July (fig. 9). As a result of this sloughing event, drifting algae clogged drinking water intakes, became entangled on docks and fishing lines, and increased turbidity in the lower Clackamas River, leading to complaints from the public (Robert Baumgartner, Oregon Department of Environmental Quality, oral commun., 1998). Declines in algal biomass indicative of sloughing losses also occurred at OAK_BLTLK, CR_BLNFK, and CR_CARVER, particularly after attaining a biomass of greater than 150–200 mg/m^2 chl *a* (fig. 9). In contrast, gradual seasonal increases in algal biomass were observed from May to September at sites such as CR_UPPER, COLLA, and ROARING (table 8 and fig. 9), where peak biomass values reached between 50 and 100 mg/m^2 chl *a*, and punctuated sloughing losses in biomass were not observed.

High algal biomass also was found at sites immediately downstream from the hydroelectric projects, where three of the four highest chl *a* values occurred (fig. 9 and table 8). Algal growth in the upper Clackamas River downstream from the Oak Grove Powerhouse was especially prolific, reaching 690 mg/m^2 chl *a* in September (the highest value measured during this study). High biomass also was observed downstream from the hydroelectric project reservoirs, especially Timothy Lake and North Fork Reservoir (at OAK_BLTLK and CR_BLNFK, respectively; table 8).

Among tributary sites, algal biomass was generally higher at sites in the lower basin in July compared with those in the upper basin, with the highest chl *a* value (371 mg/m^2) occurring at SIEBEN (fig. 9). Low-to-moderate algal biomass (50–100 mg/m^2 chl *a*) was found at most upper-basin sites, and the lowest algal biomass, ranging from 11 to 23 mg/m^2 chl *a*, occurred at well-shaded tributary sites in forested basins, including ROARING, WINSLOW, FALL, and EAGLE_W, where tree canopy densities ranged from 81 to 98% (fig. 9).

Algal Species Composition

Major types—Nearly 180 algal taxa, mostly diatoms, filamentous green algae, and blue-green algae, were identified in the Clackamas River (appendix 4) and its tributaries (appendix 5). Most sites contained a mixture of algae from the different groups, although some sites were strongly dominated by just one group. Main-stem sites, in general, had greater numbers of algal taxa compared to tributary sites. The greatest number of taxa (per site) was observed at sites downstream from reservoirs, including OAK_BLTLK and CR_MCIVER, where between 75 and 80 taxa per site were recorded. Lower taxon richness (14 to 18 taxa per site) was observed at sites in the middle basin, including EAGLE_W, EAGLE_M, and FALL (appendix 5).

Diatoms composed 139 (78%) of the taxa identified (appendixes 4 and 5). Diatom growth forms were diverse and included filament-forming genera (*Melosira*), mobile genera (*Navicula*, *Nitzschia*, and many others), tightly adhering and epiphytic genera that grow on other aquatic plants (*Achnanthes*, *Rhoicosphenia*, and *Cocconeis*), large and stalked genera (*Cymbella*, *Gomphonema*, *Gomphoneis*), and colonial genera (*Tabellaria*, *Fragilaria*). Two of the diatom genera encountered (*Epithemia* and *Rhopalodia*) are known to harbor symbiotic blue-green algae that have the ability to fix atmospheric nitrogen (Floener and Bothe, 1980; DeYoe and others, 1992), making them potentially important in N-limited rivers. Filamentous green algae included *Ulothrix*, *Zygnema*, *Cladophora*, *Stigeoclonium*, *Spirogyra*, *Mougeotia*, and *Microspora* (appendixes 4 and 5). Two filamentous golden algal taxa, *Vaucheria* and *Tribonema* were also identified. Nine species of blue-green algae, including three N-fixing species (*Nostoc*, *Calothrix*, and *Tolypothrix*), also were identified.

Algal assemblages at the lower-basin tributary sites were dominated by diatom species indicative of nutrient enrichment, including *Melosira varians*, *Nitzschia palea*, *N. frustulum*, *N. inconspicua*, and *Cyclotella meneghiniana* (appendix 5). Relatively small, tightly adhering diatoms, including *Achnanthes*, *Achnanthidium*, and *Cocconeis* (appendix 5), dominated algal assemblages at well-shaded tributary sites in the middle and upper basin, possibly due to selective grazing by benthic macroinvertebrates. The filamentous, N-heterotrophic diatom *Melosira* was frequently found at these sites, whereas filamentous green algae were either absent or present only in minor abundance.

Many of the dominant taxa in the Clackamas River (by biovolume) were filamentous green algae. In the upper main stem, these included *Ulothrix*, *Zygnema*, and *Mougeotia*, and the golden alga *Vaucheria*, whereas *Cladophora* and *Stigeoclonium* were prevalent at sites in the lower Clackamas River (appendix 4). *Cladophora* first appeared downstream of North Fork Reservoir in July, when it composed about 30% of the total algal biovolume. *Cladophora* was also a dominant taxon in the lower Clackamas River at CR_CARVER and CR_99E in July (appendix 4).

Filamentous green algae were often found in association with N-fixing algae (both blue-green and diatoms), and large diatoms, including *Gomphoneis herculeana*, *Cymbella mexicana*, *Frustulia rhomboides*, *Epithemia adnata*, and *E. turgida,* especially downstream of the reservoirs (appendix 4). This association suggests that N-fixing algae may be an important source of N for filamentous green or golden algae, which lack the ability to fix N.

Seasonal succession—In May, the algal assemblages in the Clackamas River were dominated by taxa that are able to withstand strong current by means of specialized holding structures, slippery mucilage (Sabater and others, 1998), or their small size. They included genera of filamentous algae (*Ulothrix, Zygnema, Cladophora, Stigeoclonium, Spirogyra, Mougeotia, Vaucheria, Tribonema,* and *Microspora),* cold-water algae *(Prasiola),* stalked diatoms (*Gomphoneis* and *Cymbella*), and small diatoms (*Achnanthes, Cocconeis, Diatoma,* and *Fragilaria).*

Nitrogen-fixing algae became increasingly abundant in July and September, when concentrations of N were low and concentrations of P were relatively high (fig. 9). N-fixing diatoms, including *Epithemia* and *Rhopalodia*, and the N-fixing blue-green alga *Nostoc* were dominant at main-stem sites downstream to CR_BARTON (appendix 4). In September, stalked diatoms including large-celled species of *Gomphoneis* and *Cymbella* dominated algal assemblages at sites in the upper and lower Clackamas River (appendix 4).

Algal Indicator Taxa

Several groups of algae were found in the Clackamas River Basin that may be used as “indicator species,” based on preferences or tolerances to particular environmental conditions (van Dam and others, 1994). They included alkaliphilic taxa (prefer pH >7), oligotrophic (indicating low-nutrient availability), N-fixing, N-heterotrophic (able to use organic N for energy and growth), eutrophic (indicating high-nutrient availability), and silt-tolerant taxa (table 10).

The relative abundance of indicator algal taxa varied spatially and seasonally, in step with nutrient concentrations, especially for N. Eutrophic and N-heterotrophic diatoms were found where concentrations of N and P were generally highest (fig. 15), whereas N-fixing taxa were prevalent at several sites in the upper basin where concentrations of N were low. The relative abundance of N-fixing taxa increased seasonally, as N concentrations either declined or remained low.

Relations between the different algal indicator taxa and water-quality conditions were not strongly correlated, but did show the appropriate responses in most cases (fig. 15). For example, the percentage of alkaliphilic taxa increased as the pH increased, and N-fixing taxa were primarily confined to sites where the DIN concentrations were relatively low. Silt-tolerant taxa, however, were difficult to evaluate be cause the amount of sediment was not measured in this study and other potential indicators of sediment (TP) or sediment inputs (road density), were not correlated with the percentage of silt-tolerant taxa.

Alkaliphilic taxa—Over 60 species of alkaliphilic diatoms were identified, which is consistent with the alkaline stream pH values (fig. 5). The relative biovolume of alkaliphilic taxa was significantly correlated with pH (fig. 15), excluding two sites with the lowest pH (FALL and NFCLACK) and two sites with the highest pH (SIEBEN and DEEP), which were outliers. Most sites contained a relatively high proportion of alkaliphilic taxa, particularly in July and September, when pH values were generally higher. Alkaliphilic taxa were least abundant (<10% relative biovolume) at COLLA and OAK_BLTLK in May, although proportions increased at these sites in July to 58% and 68%, respectively (table 10).

Nitrogen-fixing taxa—The abundance of N-fixing algae, including the blue-green algae *Nostoc*, *Calothrix*, and *Tolypothrix*, and the N-fixing diatoms *Epithemia* and *Rhopalodia,* generally increased from May to September in the upper Clackamas River (table 10) following the general decline in N concentrations. The N-fixer *Nostoc* was particularly abundant at sites in the upper main stem, which might be attributed to the low N:P ratios (low N and high P) that give them an advantage over non-N-fixing algae. Ward (1985) suggested that some soil stimulatory factor transported through soil erosion also might be responsible for the success of *Nostoc* in the Pacific Northwest as several species of *Nostoc* also thrive in soils (Stewart, 1973).

The relative biovolume of N-fixers in the Clackamas River was much lower immediately downstream from North Fork Reservoir in May (0.02% at CR_BLNFK) compared with the upstream sites (12–44%, table 10), possibly due to an increase in N downstream from the reservoir. The NH_4^+ concentration at CR_BLNFK was 19 µg/L in May, whereas all forms of DIN were below detection at all upstream main-stem sites (fig. 9). The elevated DIN concentrations (table 7) and high DIN:SRP ratios may explain the absence of N-fixing algae at the middle-basin sites in July (table 10).

Table 10. Relative abundance of algal indicator taxa in the Clackamas River Basin, Oregon, May–September 1998

[Values in percent of the total biovolume of diatoms and nitrogen-fixing blue-green algal taxa; site codes are listed in the glossary. Some algal taxa are ubiquitous and were not assigned to a particular guild, whereas others may be classified into more than one guild; therefore, the sums for each site may not be 100.]

Site codes and sampling month	Algal indicator taxa					
	Alkaliphilic taxa	Nitrogen-fixing taxa	Nitrogen-heterotrophic taxa	Eutrophic taxa	Oligotrophic taxa	Silt-tolerant taxa
CR_UPPER (May)	68.7	23.8	0.5	4.3	0.1	0.5
CR_UPPER (July)	67.4	26.9	3.8	10.8	0.2	6.6
CR_UPPER (September)	51.8	80.6	4.4	10.6	0.0	9.0
CR_3LYNX (May)	22.0	44.1	5.0	15.0	2.0	5.5
CR_3LYNX (July)	56.8	7.9	16.6	24.2	3.4	9.5
CR_3LYNX (September)	60.5	25.2	39.3	50.7	0.3	20.5
CR_ABNFK (May)	52.2	11.7	2.4	9.3	0.3	1.1
CR_ABNFK (July)	56.8	44.2	14.0	22.2	0.1	15.1
CR_ABNFK (September)	69.9	59.8	14.6	23.0	1.1	17.8
CR_BLNFK (May)	40.3	0.2	16.9	28.3	0.4	6.4
CR_BLNFK (July)	81.1	51.7	16.1	22.1	1.6	2.7
CR_BLNFK (September)	33.0	29.1	15.8	29.6	1.0	31.5
CR_MCIVER (May)	13.0	0.0	22.2	61.9	3.8	47.4
CR_MCIVER (July)	73.1	62.3	12.8	26.0	0.8	7.7
CR_MCIVER (September)	39.3	6.4	24.9	47.7	0.6	10.8
CR_BARTON (May)	22.5	0.0	9.9	26.1	0.0	18.8
CR_BARTON (July)	35.1	14.6	21.1	38.8	0.0	1.8
CR_BARTON (September)	50.9	48.5	4.8	43.8	1.3	7.7
CR_CARVER (July)	38.4	4.7	7.4	56.9	1.5	5.5
CR_CARVER (September)	44.9	31.3	5.7	48.6	3.6	4.8
CR_99E (May)	33.6	7.7	14.4	26.3	0.0	7.2
CR_99E (July)	16.0	2.6	7.1	24.4	0.7	2.7
CR_99E (September)	49.2	41.7	4.4	59.6	2.2	5.4
COLLA (May)	7.0	0.3	0.0	5.5	0.4	1.1
COLLA (July)	59.1	55.6	0.7	18.8	1.7	8.7
COLLA (September)	63.9	52.4	6.5	21.7	4.7	20.2
OAK_BLTLK (May)	7.4	45.8	3.4	8.3	0.0	5.7
OAK_BLTLK (July)	68.6	49.8	3.8	10.9	5.7	4.8
OAK_BLTLK (September)	25.1	57.7	0.8	3.3	1.2	9.1
OAK_RAIN (July)	45.8	41.4	0.9	8.0	2.7	12.4
ROARING (May)	48.3	15.9	3.3	18.6	0.0	2.0
ROARING (July)	62.2	21.4	10.7	22.8	0.4	16.9
ROARING (September)	50.4	0.0	14.7	30.5	3.9	21.3
FISH (July)	38.7	0.4	21.8	37.0	0.9	7.5
SFCLACK (July)	50.7	0.0	18.9	24.6	0.6	2.6
WINSLOW (July)	52.8	0.0	25.9	55.3	0.4	6.2
FALL (July)	18.3	1.0	0.0	16.0	21.2	2.8
NFCLACK (May)	83.2	0.0	4.3	91.9	0.0	4.0
NFCLACK (July)	52.5	0.0	15.8	27.4	9.5	2.5
NFCLACK (September)	11.2	0.0	28.9	36.2	2.8	31.6
EAGLE_W (July)	58.6	2.9	0.0	15.2	0.0	9.7
EAGLE_M (July)	10.5	0.0	0.5	1.5	0.0	0.0
CLEAR (July)	14.2	0.0	15.0	16.9	2.5	3.0
DEEP (July)	63.4	0.0	55.1	71.9	2.3	7.0
RICHARDSON (July)	77.2	0.0	3.1	71.5	0.0	4.3
ROCK (July)	56.2	0.0	51.6	72.1	0.3	22.0
SIEBEN (July)	81.8	0.0	82.8	96.7	1.2	5.0

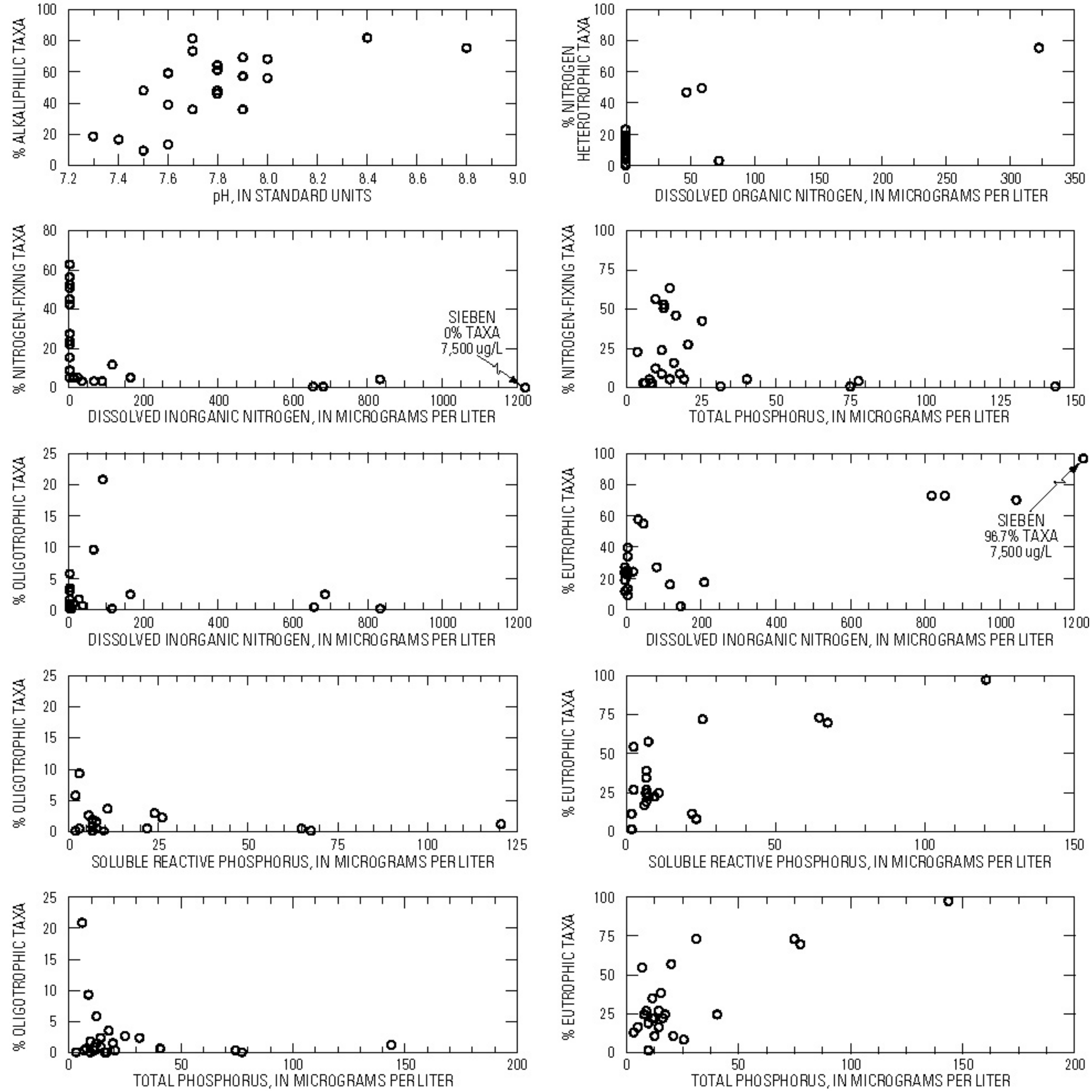

Figure 15. Relations between water quality and indicator algal taxa (as percent relative biovolume) in the Clackamas River Basin, Oregon, July 1998.

N-heterotrophic taxa—N-heterotrophic taxa were most abundant at three of the lower-basin tributary sites (DEEP, ROCK, and SIEBEN), where they composed more than 50% of the relative biovolume (table 10). The highest concentrations of dissolved organic N (dissolved Kjeldahl nitrogen, DKN) also occurred at these sites. N-heterotrophic taxa composed up to 30% of the total algal biovolume at sites where organic N was not detected (fig. 15), although the reporting limits for organic N were relatively high (100 µg/L, appendix 1). Moderate proportions (15–25% relative biovolume) of these taxa also occurred at some middle-basin tributary sites (SFCLACK, WINSLOW, NFCLACK) and at some lower main-stem sites (CR_BLNFK, CR_MCIVER, and CR_BARTON, table 10).

Eutrophic taxa—The abundance of algal taxa that thrive in nutrient-rich water was generally lowest in May and increased in July and September. Eutrophic taxa dominated algal assemblages at the four lower-basin tributary sites most affected by agriculture and urban development (RICHARDSON, DEEP, ROCK, and SIEBEN), where they composed between 72% and 97% of the total algal biovolume in July (table 10). The eutrophic and N-heterotrophic diatom *Melosira varians* was the dominant diatom taxon at the three latter sites. Reimer (1962) noted the success of this taxon in streams with appreciable NO_3^- content, which may explain its success in these Clackamas Basin streams. Eutrophic taxa were also dominant at NFCLACK, CR_MCIVER, and CR_99E, making up >50% of the relative algal biovolume in July.

Oligotrophic taxa—Only six algal taxa were found that are considered to be indicative of low nutrient concentrations (appendixes 3 and 4), generally making up less than 5% of the relative biovolume (table 10). The highest relative biovolumes of oligotrophic taxa occurred at tributary sites, including FALL, NFCLACK, and OAK_BLTLK (table 10), where the SRP concentrations were less than 3 µg/L. The highest relative biovolume of oligotrophic taxa occurred at FALL (21%), where the soluble nutrient concentrations were mixed: the DIN concentration was 116 µg/L, whereas the SRP concentration was <1 µg/L (table 7). This suggests that oligotrophic taxa might be a better indicator of low P conditions, rather than low N.

Silt-tolerant taxa—From May to September, the proportion of silt-tolerant taxa increased at sites in the upper basin, reaching about 20% relative biovolume at CR_3LYNX and CR_ABNFK. These taxa were less abundant at lower-basin main-stem sites (<10% in July and September), compared with sites in the upper main stem (table 10), possibly due to sediment interception by the reservoirs. The highest percentage of silt-tolerant taxa for the lower-basin tributary sites occurred at ROCK, where they accounted for 22% of the total biovolume.

Reservoir Conditions

North Fork Reservoir

Profiles of Field Parameters

Water temperature—Water temperatures in North Fork Reservoir were highest at the surface due, in part, to the deep-water release depth (130 feet), which entrains cooler water through the reservoir, leaving the solar-warmed water near the surface. Water temperatures near the North Fork Dam (at NFKRES_1) increased seasonally from May to August at all depths, reaching a maximum temperature of 18.7°C at the surface (fig. 16). Instantaneous surface water temperatures in the reservoir indicated possible exceedances of the State water-temperature criterion from June through September (table 5), although temperature criteria are based on the 7-day average of the maximum daily temperature, not single point measurements as were collected during this study. Surface-water temperatures were generally higher at the mid-reservoir sampling site (NFKRES_2) compared with NFKRES_1 during all months except September, whereas bottom temperatures were generally lower at NFKRES_2.

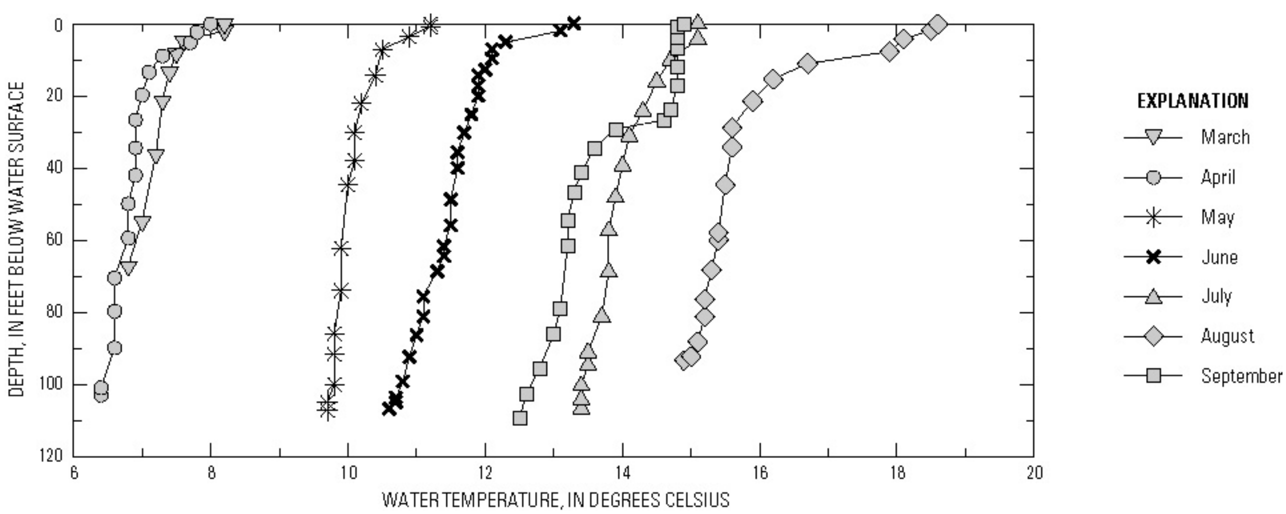

Figure 16. Monthly temperature profiles in North Fork Reservoir, station 1 (NFKRES_1), March–September 1998.

Longitudinal temperature measurements in North Fork Reservoir in August 1997 showed that surface water temperature between the inflow and NFKRES_1 increased 6°C, with most of the warming occurring in the uppermost reaches of the reservoir, around RM 32 (fig. 17).

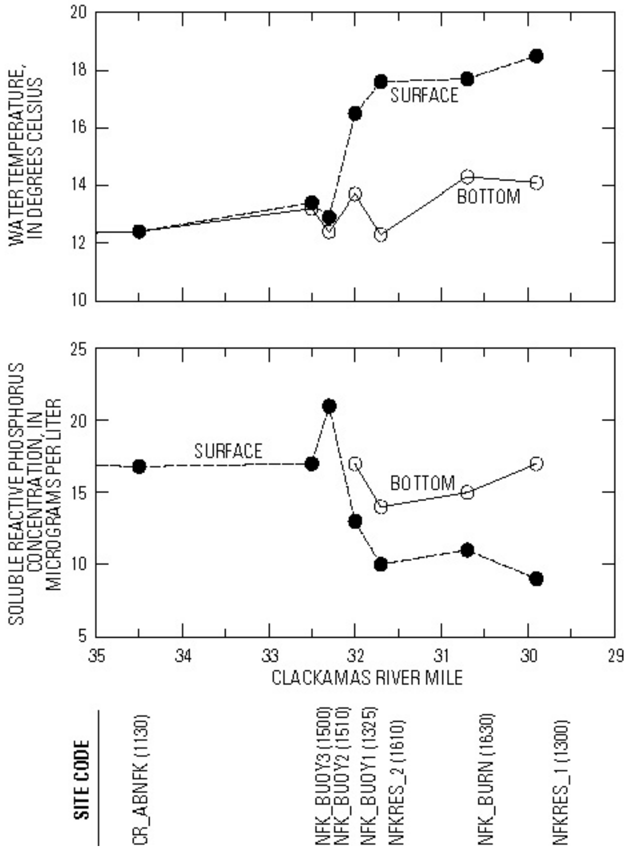

Figure 17. Longitudinal profile of water temperature and soluble reactive phosphorus concentration in the upper Clackamas River and North Fork Reservoir, August 1997. (See glossary for explanation of site codes; measurement times are given in parentheses.)

single point measurements as were collected during this study. The DO concentrations at NFKRES_1 were less than 11 mg/L throughout the water column in July and September 1998. Minimum concentrations of DO at NFKRES_1 were between 87% and 90% saturation from June to September (figs. 18 and 19).

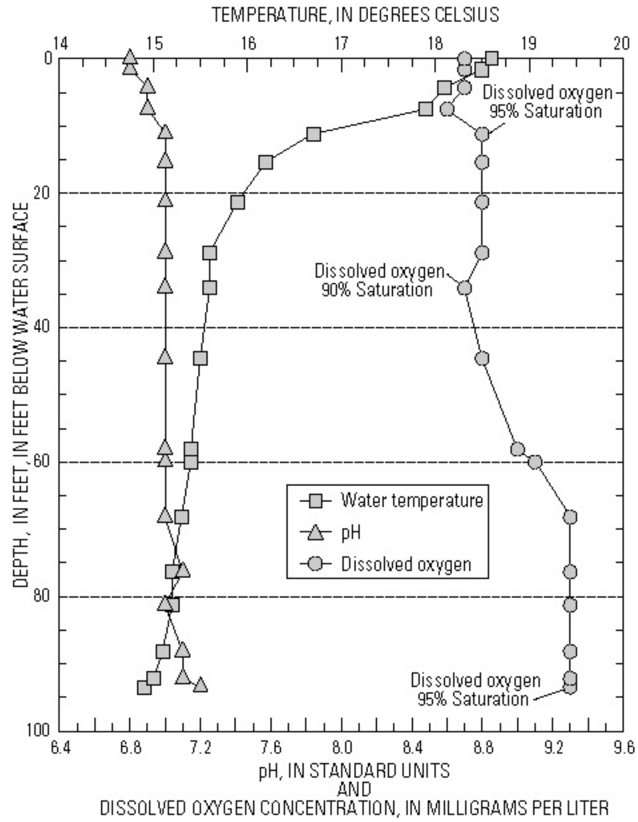

Figure 18. Depth profiles of water temperature, pH, and dissolved oxygen concentration in North Fork Reservoir, station 1 (NFKRES_1), August 1998. (Extremes in dissolved oxygen percent saturation also are shown.)

Dissolved oxygen—Concentrations of DO at NFKRES_1 and NFKRES_2 ranged from 8.6 to 11.5 mg/L (87 to 105% saturation) and showed variation with water depth that was partly related to variations in water temperature (fig. 18). The DO at NFKRES_1 and NFKRES_2 tended to be higher near or at the surface than toward the bottom, except in August, when both the DO and pH were slightly lower at the surface than at the bottom.

DO concentrations were high (>11 mg/L) in March and April at NFKRES_1, but were lower in June, when concentrations were between 9.5 and 10.2 mg/L, which is less than the State criterion of 11 mg/L (table 5); however, DO criteria are based on the 30-day average of the minimum concentration, not

DO was severely depleted in the hypolimnion of North Fork Bay (NFKRES_B), the arm of North Fork Reservoir where the North Fork of the Clackamas River enters. In July, August, and September, the DO concentrations at NFKRES_B were less than 0.5 mg/L. Anoxia at this site coincided with increasing nutrient concentrations in the hypolimnion, presumably from decomposition of organic material at the bottom.

pH—The pH at NFKRES_1 ranged from 6.8 to 8.1 units, with the latter, highest value occurring at the surface in March. The pH was between 0.2 and 0.4 units higher at the surface than at the bottom during all samplings except August, when it was lowest at the surface (6.8 units) and increased to 7.2 units at the bottom (fig. 18). The lowest pH value in North Fork Reservoir (6.3 units) was observed in August in the hypolimnion at NFKRES_B.

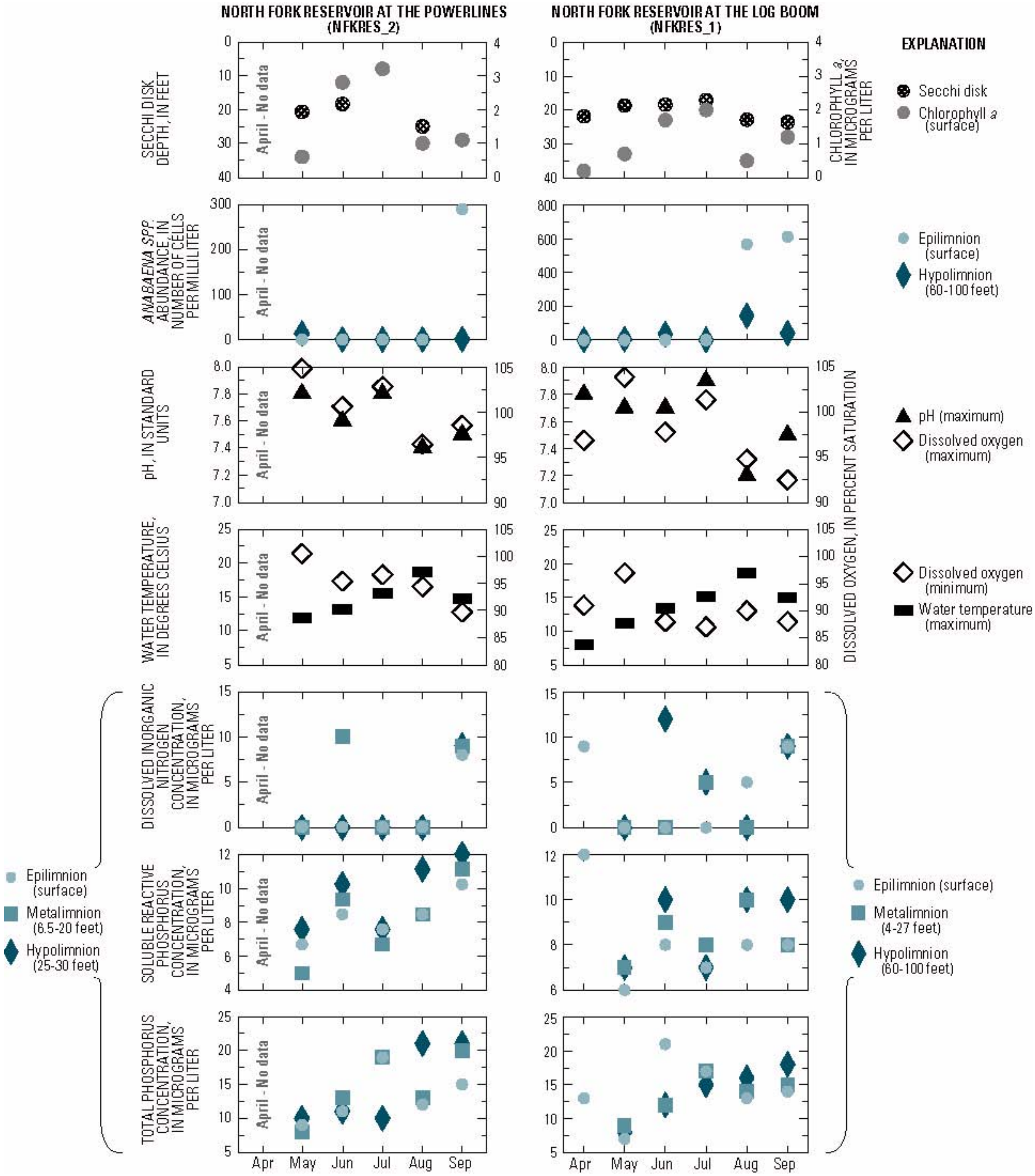

Figure 19. Seasonal variations in water-quality and environmental variables at stations 1 and 2 in North Fork Reservoir, April–September 1998. (Nutrient abbreviations are listed in the glossary. Zero values for nitrogen and phosphorus compounds indicate that the concentration was less than the minimum reporting levels [appendix 1].)

Specific conductance—SC increased in North Fork Reservoir from March to September from about 53 to 69 µS/cm, and showed only slight variations with depth at both sampling stations. The highest SC value measured in the reservoir (175 µS/cm in August) occurred at NFKRES_B near the bottom, where nutrient concentrations were highest and DO was depleted.

Nutrient and Algal Conditions

Nutrients—Nutrient concentrations in North Fork Reservoir were at low-to-moderate levels, and varied seasonally, longitudinally between stations, and also with depth (table 11 and fig. 19). Most of the dissolved, bioavailable N detected was in the form of nitrate (NO_3^-), and organic N (with higher detection levels) was found in 20% of samples at concentrations of 101–220 µg/L. Nitrogen concentrations were especially low (mostly nondetectable) until late summer, when N-fixing blue-green algae (*Anabaena circinalis* and *A. spiroides*) became abundant. In September, NO_3^- was detected at all sampling depths at both stations (fig. 19).

Phosphorus was detected more frequently than N, occurring in all samples collected from the reservoir, at concentrations ranging from 5 to 12 µg/L (table 11). From May to June, SRP (and TP) concentrations at both stations increased at all depths, as P concentrations in the upper Clackamas River also increased (fig. 9). In July, however, SRP concentrations declined, despite the continued high (and increasing) concentration in the main stem, probably the result of algal uptake of P. The longitudinal decrease in SRP concentration observed in August 1997 (fig. 17), and the lower concentrations near the surface, also demonstrate the demand for P by algae in the reservoir. Algal growth continued into July, when the highest chl *a* concentration for 1998 (3.3 µg/L) occurred at the upstream station 2 (fig. 19). These patterns indicated that small algal blooms were occurring between June and July, reducing dissolved nutrients (from algal uptake) while increasing nutrients contained in algal cells (TP) and decreasing water transparency.

In August, concentrations of TP and chl *a* were lower, and the Secchi-disk depths increased slightly, reflecting the lower phytoplankton abundance and greater water transparency. From August to September, NO_3^- concentrations increased at all sampling depths at NFKRES_1, from below detection to 8–9 µg/L (fig. 19). The seasonal maximum concentration of DKN at NFKRES_1 (220 µg/L) also occurred in September.

Silica concentrations increased seasonally, ranging from 14.1 to 20.5 mg/L, and did not vary much with depth or longitudinally between stations. This suggests a low demand for silica by diatom phytoplankton, which utilize silica during growth. The relative scarcity of DIN, combined with moderate amounts of SRP, resulted in low DIN:SRP ratios (0.8 to 1.2; table 11), which indicates that N was in short supply relative to demand.

Phytoplankton—Sixty-seven phytoplankton taxa were identified in North Fork Reservoir (appendix 6). Three distinct phytoplankton assemblages were noted: small flagellates (*Rhodomonas minuta*, *Cryptomonas erosa reflexa*, and *Euglena* sp.) in May through July; *Anabaena* and flagellates in July through September; and *Aulacoseria granulata* in September.

Blue-green algae bloomed each year in North Fork Reservoir, particularly during mid-to-late summer. The highest chl *a* concentration (24 µg/L) was measured at the surface in September 1996 during a bloom of *Anabaena circinalis* shortly after the onset of fall turnover. Although this value is relatively high (the State Action Level is 15 µg/L, based on a 3-month average), lower chl *a* values were measured in 1997 (maximum of 7 µg/L) and 1998 (maximum of 3.3 µg/L). In July 1997, another bloom of *Anabaena circinalis* occurred in North Fork Reservoir at a cell density of 749 cells/mL (cells per milliliter) at the surface, where the highest water temperature (20.4°C), highest pH (7.7 units), and highest DO value (114% saturation) was observed.

In August 1998, another bloom of *Anabaena* (560 cells/mL) occurred in North Fork Reservoir, where it composed 20% of the total biovolume and 50% of the relative abundance at the surface. This bloom occurred as the surface water temperature reached its seasonal maximum of 18.6°C (fig. 19). In September, a population of *Aulacoseria granulata*, a filamentous diatom, developed in the reservoir, composing nearly 90% of the phytoplankton biovolume. At the same time, however, the abundance of *Anabaena*, remained about the same (fig. 19).

Chlorophyll *a* values in North Fork Reservoir were low in 1998 (0.3–3.3 µg/L) despite these small blooms. Concentrations of chl *a* and TP were highest in June and July, when the seasonal minimum Secchi-disk depth occurred (fig. 19). Slightly higher chl *a* concentrations generally occurred at NFKRES_2 compared with NFKRES_1 (table 11), indicating that blooms may be forming near the inlet, where phosphorus-rich water was mixed with warm water in the shallow upper reservoir.

Table 11. Nutrient and algal conditions in North Fork Reservoir, Oregon, April–September 1998

[Samples were collected from the log boom near North Fork Dam (NFKRES_1), mid-reservoir near the powerlines crossing (NFKRES_2), and from the center of North Fork Bay (NFKRES_B); site locations are shown on plate 1; ft, feet; µg/L, micrograms per liter; mg/L, milligrams per liter; mL, milliliter; na, not analyzed; --, not applicable; <, less than minimum reporting levels (see appendix 1); E, epilimnion; M, metalimnion; R, water release depth; H, hypolimnion]

North Fork Reservoir Station 1 (NFKRES_1)

	April	May				June				July				August				September			
Parameter	E	E	M	R	H	E	M	R	H	E	M	R	H	E	M	R	H	E	M	R	H
Sampling depth (ft)	1	1	25	65	100	1	4	40	100	1	10	60	90	1	15	60	90	10	27	60	90
NH_4^+ (µg/L)	2	<2	<2	<2	<2	<2	<2	3	<2	<2	<2	<2	<2	<2	5	<2	<2	<2	<2	<2	<2
NO_3^- (µg/L)	7	<5	<5	<5	<5	<5	<5	9	8	<5	5	5	<5	<5	<5	<5	<5	9	9	9	8
SRP (µg/L)	12	6	7	7	7	8	9	10	8	7	8	7	6	8	10	10	10	8	8	10	10
DIN:SRP	0.8	<1.2	<1	<1	<1	<1	<1	1.2	1.0	<1	<1	<1	<1	<1	<1	<1	<1	1.1	1.1	<1	<1
TP (µg/L)	13	7	9	8	9	21	12	12	13	17	17	15	15	11	13	14	16	14	15	18	18
SiO_2 (mg/L)	na	14.1	14.6	14.6	14.6	15.9	15.0	14.5	16.1	18.1	17.9	18.4	18.2	20.1	19.5	20.5	20.0	21.0	21.3	20.4	20.6
Chlorophyll *a* (µg/L)	0.2	0.7	0.3	0.3	0.3	1.7	1.2	0.3	1.3	2.0	na	2.8	0.5	0.5	na	0.3	na	1.2	1.5	0.8	0.7
Anabaena (cells/mL)	na	0	0	0	5	0	0	0	35	0	0	0	na	566	0	0	144	356	0	0	40

North Fork Reservoir Station 2 (NFKRES_2)

	April	May				June				July				August				September			
Parameter	E	E	M	R	H	E	M	R	H	E	M	R	H	E	M	R	H	E	M	R	H
Sampling depth (ft)	na	1	6.5	--	30	1	10	--	30	1	10	--	25	1	12	--	25	1	20	--	25
NH_4^+ (µg/L)	na	<2	<2	--	<2	<2	3	--	<2	<2	<2	--	<2	<2	<2	--	<2	<2	<2	--	<2
NO_3^- (µg/L)	na	<5	<5	--	<5	<5	7	--	<5	<5	<5	--	<5	<5	<5	--	<5	8	9	--	9
SRP (µg/L)	na	6	5	--	7	8	9	--	10	7	6	--	7	8	8	--	11	10	11	--	12
DIN:SRP	na	<1.2	<1.4	--	<1	<1	1.1	--	<1	<1	<1.2	--	<1	<1	<1	--	<1	<1	<1	--	<1
TP (µg/L)	na	9	8	--	10	11	13	--	11	19	19	--	10	12	13	--	21	15	20	--	21
SiO_2 (mg/L)	na	14.4	14.4	--	15.1	15.9	15.9	--	15.4	18.0	18.0	--	18.5	19.5	20.1	--	20.3	19.9	19.9	--	19.6
Chlorophyll *a* (µg/L)	na	0.6	0.8	--	na	2.8	na	--	na	3.2	3.3	--	1.7	1.0	0.8	--	0.5	1.1	0.9	--	0.7
Anabaena (cells/mL)	na	0	14	--	na	0	0	--	0	0	0	--	0	0	0	--	0	289	1	--	1

North Fork Bay (NFKRES_B)

	August		September	
Parameter	E	H	E	H
Sampling depth (ft)	1	25	10	25
NH_4^+ (µg/L)	6	67	38	99
NO_3^- (µg/L)	24	37	50	47
SRP (µg/L)	3	1	2	1
DIN:SRP	10	104	44	146
TN (µg/L)	306	329	192	237
TP (µg/L)	13	28	13	24
SiO_2 (mg/L)	20	19.3	20.4	20.4
Chlorophyll *a* (µg/L)	7.2	na	2.9	na

Timothy Lake

Profiles of Field Parameters

Water temperature—Timothy Lake had already started to stratify with respect to temperature by May, when the water temperature was 13.7°C at the surface and 5.9°C at the bottom (fig. 20). Warming in the lake continued until August, when the maximum water temperature of 20°C occurred. Surface water temperatures in Timothy Lake were high enough to have exceeded the State temperature criterion in May, August, and September (table 5). Fall turnover started after the August sampling, and by September, surface water temperatures decreased while bottom temperatures increased (fig. 20), showing the effects of mixing within the reservoir.

Dissolved oxygen—Concentrations of DO in Timothy Lake were more dynamic compared with North Fork Reservoir, with higher DO in the metalimnion and lower DO in the hypolimnion. High DO levels (up to 121% saturation), indicative of phytoplankton photosynthesis, were observed in May, August, and September (figs. 21 and 22). Concentrations of DO in the hypolimnion of Timothy Lake were lower than 11 mg/L and so possibly did not meet the State criterion from May to September. DO criteria, however, are based on the 30-day mean of the daily minimum concentrations, not instantaneous measurements as were collected during this study. DO concentration near the bottom of Timothy Lake steadily declined from 9.8 mg/L (87% saturation) in May to 0.9 mg/L (8% saturation) in September (fig. 22), and coincided with increasing concentrations of N in the lake.

pH—The highest pH measured in Timothy Lake (8.6 units in July 1996) occurred in the metalimnion during an *Anabaena* bloom, slightly exceeding the State criterion (table 5). In 1998, the pH in Timothy Lake ranged from 6.8 to 8.2 units, and the maximum pH increased 0.5 pH units from May to September (fig. 22). The pH decreased slightly with increasing depth, especially in August (fig. 21), and a seasonal decline of 0.7 pH units was observed in the hypolimnion from May to September.

Specific conductance—SC values in Timothy Lake were slightly higher at the surface and declined with depth, although SC varied only about 5 μS/cm throughout the water column during each sampling. The SC exhibited a slight seasonal increase from about 48 μS/cm in May to 54 μS/cm in September.

Nutrient and Algal Conditions

Nutrients—Dissolved N and P concentrations in Timothy Lake were mostly low, especially SRP, which was always less than or equal to the MRL of 1 μg/L (table 12 and fig. 22). DIN was detected more frequently, at concentrations ranging from 5–18 μg/L, with the highest concentrations typically occurring in the hypolimnion (fig. 22). DIN:SRP ratios, therefore, ranged from 5 to 18, with the higher ratios likewise occurring in the hypolimnion (table 12). With SRP generally <1 μg/L and DIN typically low too, Timothy Lake was apparently P limited most of the time, with apparent co-limitation by N and P during some periods.

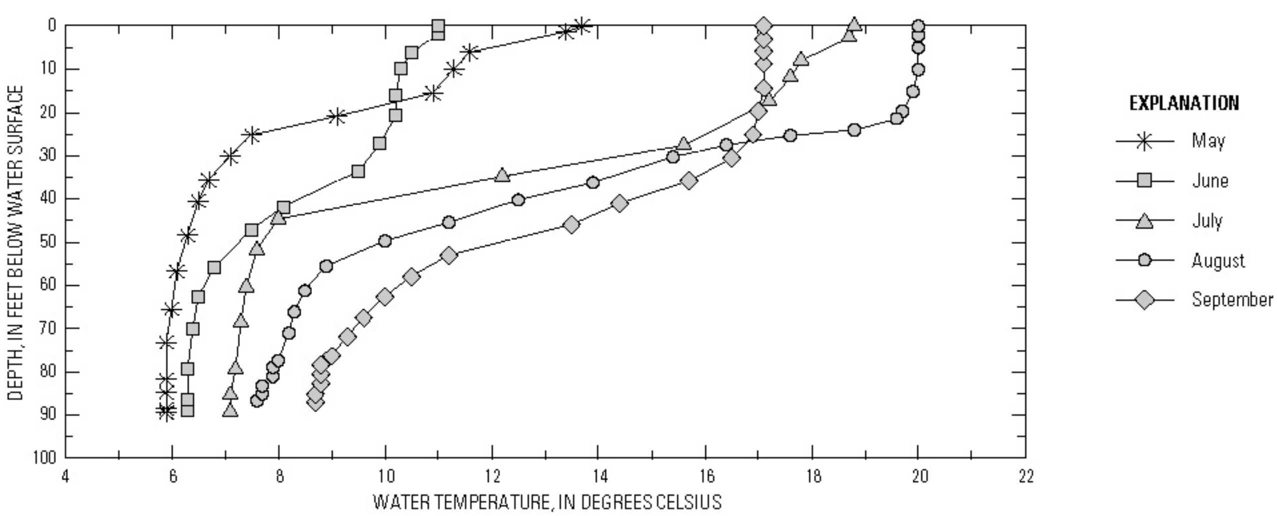

Figure 20. Water temperature profiles in Timothy Lake at the log boom, May–September 1998.

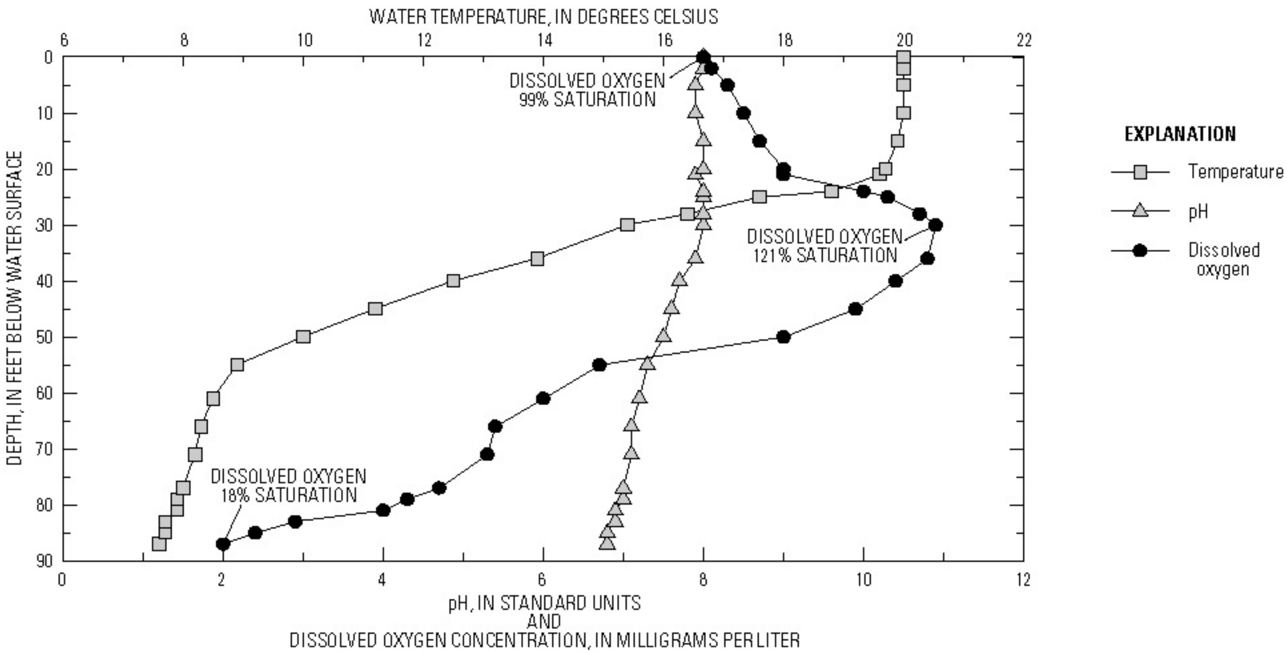

Figure 21. Depth profile of water temperature, pH, and dissolved oxygen in Timothy Lake at the log boom, August 1998.

TP concentrations ranged from 3–15 µg/L and showed a seasonal increase from May to July, then declined in August and September (fig. 22). Regression analysis showed that TP concentrations in the epilimnion and metalimnion were significantly correlated with concentrations of chl *a* (fig. 23). In other words, much of the TP occurred within algal cells.

Phytoplankton—Forty phytoplankton taxa were identified in Timothy Lake (appendix 7), including small flagellates (*Rhodomonas minuta*, *Cryptomonas erosa reflexa*, and *Chlamydomonas* sp.), blue-green algae (*Anabaena circinalis*, *Microcystis*, and *Schizothrix calcicola*), and diatoms (*Asterionella Formosa*, *Urosolenia* sp., and *Aulacoseria granulata*). The abundance of *Microcystis* in Timothy Lake was low (10 cells/mL), but its presence is noteworthy because this alga often produces toxins (Carmichael, 2001; Carmichael and others, 2001). *Microcystis* was not found in North Fork Reservoir during this study.

Blue-green algae blooms were observed each year in Timothy Lake, with the largest bloom occurring in July 1996, when visible *Anabaena* colonies clouded the surface waters of the lake. The chl *a* concentration was 18 µg/L at the surface, but may have been higher at mid-depth (about 20 feet), where the maximum pH (8.6 units) and DO (108% saturation) values occurred. Although this chl *a* value is relatively high (the State Action Level is 15 µg/L, based on the 3-month mean), such high chl *a* values were not typically observed in Timothy Lake. In July 1997, another bloom occurred, with *Anabaena* composing 85% of the relative biovolume at the surface with an abundance of 3,300 cells/mL. Despite the high cell numbers, the chl *a* concentration was low (0.7 µg/L), which could indicate a declining (senescing) population.

In May 1998, the abundance of *Anabaena circinalis* in Timothy Lake exceeded 3,600 cells/mL throughout the water column, composing about 80% of the algal biovolume. The highest cell density and chl *a* concentration (7,600 cells/mL and 7 µg/L) occurred at mid-depth (22 feet, table 12 and fig. 22). Concentrations of *Anabaena* declined thereafter, and higher concentrations were observed towards the bottom of the reservoir, especially in July and August.

In July 1998, a population of *Schizothrix calcicola*, another blue-green alga, developed in Timothy Lake, reaching a density of 3,000 cells/mL at a depth of 40 feet (table 12). Concentrations of chl *a* and TP increased during this bloom, and the seasonal minimum Secchi-disk value also occurred at this time (fig. 22). Smaller quantities of diatoms and small flagellates dominated surface and metalimnetic samples in September, when *Anabaena circinalis* shared dominance with small flagellates in the hypolimnion (appendix 7).

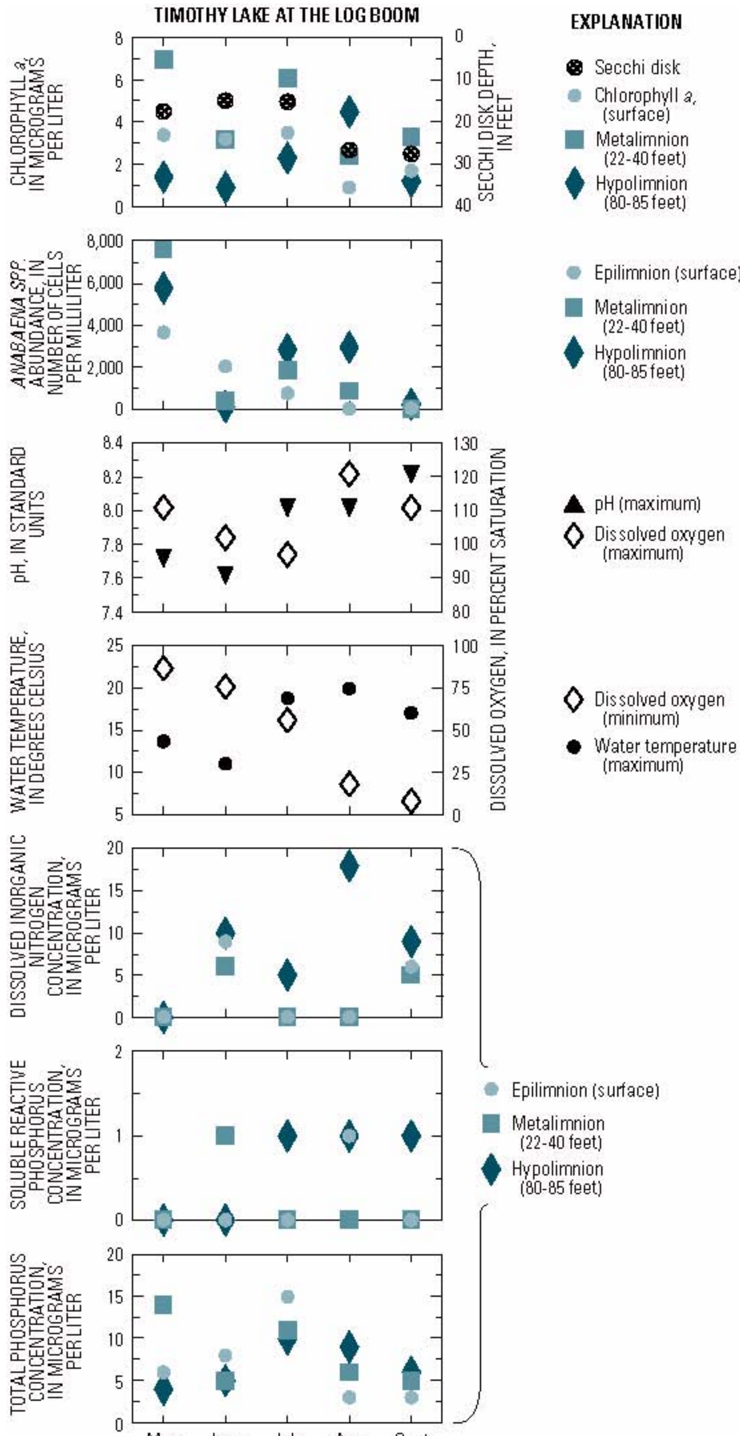

Figure 22. Seasonal variations in water-quality and environmental variables in Timothy Lake, May–September 1998. (Nutrient abbreviations listed in the glossary. Zero values for nitrogen and phosphorus compounds indicate that the concentration was less than the minimum laboratory reporting levels [appendix 1].)

Table 12. Nutrient and algal conditions in Timothy Lake, Oregon, May–September 1998

[Data collected from the log boom at Timothy Lake. Site location is shown on plate 1; E, epilimnion; M, metalimnion; R, water release depth; H, hypolimnion; ft, feet; µg/L, micrograms per liter; mg/L, milligrams per liter; mL, milliliter; na, not analyzed; <, less than minimum reporting levels (see appendix 1)]

	May				June				July				August				September			
	E	M	R	H	E	M	R	H	E	M	R	H	E	M	R	H	E	M	R	H
Sampling depth (ft)	1	22	60	85	1	37	60	85	1	40	60	80	1	24	60	85	10	35	60	85
NH_4^+ (µg/L)	<2	<2	<2	<2	2	<2	5	3	<2	<2	4	<2	<2	<2	<2	13	<2	<2	<2	4
NO_3^- (µg/L)	<5	<5	<5	<5	7	6	9	7	<5	<5	<5	5	<5	<5	<5	5	6	5	5	5
SRP (µg/L)	<1	<1	<1	<1	<1	1	<1	<1	<1	<1	1	<1	1	<1	1	1	<1	<1	1	1
DIN:SRP	na	na	na	na	>9	6	>14	>10	na	na	>4	>5	<7	na	na	18	>6	>5	5	9
TP (µg/L)	6	14	4	5	8	5	5	5	15	11	10	16	3	6	9	7	3	5	6	7
SiO_2 (mg/L)	na	na	na	na	16.5	15.9	15.9	17.2	17.4	17.5	17.4	17.6	17.6	18.3	17.2	17.7	18.1	18.6	17.6	17.6
Chlorophyll *a* (µg/L)	3.4	7.0	1.4	na	3.2	3.2	0.9	0.7	3.5	6.1	2.3	na	0.9	2.4	4.5	na	1.7	3.3	1.2	1.1
Anabaena (cells/mL)	3,668	7,620	5,789	na	2,033	398	104	8	742	1,850	2,840	na	0	860	2,950	na	37	0	214	3

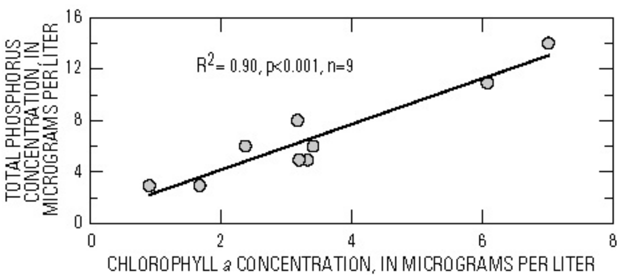

Figure 23. Phytoplankton chlorophyll *a*–total phosphorus relationship in Timothy Lake, May–September 1998. (Includes epilimnion and metalimnion samples only.)

Reservoir Drawdown

The annual fall drawdown of Timothy Lake started unusually early in 1998, and releases up to 220 ft^3/s occurred for about a 3-week period in July and early August. Steady releases from the reservoir began on September 23, when streamflow at the USGS gage downstream of Timothy Lake increased 420%, from 81 to 343 ft^3/s (table 13). Streamflow at the USGS gage upstream of Harriet Lake (at OAK_PP, about 10 miles downstream from Timothy Lake) increased 140%, from 440 to 640 ft^3/s during drawdown.

Reservoir drawdown increased stream water temperatures about 2–2.5°C in the Oak Grove Fork, while a smaller increase in temperature (0.3°C) was observed in the Clackamas River at CR_3LYNX (table 13). Drawdown appeared to increase concentrations of DOC at downstream sites in the Oak Grove Fork and upper Clackamas River, whereas increases in SOC concentrations were observed only at the two most downstream sites (table 13). The observed declines in concentrations of SRP, SiO_2, and SC were consistent with chemical conditions in Timothy Lake at the water release depth prior to drawdown (table 13) indicating dilution by Timothy Lake water.

The concentrations of *Anabaena* in the Oak Grove Fork downstream of Timothy Lake (at OAK_BLTLK) were unaffected by drawdown, but the higher streamflow increased the total numbers (load) of *Anabaena* cells being transported to 420% of predrawdown levels. *Anabaena*, which was not detected at CR_3LYNX prior to drawdown, was found at a low concentration (6 cells/mL) during drawdown.

In 1997, resting "seeds" of *Anabaena*, called akinetes, were observed in water samples collected from two sites in Oak Grove Fork (OAK_BLTLK and OAK_PP) during drawdown. These cells are capable of germinating into viable cells (Fogg and others, 1973) and may be a source of *Anabaena* for downstream reservoirs. It is unknown, however, to what extent *Anabaena* filaments or akinetes survive in the river between Timothy Lake and downstream reservoirs.

Table 13. Conditions in the Oak Grove Fork and upper main-stem Clackamas River before and during the drawdown of Timothy Lake, Oregon, September 1998

[Water releases began midday on September 23; predrawdown samples were collected on September 23; drawdown samples were collected on September 24 (stream sites) and on September 25 (Timothy Lake); site codes and parameter definitions are listed in the glossary; ft^3/s, cubic feet per second; °C, degrees Celsius; µS/cm, microsiemens per centimeter at 25°C; mg/L, milligrams per liter; %, percent; µg/L, micrograms per liter; #, number; <, less than minimum reporting levels; --, not applicable; na, not analyzed]

Parameter	Timothy Lake (60 feet)	Oak Grove Fork (OAK_BLTLK)		Oak Grove Fork (OAK_PP)		Clackamas River (CR_3LYNX)	
	During	Before	During	Before	During	Before	During
Streamflow (ft^3/s)	--	81	343	442	644	816	947
Water temperature (°C)	10.5	8.3	10.3	7.0	9.5	9.9	10.2
Specific conductance (µS/cm)	50	57	52	57	55	66	65
pH (standard units)	7.3	7.8	7.6	7.6	7.8	7.7	na
DO (mg/L)	4.2	10	10	11.2	10.7	10.2	9.8
DO (% saturation)	42	95	99	99	101	94	91
NH_4^+ (µg/L)	4	<2	<2	<2	<2	<2	<2
NO_3^- (µg/L)	5	10	7	10	7	7	9
TP (µg/L)	6	11	7	15	15	20	19
SRP (µg/L)	1	7	1	13	10	16	13
SiO_2 (mg/L)	17.6	18.4	17.4	18.8	18.2	20.4	19.1
SOC (µg/L)	na	300	300	<200	400	200	300
DOC (µg/L)	na	600	900	300	500	400	500
Chlorophyll *a* (µg/L)	1.2	1.0	1.6	0.3	0.9	0.4	0.7
Anabaena spp. (# cells/mL)	214	46	46	0	8	0	6

Ground-Water Conditions

Ground-water samples contained high concentrations of nutrients compared with stream samples (table 14). Concentrations of NH_4^+, SRP, iron, SiO_2, alkalinity, and SC were higher in the wells, where concentrations of DO were notably low (≤0.2 mg/L). Springs, however, were well oxygenated (9–12 mg/L; table 14), with high NO_3^- concentrations (up 3,000 µg/L) and relatively higher chloride (Cl^-) concentrations, compared with wells (table 14). Arsenic was detected in all three well water samples, at concentrations between 2 and 6 µg/L (table 14).

Although springs and seeps occur throughout the upper basin, inputs of ground water to the Clackamas River were most apparent between Estacada and Barton, where an unexplained increase in streamflow of between 8.5 and 27% was observed, possibly from inputs of ground water (refer to streamflow results, fig. 6, p. 27).

Table 14. Chemical characteristics of ground-water wells and springs in the lower Clackamas River Basin, Oregon, January 1999

[Sites were located within 1 mile of the Clackamas River (plate 1). Site codes are listed in table 3 and nutrient abbreviations are listed in the glossary; µg/L, micrograms per liter; mg/L, milligrams per liter; <, less than minimum reporting levels; na, not analyzed]

Site	Depth (feet)	Constituent: DO (mg/L)	NH_4^+ (µg/L)	NO_3^- (µg/L)	SRP (µg/L)	SiO_2 (mg/L)	Cl^- (mg/L)	Iron (mg/L)	Arsenic (µg/L)
WELL_1	103	0.2	480	<50	520	45	1.5	140	6
WELL_2	85	0.1	570	<50	390	42	2.0	140	4
WELL_3	80	0.1	260	<50	160	39	1.9	170	2
SPRING_1	surface	11.9	<20	680	40	30	2.6	73	na
SPRING_2	surface	8.7	20	3,000	30	31	7.8	21	na
SPRING_3	surface	10.8	20	2,100	40	31	4.5	<10	na
SPRING_4	surface	na	na	700	30	na	na	na	na
SPRING_5	surface	na	na	160	10	na	na	na	na

Relations Between Land Use and Nutrient and Algal Conditions

Forest Management

Nutrients—Nutrient concentrations in streams draining forestland showed spatial differences among sites, with higher levels of N and lower levels of P occurring at sites in the middle basin, and the opposite (low N and high P) occurring at upper-basin sites. Nitrate levels in middle-basin tributaries increased steadily as the percentage of nonforest upland in the basins increased (fig. 24), which suggests that higher N levels might be related to forest management. As described earlier, nonforest upland includes areas in Landsat images without a green vegetation signature (table 4), which were interpreted as recently harvested land. Tree removal reduces uptake of N by vegetation in the short term, and post-harvest burning of slash debris releases N (Fenn and others, 1998). Moreover, fertilization of forestland with N, which is discussed in more detail later in this report, also may contribute to elevating N levels in streams if fertilizer leaches into ground water. Other potential sources of N, however, including proliferations of N-fixing plants such as red alder and scotchbroom, atmospheric deposition, and wildfires, also may contribute N to streams. NO_3^- concentrations at the upper-basin tributary sites, however, were mostly low and did not increase with the percentage of nonforest upland in these basins, despite the sometimes-higher levels of nonforest upland. This may be due to the higher P availability, which may have induced uptake of N by algae in the upper-basin streams.

A similar positive relationship was found between nonforest upland and TP concentration for all forested tributary sites (fig. 24). Phosphorus in the upper basin probably originates from a geologic source, as TP concentrations were positively correlated with silica (fig. 12). Silica is an important component of most soils and when taken together, these associations suggest that forest management activities (timber harvesting or associated road system) might be enriching ground water and streams with P through erosion or dissolution of naturally occurring phosphorus-rich volcanic soils.

Algal biomass—Algal biomass in streams draining forestland also showed spatial differences among sites, with the highest chl *a* values ranging from 95 to 235 mg/m^2, occurring at CLEAR, SFCLACK, FISH, and OAK_RAIN (table 7). Algal biomass at other sites in forested basins was lower, possibly due to reduced availability of light needed for photosynthesis and/or lower nutrient concentrations (DIN was not detected, and SRP was ≤3 µg/L; table 7). Algal biomass at sites in "reference" basins containing high amounts (77–91%) of mature forest was lowest of all, ranging from 11 to 20 mg/m^2 chl *a* (ROARING and EAGLE_W; table 7).

Agriculture and Urban Development

Nutrients—Water quality was most impaired at the four lower-basin tributary sites (DEEP, RICHARDSON, ROCK, and SIEBEN), located in basins containing moderate-to-high proportions (28–62%) of agricultural and urban land. The highest nutrient concentrations and the highest SC values occurred at these sites (table 7). Moreover, concentrations of SRP and SC values generally increased as the percentage of agricultural and urban land increased.

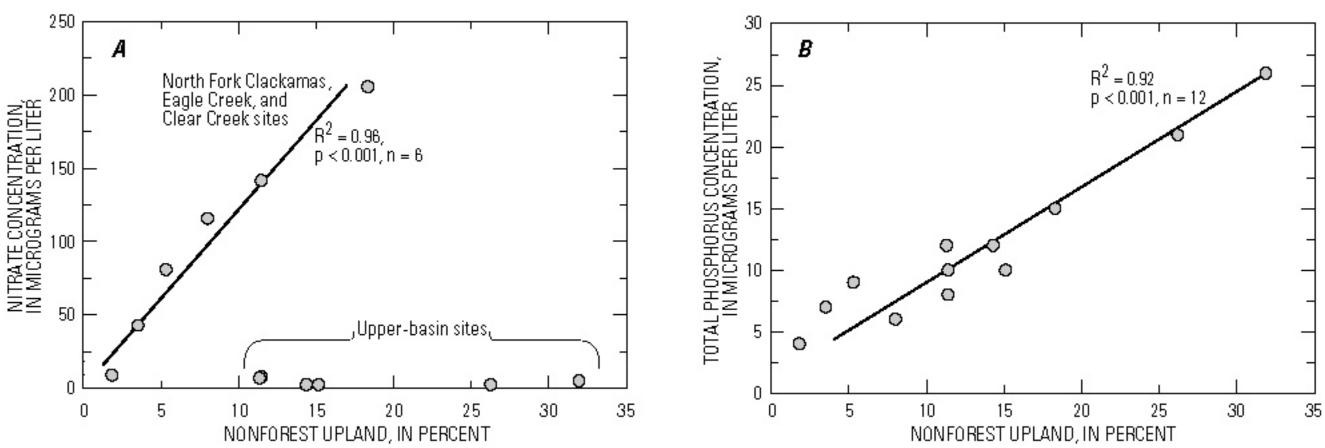

Figure 24. Relations between percentage of nonforest upland and concentrations of nitrate (A) and total phosphorus (B) at forested tributary sites in the Clackamas River Basin, Oregon, July 1998.

Due to the relatively small streamflow values in Rock and Richardson Creeks (about 1–2 ft^3/s in July), nutrient loads from these streams were less than from most other tributaries (fig. 11). Sieben Creek, however, with its high concentration of NO_3^-, contributed a disproportionately high load of N given its small drainage area (<2 square miles) and low streamflow (1 ft^3/s, table 7). The higher streamflow at DEEP (26 ft^3/s), combined with relatively high nutrient concentrations (1,045 µg/L NO_3^- and 68 µg/L SRP), resulted in the highest loads of N and P for the lower-basin tributaries (fig. 11). The yield of DIN (load per unit basin area) was highest at SIEBEN and DEEP (fig. 10).

Eagle and Clear Creeks, which drain basins containing a relatively low proportion of agricultural and urban land (7–12%), had lower nutrient concentrations compared with Deep, Richardson, Rock, and Sieben Creeks (table 7). The higher streamflows at EAGLE_M and CLEAR, however, resulted in relatively high NO_3^- loads for these sites (fig. 10) despite their lower NO_3^- concentrations.

Algal biomass—Algal biomass at 3 of the 4 sites most affected by agricultural and urban influences (DEEP, ROCK, and SIEBEN) was within or well above the nuisance level of 100–150 mg/m^2 chl *a* in July (fig. 9 and table 7). The chl *a* at RICHARDSON, however, was much lower (51 mg/m^2), possibly due to the higher density of grazing macroinvertebrates that were observed during sampling. Algal taxa indicative of high nutrient conditions (eutrophic taxa), however, composed between 72 and 97% of the algal biovolume at all four of the lower basin sites, including RICHARDSON (table 10).

Effects of Hydroelectric Projects on Stream Conditions

Streamflows

About 70 miles of stream reaches (53 miles of the main stem and 15 miles of the Oak Grove Fork) are affected by the hydroelectric projects. The lower 6 miles of the Oak Grove Fork downstream from Harriet Lake Dam, for example, is typically dewatered and all of the flow (several hundred cubic feet per second) is diverted to Frog Lake (the forebay of the Oak Grove Powerhouse, fig. 2). As a result, streamflow near the mouth of the Oak Grove Fork was only 22 ft^3/s in July (at OAK_RAIN, table 7). For comparison, streamflow at OAK_PP, upstream from the diversion, was 376 ft^3/s, or 17 times higher than at OAK_RAIN at this time (Hubbard and others, 1999).

The effects of the hydroelectric projects on main-stem streamflows were most apparent when discharge at the Three Lynx gage was less than about 2,500 ft^3/s —the approximate value below which power peaking typically occurs. During peaking operations, daily fluctuations in streamflow occurred in the Clackamas River downstream from the Oak Grove Powerhouse (fig. 7). Water releases from Frog Lake occur during the day when power demands are high, producing higher day-time flows, which are followed by smaller releases (and lower streamflows) at night when Frog Lake is refilled.

During the July sampling (see shaded area in fig. 7), power peaking increased the streamflow in the upper Clackamas River by 51% in one day, from 890 ft^3/s to 1,340 ft^3/s. Daily fluctuations in streamflow of more than 300 ft^3/s were recorded in the upper Clackamas River on about 50% of the days in 1998 (Gomez and Sullivan Engineers, P.C., 2000). A 300 ft^3/s change in streamflow equates to an approximate 0.6-foot fluctuation in river stage at a discharge of 1,500 ft^3/s. Typical summertime fluctuations were between 400 and 500 ft^3/s (the largest daily fluctuation of about 700 ft^3/s occurred in July). To accommodate the streamflow fluctuations, water was alternately stored and released in downstream hydroelectric impoundments, causing fluctuating streamflows downstream from River Mill Dam, where discharge increased 55% in one day, from 998 to 1,550 ft^3/s, during the July sampling (fig. 7).

Water Quality

Water temperature—The effects of the hydroelectric projects on water temperatures in the main-stem Clackamas River were most apparent during low-flow in September, when streamflows were lowest. At this time, discharges from the Oak Grove Powerhouse, fed by the cold ground waters in the Oak Grove Fork Basin, reduced temperature in the main stem by about 2°C. In late September, however, during the drawdown of Timothy Lake, water temperatures in the Oak Grove Fork were increased by roughly 2°C.

The effects of lower streamflow on water temperature in the Oak Grove Fork caused by the upstream hydropower diversion (described in the preceding section) were apparent at OAK_RAIN in July, when the water temperature was 15.3°C at 2:20 p.m. For comparison, Roaring River, which had about 5 times the flow, was 13.5°C at 6:25 p.m. the same day.

Water temperature in the Clackamas River increased nearly 4°C from upstream of North Fork

Reservoir to downstream of River Mill Dam in September (fig. 5), based on instantaneous temperature measurements between 9 and 10 a.m. Continuous data (not collected), however, would be more appropriate to evaluate warming in the projects due to variable project operations, which affect travel times through the project. Nevertheless, in August 1997, a 6°C longitudinal increase in surface water temperature was observed between the inflow to North Fork Reservoir and the log boom, with most of the warming occurring within about a mile of the reservoir inflow (fig. 17), resulting in water temperatures that probably did not meet the State water-quality criterion.

Dissolved oxygen—Concentrations of DO in the Clackamas River downstream from the Oak Grove Powerhouse resembled those at upstream sites, and were close to saturation (94–97%, table 8). Immediately below the project reservoirs, however, concentrations of DO were sometimes depressed. This was particularly true downstream from Timothy Lake in July and September, when the DO saturation was 91% at OAK_BLTLK (table 8), reflecting the release of hypolimnetic (deep) water that was nearly anoxic at the time (fig. 22). DO concentrations also were slightly lower in the Clackamas River downstream from North Fork Reservoir (at CR_BLNFK) compared with the upstream site (CR_ABNFK). This was most pronounced in September (table 8), concurrent with seasonal minimum DO values in the reservoir (fig. 19).

pH—The pH levels in the Clackamas River immediately downstream from North Fork Reservoir were 0.3 and 0.5 pH units lower in July and September, respectively, compared with those at the upstream site. Declines in pH also were observed in the reservoir near the water release depth during this time (fig. 19). The pH values downstream from Timothy Lake (at OAK_BLTLK) mirrored those at the water release depth in the lake, with the lowest value occurring in September (table 8).

Nutrients—Nitrogen concentrations immediately downstream from the reservoirs were typically below detection. One sample collected in May immediately downstream from North Fork Reservoir (at CR_BLNFK), however, contained 19 µg/L NH_4^+. Although not exceptionally high, the concentration was nearly 10 times higher than the concentration at the upstream site (table 8). No other NH_4^+ detections were observed immediately downstream from either North Fork Reservoir or Estacada Lake. A low-level concentration of NO_3^- was detected downstream of Timothy Lake (at OAK_BLTLK) during reservoir drawdown in late September (table 13), consistent with NO_3^- concentrations in the lake at that time (fig. 22).

Concentrations of P were lower immediately downstream from the main-stem reservoirs (North Fork Reservoir and Estacada Lake), compared with those at sites upstream from the reservoirs, especially in July and September (table 8 and fig. 9), indicating that the main-stem reservoirs were sinks for P. The SRP concentration downstream from Timothy Lake (at OAK_BLTLK), however, was higher in September (8 µg/L) than in July (2 µg/L, table 8), possibly due to the release of P from reservoir sediments. The DO in Timothy Lake decreased with depth and was 0.9 mg/L at the bottom in September (fig. 22), and probably lower in the bottom sediments. The SRP concentration in Timothy Lake bottom water, however, was only 1 µg/L in September, which suggests that the source of the P was seepage water originating from within the anoxic reservoir sediments.

Algal Conditions

One apparent effect of the hydroelectric projects was to stimulate the growth of algae, particularly filamentous green algae below dams and/or powerhouses. Abundant growths of filamentous green algae (*Ulothrix* in May and *Cladophora* in July, appendix 4) developed downstream from North Fork Reservoir and Estacada Lake. The chl *a* was 332 and 276 mg/m^2, respectively, at CR_BLNFK and OAK_BLTLK in July (fig. 9). *Cladophora* (a common high-biomass nuisance alga) composed about 30% of the total algal biovolume immediately downstream from North Fork Reservoir (at CR_BLNFK in July). This alga was not found at any main-stem sites upstream of North Fork Reservoir, but was found at other sites downstream of the reservoir (appendix 4).

The highest chl *a* values occurred in September, at sites directly affected by the hydroelectric projects, with the highest values occurring downstream from the Oak Grove Powerhouse (690 mg/m^2 at CR_3LYNX, fig. 9 and table 8) and downstream from Timothy Lake (545 mg/m^2 at OAK_BLTLK, table 8). The proportions of eutrophic algal taxa (high-nutrient indicators) also were typically higher immediately downstream from the hydroelectric projects compared with upstream sites (table 10). The relative proportions of eutrophic diatoms, for example, increased two- to threefold at CR_3LYNX compared with the next upstream site (CR_UPPER) in May, July, and September. In May, eutrophic taxa composed 28% and 62% of the biovolume downstream from North Fork Reservoir

(CR_BLNFK) and Estacada Lake (CR_MCIVER), respectively, whereas these taxa comprised only 9% of the biovolume at the upstream site (CR_ABNFK, table 10). Interestingly, N-fixers were nearly absent (0.02% of the biovolume) immediately downstream from North Fork Reservoir (at CR_ BLNFK) in May, presumably due to the higher N concentration (19 µg/L NH_4^+), which may have eliminated the advantage that these taxa have over non-N-fixing algae.

Aquatic macrophytes (rooted plants) and associated filamentous green algae also were observed at some locations in the hydroelectric projects, including the fish ladder between North Fork Reservoir and Faraday Diversion Dam, in Faraday Lake, and in the northeastern end of Timothy Lake (fig. 2), particularly in July and August. Fouling of canal racks and screens by dislodged macrophytes and algae occasionally occurs in the main-stem hydroelectric projects, especially in the fall (Doug Cramer, Portland General Electric, written commun., 2001).

DISCUSSION

Stream Nutrient Conditions

Nutrient concentrations in the main-stem Clackamas River were dynamic and appeared to respond to seasonal declines in streamflow, inputs of tributaries with differing nutrient levels, biological processes such as cycles in algal nutrient uptake (growth) and senescence (death and decay), and in-reservoir processes (uptake, senescence, and sedimentation). Higher spring streamflows resulted in lower concentrations of P at most sites in May, for example, compared with July and September, when lower streamflows produced less dilution and hence higher concentrations of dissolved constituents, including P.

The spatial distribution of nutrient concentrations in streams appeared related to land use and basin location (elevation), with the highest concentrations of N and P occurring at tributary sites in the lower basin, where most of the agriculture and urban development is located. Among the tributary sites at higher elevations in forested basins, three groups of sites were recognized: (1) the upper-basin sites, characterized by relatively high concentrations of P and low concentrations of N, (2) Fish Creek and the South Fork Clackamas River, which had intermediate concentrations of N and P, and (3) middle-basin sites, where concentrations of P were low, but N concentrations (especially NO_3^-) were high (tables 7 and 9). This spatial pattern generally corresponds to the U.S. Environmental Protection Agency (USEPA) Level IV Ecoregions, which are delineated for the Clackamas River Basin in Metro (1997): lower-basin sites in the Willamette Valley Foothills and Prairie Terraces Ecoregions, middle-basin sites in the transition area from the Western Cascades Lowlands Ecoregion to the Western Cascades Montane Highlands Ecoregion, and upper-basin sites in the Cascade Crest Montane Forest Ecoregion (sometimes referred to as the High Cascades Ecoregion). Differences in the geology, soils, vegetation, fire history, and land use among the different ecoregions are reflected in the observed pattern in N and P concentrations among the sites.

Low DIN concentrations, low DIN:SRP ratios, and high abundances of N-fixing taxa in the Clackamas River all indicate low N availability, and likely N limitation, an assertion that is consistent with other studies on western Cascade streams (Triska and others, 1983; Leland, 1995; Bakke and Pyles, 1997; Anderson and Carpenter, 1998). Seasonal and longitudinal declines in DIN concentrations and loads were observed that demonstrate the high demand for N by algae in the Clackamas River. In contrast to other dissolved substances, such as SiO_2 and SRP, which increased from May to September, DIN concentrations generally decreased (fig. 9 and table 8). DIN loads in the Clackamas River in July increased substantially between CR_MCIVER and CR_BARTON due to the inputs from Eagle Creek (figs. 10 and 11) and other unmeasured sources, such as ground-water discharges. The DIN load at CR_ BARTON, however, was about 30% less than that from Eagle Creek alone, suggesting that periphytic algae used a significant amount of the DIN in the 3.2 miles between the mouth of Eagle Creek and Barton.

Loads and concentrations of DIN in the lower reaches of the Clackamas River also declined, especially downstream from Barton in May, and downstream from Carver in July. This pattern of declining N in the lower Clackamas River was somewhat unexpected, given the relatively high N inputs from the lower-basin tributaries, ground-water discharges, and other sources. High rates of N uptake by algae in the lower Clackamas River, as confirmed by the high algal biomass, may explain the observed decrease in DIN in this reach. Efficient uptake of inorganic nitrogen (NH_4^+ and NO_3^-) by algae has been shown in other Cascade streams (Munn and Meyer, 1990; Peterson and others, 2001), and low concentrations of DIN often coincide with high algal biomass (Anderson and Carpenter, 1998) owing to the efficient use of N in these presumed N-limited streams.

Comparison of Nutrient Concentrations to Suggested Criteria

The effects of nutrient enrichment on aquatic ecosystems have been well-documented (Vitousek and others, 1997; Correll, 1998; Litke, 1999; Fuhrer and others, 1999). Although the U.S. Environmental Protection Agency has established upper-limit goals for TP to prevent nuisance plant growth in aquatic ecosystems (U.S. Environmental Protection Agency, 1986), it is generally accepted that the criteria for N (ammonia and nitrate), which were developed to address toxic effects, do not protect aquatic ecosystems from excessive plant growth (U.S. Environmental Protection Agency, 2000b). In recognition of the pervasive problem of nutrient enrichment, the USEPA has recently published suggested nutrient criteria on a regional scale to protect water bodies from the negative effects of nutrient overenrichment, including excessive algal growth (U.S. Environmental Protection Agency, 2000b). The recommended criteria are not water-quality standards; they are intended to be starting points for States and Tribes to use in setting their own regional nutrient criteria. If the States or Tribes do not develop their own criteria by the end of 2004, the U.S. Environmental Protection Agency will decide whether to promulgate the suggested criteria (Grubbs, 2001).

The suggested nutrient criteria for streams in the Willamette Valley and Cascade Range Ecoregions (U.S. Environmental Protection Agency Level III Ecoregions) were based on a reference condition that represents the natural or least impacted condition, or what is considered to be the most attainable condition (U.S. Environmental Protection Agency, 2000a). The recommended criteria proposed by USEPA were derived from the 75th percentile of the distribution of reference condition values (averaged for all four seasons) within a given nutrient ecoregion, a target that would theoretically provide protection against the effects of nutrient overenrichment while removing the effects of outliers (Grubbs, 2001).

Suggested reference conditions for Clackamas Basin streams located in the Willamette Valley and Cascade Range Ecoregions are given in table 15. Comparing the values in these tables to data collected in the Clackamas Basin (tables 7 and 8) shows that many of the streams exceeded the recommended criteria. This was especially true of most of the lower-basin streams, which typically exceeded the total nitrogen (TN) and TP criteria, often by several-fold, with most of the TN exceedances due to excessive amounts of NO_3^-.

Stream sites in the Cascade Range Ecoregion occasionally exceeded the suggested TN or TP criteria, depending on the location and season. Most of the nutrient concentrations in the high-elevation streams of the Cascade Range Ecoregion were near or below the suggested TN criterion (55 µg/L) and were close to the suggested reference condition for $NO_2^- + NO_3^-$ of 5 µg/L. Some of the middle-basin tributary sites, however, significantly exceeded the suggested reference condition for $NO_2^- + NO_3^-$ (tables 7 and 8). Although the suggested reference value for $NO_2^- + NO_3^-$ may appear low, it may not be unreasonable for streams in the Clackamas Basin given that it was often met, particularly at sites in the upper basin. Exceedingly low concentrations of N are often observed in other Cascade streams, leading numerous researchers to conclude that N limits algal growth in these streams (Triska and others, 1983; Gregory and others 1987; Bothwell, 1992; Borchardt, 1996). Low N concentrations, however, also may result from efficient uptake of N by algae, which suggests that other measures of nutrient enrichment, such as algal biomass, might be more informative than nutrient concentrations.

Although middle-basin tributaries were often enriched with N, possibly due to the effects of forest management (timber harvesting, forest fertilization, and prescribed burning), streams in this area also may be enriched with NO_3^- from other sources including N-fixing plants, atmospheric deposition, and wildfires. However, the NO_3^- concentration at the reference site (EAGLE_W, located in the Salmon-Huckleberry Wilderness Area) was 9 µg/L, which suggests that concentrations of N in the western portion of the Cascades Ecoregion are quite low. Such a low reference condition for NO_3^- underscores the importance of obtaining low laboratory detection levels for N in future studies in the Clackamas River Basin.

The suggested TP criterion (9 µg/L, table 15) was often exceeded by a factor of two or more at some sites in the upper basin (tables 7 and 8). There is some indication that the TP criterion may be too low to represent reference conditions in the Clackamas Basin streams located in the Cascade Range Ecoregion, as TP concentrations in Roaring River, an unmanaged “reference” basin, exceeded this value with TP concentrations ranging from 10 to 14 µg/L. Higher concentrations of P were observed in some streams draining the eastern portion of the Cascades Ecoregion (CR_UPPER and OAK_RAIN, tables 7 and 8).

Table 15. Reference conditions suggested by the U.S. Environmental Protection Agency for streams in the Willamette Valley (Nutrient Ecoregion I, Subecoregion 3) and streams and reservoirs in the Cascade Range (Nutrient Ecoregion II, Subecoregion 4)

[Nutrient abbreviations are listed in the glossary; µg/L, micrograms per liter; NTU, Nephelometric turbidity units; chl *a*, chlorophyll *a*; mg/m^2, milligrams per meter squared; <, less than; MRL, minimum laboratory reporting level; nd, no data]

Parameter	Number of sites	Reported values: Minimum	Reported values: Maximum	Reference condition (seasonal average)
WILLAMETTE VALLEY STREAMS				
$NO_2^- + NO_3^-$ (µg/L)	85	20	8,640	150
TKN (µg/L)	96	50	2,750	210
TN (µg/L)	13	0.00	2,990	320
TP (µg/L)	138	2	816	40
Turbidity (NTU)	31	0.78	34.5	4.66
Phytoplankton chl *a* (µg/L)[a]	57	0.4	31.1	1.8
Periphyton chl *a* (mg/m^2)[a]	7	63.7	153.8	63.7
CASCADE RANGE STREAMS				
$NO_2^- + NO_3^-$ (µg/L)	75	< MRL	1,910	5
TKN (µg/L)	65	< MRL	950	50
TN (µg/L)	27	< MRL	2,860	55
TP (µg/L)	95	< MRL	242.5	9.06
Turbidity (NTU)	32	0.1	13.1	0.25
Phytoplankton chl *a* (µg/L)[a]	19	0.58	12.75	1.01
Periphyton chl *a* (mg/m^2)[a]	11	24.3	209.7	33
CASCADE RANGE LAKES AND RESERVOIRS				
$NO_2^- + NO_3^-$ (µg/L)	85	< MRL	70	1
TKN (µg/L)	8	120	280	120
TN (µg/L)	nd	120	350	120
TP (µg/L)	74	1.5	98	6.25
Turbidity (NTU)	97	0.0	34.4	18.4
Phytoplankton chl *a* (µg/L)[a]	78	0.3	41.4	0.9

[a] Chlorophyll *a* determined by fluorometric method with acid correction.

However, because P concentrations in the Clackamas Basin streams tended to increase seasonally as streamflows declined, the seasonal averages were probably lower than these instantaneous measurements. This suggests that the 9 µg/L criterion might be suitable for the Clackamas Basin, although more data are needed to verify this.

Nutrient Sources in the Clackamas River Basin

Nutrients in the Clackamas Basin have both point and nonpoint sources. Point sources in the basin include individual tributary inputs and industrial discharges, such as wastewater treatment plants (WWTPs), fish hatcheries, and food processing plants. Studies show that approximately 90% of the N and 75% of the P that contributes to nutrient pollution in streams comes from nonpoint sources such as runoff from farms and urban areas, ground water, and atmospheric deposition (Fuhrer and others, 1999).

Point Sources

Wastewater treatment plants—WWTPs discharge effluent into surface water in the Clackamas Basin from several locations, including the Job Corps Center (into the Clackamas River near Ripplebrook

Ranger Station), the City of Estacada (into Estacada Lake), the town of Boring (into Tickle Creek, a tributary of Deep Creek), and the City of Sandy (into North Fork Deep Creek). The total discharge from these plants is less than 2 ft^3/s, but the nutrient concentrations are sometimes high, up to about 7,000 µg/L TP and 16,000 µg/L NH_4^+ during summer months. Nutrient loads from the WWTPs were significant during this study, discharging nearly as much as the highest-contributing tributaries (figs. 10 and 13).

Other potential sources of sewage in the basin include overused and leaky pit toilets along the Clackamas River, dispersed camping (U.S. Forest Service, 1995c), septic tank effluent from unsewered residential areas, and some RV parks that sometimes use land application for disposal of sewage wastewater. Relatively high concentrations of NO_3^- and Cl^- were observed in shallow ground water, which could indicate a septic origin. The highest NO_3^- concentration measured in this study (7,000 µg/L) occurred in July in Sieben Creek; septic systems are prevalent in a residential area a short distance upstream of the sampling location (Andrew Swanson, Clackamas County Department of Water Environment Services, oral commun., 2000). The dominant alga in Sieben Creek was *Melosira varians*, a diatom that is known to respond to high levels of organic N (Reimer, 1962). Its abundance may indicate a septic source for the NO_3^-, although additional information is needed to verify this.

Fish hatcheries—Eagle Creek fish hatchery effluent contained about 100 µg/L NO_3^- and 20 µg/L SRP in April, when the respective concentrations upstream of the hatchery were 90 µg/L and <1 µg/L. Discharges from the two hatcheries total approximately 70 ft^3/s during peak operations. In July, the load of N from the Eagle Creek hatchery was about the same as that from the North Fork Clackamas River (fig. 10), and the P load was about the same as that for Clear Creek (fig. 13). A one-time sampling of nutrients from the fish hatcheries may not be representative, however, because of variations in the numbers and types of fish, methods for raising and feeding them, and release times.

Nonpoint Sources

Nonpoint sources of nutrients are potentially important in the Clackamas River Basin. Data on most nonpoint sources in the basin are limited, and determining the relative contributions and importance of these sources was beyond the scope of this study. However, this knowledge would be a valuable contribution to understanding the potential effects of different land uses or management scenarios on stream conditions. Nonpoint sources that would bear investigation include (1) fertilizer use in agricultural, urban, and forested settings, (2) soil erosion, which is discussed separately below (3) field burning in agricultural and forested areas, which converts organic matter into NO_3^- (Fenn and others, 1998) that can subsequently leach into ground water and streams, (4) livestock, which contribute nutrients and bacteria to streams, (5) atmospheric deposition of N from being located in Portland's airshed, also discussed below, and (6) ground water, which has already been shown to contain nutrients, often at high levels (discussed below).

Soil erosion—Erosion of soils in the Clackamas River Basin is widespread. Unstable geology and steep slopes in many upper-basin drainages contributes to mass wasting and erosion, particularly in the Fish Creek and Collawash River Basins and along portions of the upper Clackamas River, where the surface erosion potential is relatively high (Metro, 1997). An ancient landslide currently being eroded by the Collawash River, for example, contributes fine sediment that often causes high turbidity during winter storms (U.S. Forest Service, 1995b). The suspended sediment may contribute to occasionally high concentrations of TP, resulting in depressed water-quality scores in the upper Clackamas River at the Oregon Department of Environmental Quality's Memaloose Road sampling site (Greg Petit, Oregon Department of Environmental Quality, written commun., 1998).

Turbidity levels in some of the lower-basin tributaries, including Rock, Richardson, Deep, and Sieben Creeks, have been especially high (150–1,200 NTU [nephelometric turbidity units]) after rainfall events (U.S. Geological Survey, unpub. data, 2000). Other studies have found streambank erosion in the lower reaches of Sieben Creek (KCM, Inc., 1995) and Ecotrust (2000) reported excessive streambed sedimentation and marginal visibility in the lower reaches of Rock Creek. High levels of turbidity in the Clackamas River also sometimes results from gravel mining operations in the lower Clackamas Basin (Andrew Swanson, Clackamas County Department of Water Environment Services, oral commun., 2001). In addition to the habitat problems associated with such erosion, sediment-bound contaminants and nutrients, especially P, also may be transported to the river through erosion.

Naturally occurring phosphorus—One of the likely sources of P in the upper basin is naturally occurring phosphate rock, which may enrich ground water with soluble P upon weathering and dissolution. The highest P concentrations for the forested sites (about 25 µg/L TP, most of which was soluble) occurred in the upper Clackamas River and Oak Grove Fork Basins, where ground water contributes significantly to streamflows.

The positive correlation (fig. 12) between concentrations of TP and silica (an important component of most soils) suggests a naturally occurring mineral source of P in the upper basin, which has been reported in other Oregon watersheds (Abrams and Jarrell, 1995; Wilson and others, 1999). However, TP concentrations also were positively correlated with the percentage of nonforest upland (includes clear cuts and other nonvegetated areas) in the forested basins (fig. 24). This suggests that timber harvesting and the associated network of roads in these watersheds may be transporting P through erosion of phosphate-rich soils. Mapping the geographic distribution of naturally occurring P may help guide future erosion/phosphorus management strategies. The positive correlation between SC and concentrations of P suggests that monitoring conductance may be an inexpensive screening tool for determining which streams to test for P.

Atmospheric deposition—Nitrogen enters the air through the combustion of fossil fuels from automobiles, powerplants, and other industries. In the United States, more than 3.2 million tons of N are deposited annually through atmospheric deposition, which is about 54% of the total amount released to the air (Puckett, 1994). Atmospheric deposition is generally less in Oregon compared with other States (Puckett, 1994). Nevertheless, atmospheric deposition may deliver appreciable quantities of N to the Clackamas Basin, especially considering that this area is contained in the airshed for Portland. Although the amount of N in precipitation was not measured during this study, the National Atmospheric Deposition Program (NADP) collects precipitation and dry deposition data from a nearby station, located at Bull Run in the Sandy River Basin. At an elevation of 875 feet, this station best approximates atmospheric deposition in the foothills and valleys of the Clackamas Basin. The average DIN concentration (NH_4^+ + NO_3^-) in precipitation from May to September 1996–2000 was about 900 µg/L, and concentrations exceeding 1,000 µg/L occurred in nearly 15% of samples (NADP website http://nadp.sws.uiuc.edu/, accessed 5/28/2001).

Ground water—Infusions of nutrient-rich ground water are another potential nonpoint source. Ground-water samples collected from springs and wells located near the lower Clackamas River between Estacada and Carver contained high concentrations of N and P. Springs that are probably fed by shallow ground water contained high levels of NO_3^- (up to 3,000 µg/L, table 14), a finding that Hinkle (1997) also reported for ground water in the Willamette Basin. Nitrate originating from nearby recharge areas may leach into ground water from a wide variety of sources because of its high solubility in water. The deeper ground water, represented by the well samples, contained high concentrations of NH_4^+ and SRP similar to those reported by Leonard and Collins (1983).

The amount of ground water entering the Clackamas River, although not measured in this study, is likely significant in selected reaches, given that there are no glaciers or permanent snowfields in its headwaters, yet late summer base flows of about 1,000 ft^3/s in the upper basin are common (fig. 4). Numerous springs were observed flowing out of hillslopes and eroded gravel deposits near or adjacent to the Clackamas River during this study. Piper (1942) suggested that streams in the Willamette Basin, including the Clackamas River, act as drains for ground water. High amounts of precipitation, combined with abundant porous rock, support ground-water discharges to the Clackamas River and some of its tributaries, especially the Oak Grove Fork, which has a high base flow for its drainage area (Sherrod and others, 1996). This study found that significant inputs of ground water were most probable in the lower Clackamas River between Estacada and Barton. The mass loading of nutrients from ground-water sources, however, was not quantified during this study.

Algal Conditions in Streams

Differences in habitat (streamflow, riparian condition, light penetration, and water chemistry) among the sites produced a range of algal conditions. Algal assemblages at well-shaded tributary sites in forested basins (FALL, WINSLOW, and EAGLE_W) were sparse, with low biomass and low numbers of different taxa (species richness). Greater species richness and greater biomass was generally observed at sites located near the mouths of the major tributaries, where additional light and/or nutrients were typically available. Algal assemblages at main-stem sites had the highest species richness and exhibited a pronounced seasonal progression of growth (increased biomass), reflecting the more favorable conditions in the main stem (greater availability of light for photosynthesis, higher streamflow, and possibly greater nutrient availability), which sometimes led to conspicuous episodes of algal sloughing (decay and loss of biomass from the streambed to the water column).

Algal biomass was low-to-moderate (50–100 mg/m^2 chl *a*) at upper-basin sites not affected by the hydroelectric projects. Prolific algal growths exceeding 100–150 mg/m^2 chl *a*, the biomass threshold considered to represent nuisance conditions (Horner and others, 1983; Welch and others, 1988, 1989; Biggs, 1996; Dodds and others, 1997, 1998), were found at some sites, especially those immediately downstream from dams and powerhouses, and at some of the lowermost main-stem sites (fig. 9). Such high algal biomass was not observed in 1993, when 21 mg/m^2 chl *a* as measured in the lower Clackamas River at RM 0.4 (Gregory, 1993). At this time, algal biomass was less than the half the amount (50 mg/m^2 chl *a*) proposed by Nordin (1985, cited in Biggs [1996]) to protect recreational usage of streams in British Columbia, Canada, from nuisance algal growths.

Interestingly, high algal biomass was often observed in conjunction with low-to-moderate nutrient concentrations, especially where filamentous algae were prevalent. Efficient uptake of inorganic nitrogen (NH_4^+ and NO_3^-) by algae probably accounts for the observed inverse nutrient-biomass relationship. High-biomass growths of filamentous green algae have been documented in other similar-sized Western Cascade streams, including the North and South Umpqua Rivers (Tanner and Anderson, 1996; Anderson and Carpenter, 1998) and the North Santiam, Sandy, and McKenzie Rivers (personal obs., 1996–99). Stevenson (1997) suggested that increases in filamentous green algae might overtake diatom assemblages in rivers when they become enriched with nutrients.

Hypotheses to explain high biomass growths of green algae in Cascade Rivers, including the Clackamas River, include:

1. High water velocities that occur in much of the Clackamas River may stimulate algal metabolism and growth by delivering nutrients to cells at higher rates (Horner and others, 1983; Stevenson, 1996), giving the effect of higher nutrient concentrations. Many of the filamentous algae found in the Clackamas River, such as *Cladophora*, have specialized structures that enable them to remain attached to rocks in moderately fast water. High water velocities, however, also result in increased drag on cells, which may result in reduced algal biomass (Stevenson, 1996). This may explain the pattern of highest biomass along stream margins, where the drag from currents would be less than in the main current.

2. Nitrogen fixed by blue-green algae may fuel growths of filamentous green algae (Wetzel, 1983; Dodds and Mollenhaur, 1995). N-fixing diatoms and blue-green algae occurred at all main-stem sites and showed a general increase in abundance as summer progressed. These algae may release up to 40% of the N they fix (Fogg and others, 1973) and can be a significant source of N for other algae. *Cladophora*, for example, has been found to occur in association with N-fixing algae in other N-deficient waters (Dudley and D'Antonio, 1991; Dodds and Gudder, 1992), which suggests that *Cladophora* may obtain some of its N from N-fixing algae. Indeed, it was commonly observed in this study, particularly in the upper basin, that *Nostoc*, a N-fixer, and *Cladophora* occurred on the same rock. This suggests that N-fixing algae supply N for other algae in streams, similar to the role that terrestrial N-fixers, such as alder, plays in providing N for other biota in N-limited terrestrial systems (Binkley and others, 1992).

3. Infusions of nutrient-rich ground water may stimulate algal growth along stream margins, where ground water and surface water interface. If algal growth was nutrient limited, then nutrients entrained in ground water might be rapidly assimilated by algae growing on the streambed. Such nutrients would go undetected in a depth-width-integrated water sample collected from the entire cross section. One set of nutrient samples collected in the upper Clackamas River at Highway 224 milepost 37 (RM 38.3), where algal growth was prolific, showed that the near-shore NH_4^+ concentration was 6 times higher than the concentration in the main current, possibly the result of ground-water inputs that had not fully mixed into the stream.

4. Organic N might be stimulating periphytic algal proliferations. Although DIN is the preferred

form of N for algae, N-heterotrophic algae may utilize dissolved organic N for energy production and growth (Hellebust and Lewin, 1977; Rogers and Gallon, 1988; Bourdier and others, 1989). Organic N was detected sporadically downstream from the reservoirs at concentrations ranging from 264 to 500 µg/L, although detections of organic N were hampered by their higher MRLs (100 µg/L for both DKN and TKN), compared with inorganic N forms (2–5 µg/L, appendix 1). N-heterotrophic algae were found at most sites, including downstream from North Fork Reservoir and Estacada Lake, where they composed between about 13 and 25% of the algal biovolume (table 10). N-heterotrophic algae were also observed, in similar proportions, downstream from hydroelectric reservoirs in the North Umpqua Basin in southwestern Oregon (Anderson and Carpenter, 1998).

5. High algal biomass may have resulted indirectly through reduced numbers of herbivorous macroinvertebrates or through reduced grazing rates, although additional studies are needed to verify this. Power peaking by the hydroelectric projects, for example, causes fluctuations in river stage and can be detrimental to macroinvertebrates. Also, a large, 50-to-100-year flood occurred in the Clackamas Basin in 1996, which resulted in numerous landslides, road failures, and channel shifts, and caused severe bank erosion and high turbidity. The effects of the flood on benthic macroinvertebrates were not documented, but such an extreme disturbance usually causes short-term declines in benthic assemblages through scouring of stream channels. How stream organisms subsequently respond to events such as power peaking or floods depends on the various taxonomic and physiologic properties of the community (Peterson, 1996), and on local hydrology.

Algal Conditions in Reservoirs

Both reservoirs supported moderate-to-dense populations of phytoplankton, as indicated by the relatively high chl *a* concentrations (18 µg/L chl *a* at the surface of Timothy Lake in July 1996 and 24 µg/L chl *a* at the surface of North Fork Reservoir in September 1996), both during blooms of *Anabaena*. For the following 2 years, several smaller blooms of blue-green algae were observed, along with other types of phytoplankton. Blue-green algae strongly dominated some samples, particularly during summer.

Numerous hypotheses have been put forth to explain the success of blue-green algae in freshwaters (Sommer and others, 1986; Shapiro, 1990). River impoundment creates a lake environment that slows the flow of water and increases the residence time, which may play a role in determining whether blue-green algae become dominant (Rickert and others, 1977). Timothy Lake, with a relatively long residence time (8.5 months on average, table 1) and strong thermal stratification, provides phytoplankton with enough growing time to become abundant. The shorter residence time for North Fork Reservoir (about 7 days on average, table 1) may have been responsible for the smaller phytoplankton blooms that were observed compared with those in Timothy Lake. Thermal stratification and creation of a stable warm surface layer, however, may increase the residence time of the epilimnion, which gives phytoplankton additional time to develop. This is especially true for run-of-the-river reservoirs with deep-water releases and cold-water inflows, such as North Fork Reservoir. Here, cold water from the Clackamas River probably flows preferentially near the bottom, effectively reducing interaction between the surface and bottom water, thus slowing the exchange of water between the inflow and the epilimnion. This may increase the amount of time available for phytoplankton to develop near the surface, where blue-green algae often form surface scums (Oliver and Ganf, 2000).

High water temperatures and/or high pH in reservoirs and lakes have also been used to explain the success of blue-green algae (Shapiro, 1990). However, blue-green algae blooms were observed in water as cool as 12°C (in North Fork Reservoir). Another possibility, elevated pH, which was observed during blooms and is likely related to algal metabolism, did not appear to act as a stimulus for bloom formation. Many blue-green algae have special adaptations that may enable them to proliferate in certain lakes and reservoirs (Shapiro, 1990, and references contained therein), including (1) the ability to fix N_2 gas into useable N, (2) the ability to regulate their position in the water column with gas vesicles (Fogg and others, 1973), (3) blue-green photosynthetic pigments that allow them to capture light effectively, (4) wide tolerances for water temperature, pH, and concentrations of carbon dioxide (CO_2), and (5) the ability to produce mucilage and toxins (Carmichael, 2001) that may discourage grazing by zooplankton.

In North Fork Reservoir, relatively high concentrations of P and low concentrations of N resulted in low DIN:SRP ratios (0.8–1.1), which may have contributed to the development of N-fixing blue-green algae. TP concentrations in the reservoir (5 to 12 µg/L) exceeded the reference condition value (6.25 µ/L) suggested by USEPA for reservoirs in the Cascade Range Ecoregion (table 15), possibly due to naturally occurring sources of P from the upper basin. Potential factors that may have contributed to the low concentrations of N in the reservoir include the growth of periphyton in the Clackamas River upstream, particularly in the reach immediately downstream of the Oak Grove Powerhouse. If algal biomass in the upper main stem were lower, then nutrient uptake by periphyton would be less, and higher loads of soluble nutrients (N and P) would likely be transported to the reservoir, resulting in higher concentrations in North Fork Reservoir. Although higher concentrations of N and P might stimulate more phytoplankton growth overall, it might result in a lower incidence of blue-green algae blooms, because the advantage to N-fixers (low N) would be gone, and other algae such as diatoms might compete better. Blue-green algae blooms have not occurred in the Bull Run River reservoirs, the drinking-water source for the City of Portland. Concentrations of NO_3^- in those reservoirs (typically about 40 µg/L) are much higher than in the Clackamas Basin reservoirs, which might allow other types of algae (diatoms and small flagellates) to outcompete the N-fixing blue-green algae.

Schindler (1977) demonstrated that P may control phytoplankton growth in lakes dominated by N-fixers because their ability to fix N from the atmosphere frees them from limitation by N. Nonetheless, the largest abundances of *Anabaena* observed in this study were in Timothy Lake, where, although concentrations of N were low, the SRP concentrations also were low (about 1 µg/L). Although the uptake of nutrients by phytoplankton likely contributes to the low-nutrient concentrations in Timothy Lake, more focused studies are needed to determine what factors limit phytoplankton growth in the reservoir.

Meteorological factors such as wind, light, and precipitation also may stimulate algae blooms (Soranno, 1997). Late summer storms, for example, may deliver nutrients directly to the reservoir through surface runoff, and winds associated with storms may mix nutrient-rich bottom water to the surface, where phytoplankton growth may be stimulated. The September 1994 algae bloom in North Fork Reservoir, which coincided with a taste and odor event, occurred about 5 days after a 0.85-inch rain storm in the basin (Gordon McGhee, Clackamas River Water, written commun., 1996). Cool air temperatures and wind also may destabilize the thermocline and stimulate phytoplankton. In late September 1996, a bloom of *Anabaena* appeared in North Fork Reservoir, when water temperatures at NFKRES_1 were isothermal (11.6–12°C), indicating the onset of fall turnover (mixing of the lake). During turnover, mixing in the reservoir causes colder bottom water, which is rich in P relative to water at the surface, to upwell. This event may have transported P to the surface, where an existing algal population was stimulated into a bloom.

In August 1998, the distribution of *Anabaena* in North Fork Reservoir was uneven through the water column. Two populations of *Anabaena* were found: a surface population (about 500 cells/mL) and a bottom population (about 140 cells/mL), whereas no *Anabaena* was found at depths of 15 and 60 feet. Like many other blue-green algae, *Anabaena* cells contain gas vacuoles that cause cells to float toward the surface, thereby maintaining their position in the photic zone, where light is available for photosynthesis (Fogg and others, 1973). This explains the surface population. The bottom population may be explained by at least two hypotheses: (1) Because gas vacuoles can expand and contract, allowing for variable water column position, cells migrate to the bottom to obtain nutrients from the bottom water, and (2) cells may have originated from within the sediments. Blue-green algae, including *Anabaena*, develop from akinetes (resting seeds) that have germinated within the sediments, apparently stimulated by an increase in light availability (Reynolds, 1972).

The shift in dominance from *Anabaena circinalis* to *Aulacoseria granulata* in North Fork Reservoir may have been related to the cooler surface water temperatures in September (14.9°C) compared to August (18.6°C) or to a destabilization of the water column caused by wind and resulting entrainment of nutrient-rich bottom water. *Aulacoseria granulata* is regarded as a eutrophic species and has been shown to compete with *Anabaena* in other rivers and reservoirs, the outcome being dependent on factors including light, water temperature, and flushing rate of the reservoir (Wehr and Descy, 1998). *Anabaena circinalis* has been shown to prefer slower current and greater temperature stratification than *Aulacoseria granulata* (Wehr and Descy, 1998).

Effects of Algae Blooms on Water Quality and Drinking Water

Stream Algae Blooms

Proliferations of periphyton, mostly filamentous green algae and stalked diatoms, in the lower Clackamas River produced fluctuations in pH and DO concentration, smothered riffle habitats, particularly along stream margins, and contributed to problems with the drinking water supply. These effects are summarized below.

Effects on dissolved oxygen and pH—Thick growths of the green alga *Cladophora* in the lower Clackamas River produced diel fluctuations in pH and DO concentrations in June and July 1998. Concentrations of DO in the lower Clackamas River decreased from 10.5 mg/L in the afternoon to 7.9 mg/L in the morning (fig. 8). Such fluctuations in DO can be stressful for aquatic life (Welch and others, 1989). The pH also fluctuated about 1.4 units through the day in June and July (fig. 8).

The Clackamas River, and possibly some tributaries, is susceptible to pH fluctuations from algal metabolism because of its low alkalinity (<30 mg/L as calcium carbonate [$CaCO_3$] which provides only minimal buffering to changes in pH. Variation in pH occurs because the algae utilize CO_2 during photosynthesis and release it during respiration, and the CO_2 concentration drives pH. In productive streams, the highest pH values occur in the afternoon, when much of the available CO_2 has been taken up for photosynthesis, and the lowest pH values occur in the early morning, after the algae have been respiring all night. The pH in the lower Clackamas River slightly exceeded the State criterion of 8.5 pH units in late June, and again in mid-July. Past research has shown that brook trout gill lamellae become injured at a pH of 9.0 units (Daye and Garside, 1976). The effects at pH values between 6.8 and 9.0 were not, however, evaluated during their study.

Effects of algae on streambed habitats—The spring bloom of *Cladophora* in the lower Clackamas River also smothered stream substrates (river cobbles), enough to make them notably green and slippery. Excessive algal growths may clog the top layer of channel sediments, which interferes with the downward movement of stream water into the streambed (Brunke and Gonser, 1997). This has several potential effects, including (1) the loss of pollution-sensitive invertebrates (Quinn and Hickey, 1990), (2) reduced delivery of oxygenated water to developing fish eggs or early life stages of aquatic invertebrates, and (3) a reduction in the respiration rates of the hyporheic interstitial community (Brunke and Gonser 1997), which could result in higher stream pH (Powell, 1997) because respiration produces CO_2, thereby lowering pH.

Further, periphyton mats that smother streambeds can interfere with upwelling of ground or hyporheic water into streams, thereby increasing the transient storage of such water (Brunke and Gonser 1997). If enriched in nutrients, as was suggested by data collected in the present study, then ground water may stimulate further algal growth in a positive feedback loop. Periphyton mats, while providing beneficial habitat for some organisms, particularly chironomid midges (Dodds and Gudder, 1992), also may modify existing habitats by reducing water velocity in streams (Dodds and Biggs, 2002), which may increase the water temperature. These habitat effects were not evaluated during this study, however.

Effects on water supplies—In May 1998, the algal biomass near the mouth of the Clackamas River was high (300 mg/m^2 chl *a* at CR_99E), about two to three times higher than the nuisance level. In June, clumps of filamentous green algae and stalked diatoms began sloughing from the streambed, increasing turbidity and entangling docks and fishing lines downstream. Drinking-water intakes became clogged (Gordon McGhee, Clackamas River Water, oral commun., 1998) and organic carbon from the algae may have contributed to the observed increase in the concentration of disinfection by-products in chlorinated drinking water in June (fig. 25).

Drinking-water treatment plants using Clackamas River water all use chlorine as a disinfecting agent. When raw water containing organic matter is treated with chlorine, a number of toxic compounds, collectively referred to as disinfection by-products, can form (des Eaux, 1987). Two classes of these compounds, trihalomethanes (THM compounds, including chloroform) and haloacetic acids (HAA compounds), are frequently detected in treated drinking-water samples collected from the distribution systems served by the Clackamas River (Gordon McGhee, Clackamas River Water, written commun., 1998). The current maximum contaminant level (MCL) for THM in drinking water is 80 µg/L and 60 µg/L for HAA (U.S. Environmental Protection Agency, 2001). The highest concentrations of THM and HAA in treated drinking water from the Clackamas River have been as high as 60 and 56 µg/L, respectively (Gordon McGhee, Clackamas River Water, written commun., 1996).

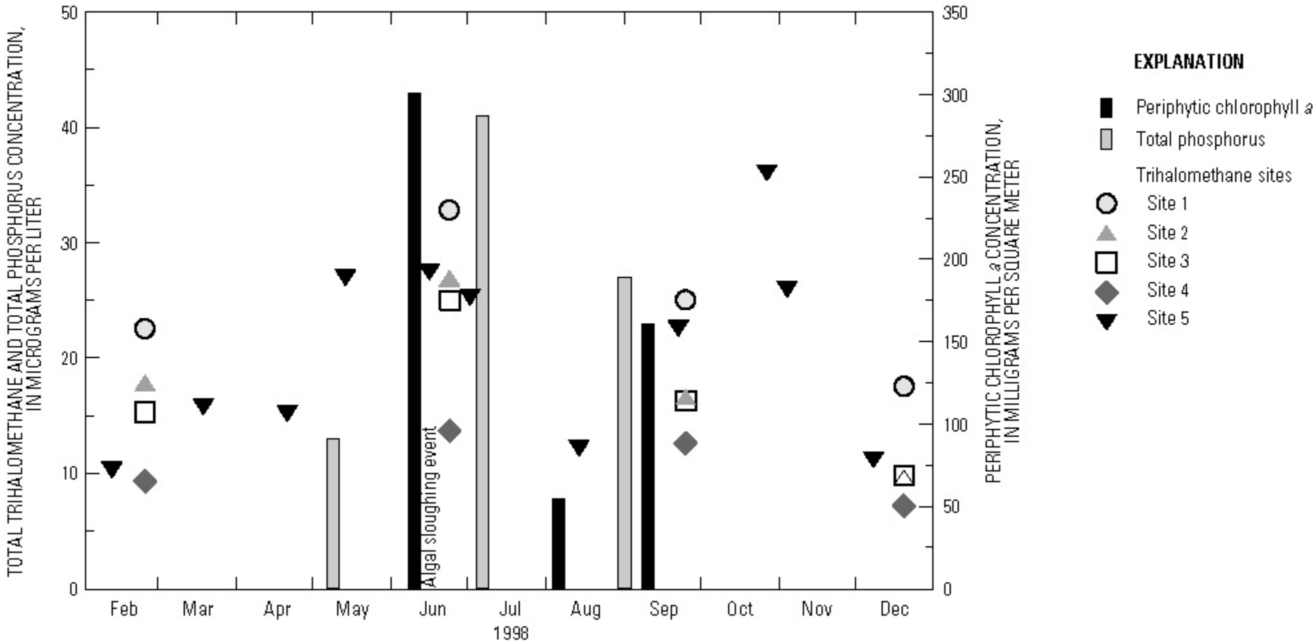

Figure 25. Seasonal pattern in concentrations of disinfection by-products (total trihalomethanes [THMs]) in treated drinking water from the Clackamas River, 1998. (Chlorophyll *a* and total phosphorus data were collected in the Clackamas River at CR_99E, and THM sites were as follows: 1-8533 SE Luther Street, 2-7000 SE Thiessen Street, 3-152nd/Morning Way, 4-9100 SE Mangan Drive, 5-treated water from the Lake Oswego drinking-water treatment plant [THM data provided by Gordon McGhee, Clackamas River Water, and Glen MacDonell, Lake Oswego drinking-water treatment plant]. Sloughing of periphytic algae in June 1998 is also noted).

Although these concentrations do not currently exceed the MCL for these compounds, they do indicate a potential problem, and one that could worsen if algal problems worsen. The quarterly peak in THM concentration observed in treated drinking water obtained from the Clackamas River occurred in June, following the algal sloughing event described above (fig. 25). Future monitoring for disinfection by-products is discussed later in this report.

Blue-Green Algae Blooms in Reservoirs

Blue-green algae are notorious for causing water-quality problems in lakes and reservoirs. Large blooms of certain types of blue-green algae, including *Anabaena*, also may form surface scums that are aesthetically displeasing, may produce toxins that are harmful to aquatic life (Carmichael, 2001), and may lead to taste-and-odor problems in drinking water supplies.

With few exceptions, *Anabaena* was the dominant blue-green alga observed in Timothy Lake and North Fork Reservoir during this study, forming near-monocultural populations in the reservoirs at times. DO and pH were often found elevated at the same depth as the chl *a* maxima, reflecting the bloom conditions. Although not extreme, surface scums of blue-green algae were sometimes observed in both reservoirs.

Taste and odor events—No episodes of poor tastes or odors were reported during 1996–98, despite the relatively high abundances of *Anabaena* in both Timothy Lake and North Fork Reservoir. For example, a surface sample from North Fork Reservoir collected in August 1997 was strongly dominated by *Anabaena*, containing 14,500 cells/mL, 33 times higher than that observed during the taste and odor event in September 1994, when 430 cells/mL were found (Gordon McGhee, Clackamas River Water, written commun., 1996). Why no taste and odor event occurred in 1997 is not clear, given the high cell density at the surface, although thermal stratification (the surface temperature was 18.5°C or 4°C warmer than the rest of the water column) may have restricted the bloom to the epilimnion, away from the water-release depth.

During the September 1994 taste and odor event, cell densities were much lower, but a summer storm delivered 0.85 inches of rain to the basin just 5 days prior to the onset of taste and odor problems, which may have resulted in partial turnover of the reservoir.

This might explain the lower cell densities, as turnover would mix the cells down into the bottom portions of the reservoir, where cells or their taste and odor producing compounds could be transported downstream to drinking water intakes. Other factors, such as sustained periods of calm, sunny weather after the storm may have been important because algal cells at the surface are subject to photo-oxidation and are prone to rapid decay more than when under the surface (Dae-Young and G-Yull, 1997). If rapid decay occurs, intracellular compounds, including geosmin and methylisoborneol (Hayes and Burch, 1989), may cause taste-and-odor problems in drinking water supplies (des Eaux, 1987).

Algal toxins—While toxins were not addressed in this study, two types of blue-green algae known to produce toxins (*Anabaena* and *Microcystis*) were found in the reservoirs. *Anabaena spiroides*, which occurred in North Fork Reservoir at an abundance of 128 cells/mL in September 1998, has been shown to produce toxins that can impact public drinking-water supplies (Beasley and others, 1983; Carmichael, 1986, 1994), and *Microcystis*, another blue-green alga that often produces harmful toxins (Carmichael, 1986, 1994, 2001), was found in Timothy Lake at low abundance (20 cells/mL) in May 1998.

Algal toxins have been detected in other western Oregon Lakes, such as Diamond Lake, near the headwaters of the North Umpqua River, and Ten Mile Lake, near the Oregon coast. In August 2001, a toxic bloom of *Anabaena* occurred in Diamond Lake that closed the lake to fishing and contact recreation for about 2 weeks (Mikeal Jones, U.S. Forest Service, written commun., 2001). Future monitoring for algal toxins is discussed later in this report.

Land Use and Water Management in the Clackamas River Basin

Land-use activities such as forestry, agriculture, and urban development have occurred extensively throughout much of the Clackamas River Basin, potentially causing impacts on habitat and water-quality conditions. In addition, the magnitude and timing of streamflows, which exert strong controls on aquatic life, are affected by the hydroelectric projects. Moreover, the two large reservoirs created by these projects provide suitable habitats for blooms of blue-green algae that have the potential to degrade water quality, affecting drinking-water supplies and aquatic ecosystems.

Forest Management

Timber harvesting in the Clackamas River Basin dates back to the late 1800s, when roads were few and harvesting occurred in riparian areas by felling logs into streams and routing them downstream (Taylor, 1999). In small tributaries, splash dams, log-and-cable structures that would store logs in temporary holding pools, aided the downstream transport of logs. When the cables were released, the water would carry the logs downstream to the mills. This practice scoured stream channels, damaged riparian vegetation, caused bank erosion, and degraded water quality.

The construction of logging roads and advancements in timber harvesting methods led to the expansion of logging to nearly all parts of the basin; between 1950 and 1994, timber harvest occurred in about 65% of the upper Clackamas Basin (U.S. Forest Service, 1995c). Today, timber harvest on public lands is much reduced compared with 10 years ago, when harvest levels peaked at over 5,000 acres per year (fig. 26).

Nitrogen—The highest concentrations of NH_4^+ and NO_3^- on forestland were found at sites in the middle basin, where average concentrations were 3 and 10–20 times higher, respectively, compared with sites in the upper basin (tables 7 and 9). Lower DIN concentrations at the upper-basin sites might be attributable to N uptake by algae, especially at sites where P and light were more available. The relatively high concentrations of DIN at middle-basin sites might be attributable to a combination of forest management activities (harvest, prescribed burning, and fertilization), the abundance of N-fixing plants, atmospheric deposition, and fire history. Also, the lower concentrations of P and reduced light availability at middle-basin sites probably limited algal growth, thus reducing uptake of N by algae.

The positive and significant relationship between the percentage of nonforest upland (primarily clear cuts and other nonvegetated areas) and DIN concentrations at middle-basin tributary sites (fig. 24) suggests that timber harvesting may be accelerating the transport of N to these streams. Disturbance from timber harvesting and road building has been shown to increase N in other streams (Murphy and Meehan, 1991; Greene 1996; Adams and Stack, 1989; Fredricksen, 1971) and prescribed burning after harvest also may increase NO_3^- levels in soils (Fenn and others, 1998), which can be transported to streams.

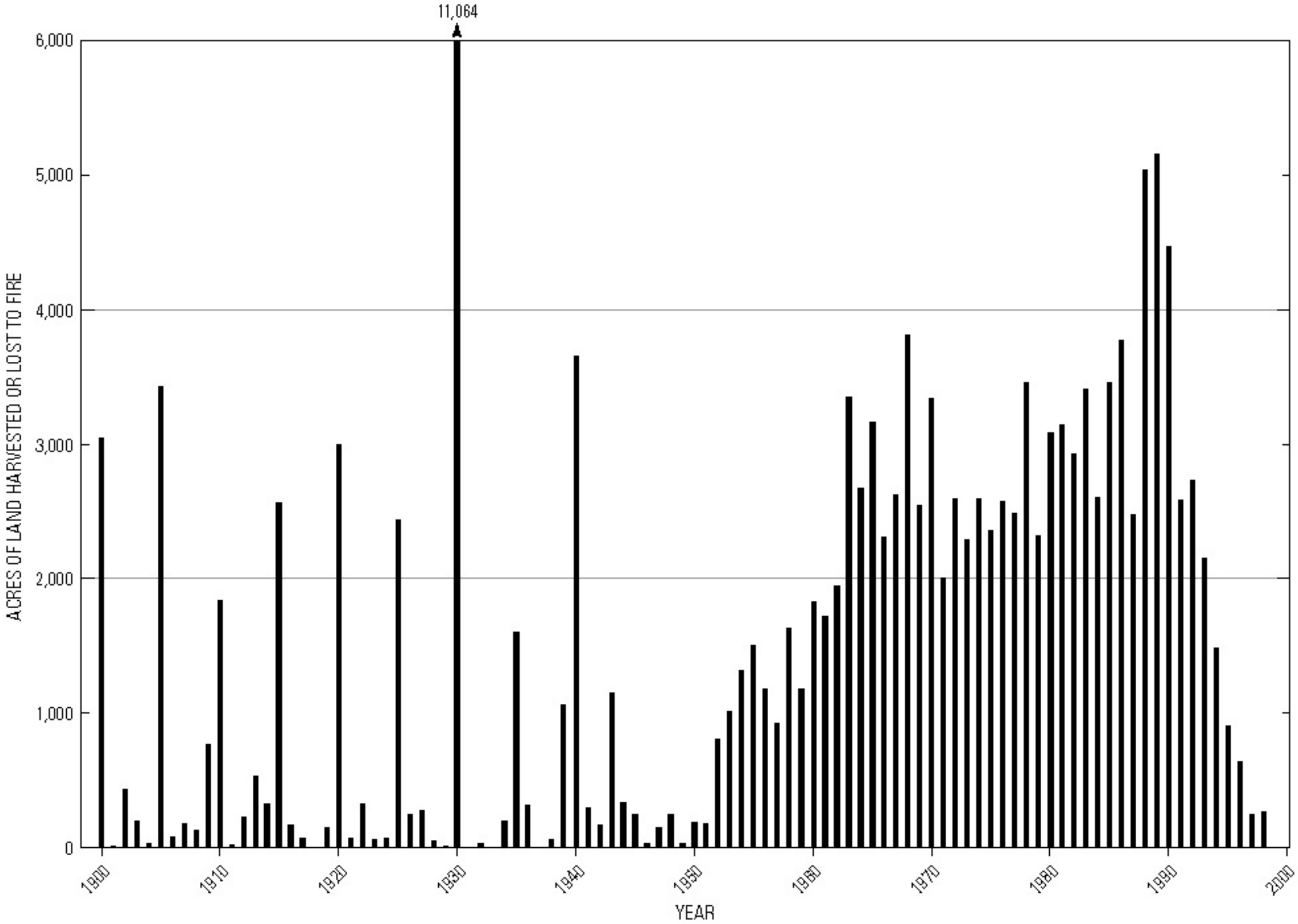

Figure 26. Acres of timber harvested or lost to fire in the Clackamas River Basin, Oregon, 1900–98 (after Gomez and Sullivan Engineers, P.C., 2000).

Forest fertilization, particularly on private forestland, also may contribute to enriching streams with N. Urea-N fertilizer is applied to 15- to 25-year-old (regrowth) forest stands, often in combination with tree thinning, to increase productivity. The highest proportions of regrowth forest, ranging from 30 to 45% were in watersheds located in the middle Clackamas Basin, where the highest DIN concentrations (for the forested sites) were observed (table 7).

Forest management practices aimed at accelerating tree growth were initiated in the Clackamas River Basin during the 1970s, when thinning and herbicide treatments began (U.S. Forest Service, 1995c). The use of urea fertilizers on private and public timber land increased in the mid-to-late 1980s (Edward Hendrix, Longview Fibre Co., oral commun., 1999; Tom Rottman, U.S. Forest Service, written commun., 1999). Application rates on public lands, for example, exceeded 1 million pounds of N at this time (fig. 27), and in 1995–96, over 300,000 pounds of N were applied in the North Fork Clackamas River Basin alone (Tom Rottman, U.S. Forest Service, written commun., 1999). Although fertilizer use has declined on public forests in recent years, fertilization on private land, is expected to increase nationally in the future (NCASI, 1999).

A recent literature review on the effects of forest fertilization found that runoff of N to streams from forest fertilization in the Pacific Northwest has ranged from less than 0.5% to 14.5% of the applied N (Anderson, 2002). Most studies, however, only examined N concentrations in streams (not ground water), were relatively short in duration, and did not address the long-term or cumulative effects of fertilizer applications on stream ecosystems. Potential factors affecting retention or loss of N to ground or surface waters following fertilization include the extent of timber harvesting in the basin, forest composition and age, number and frequency of previous fertilizations, soil characteristics, fire history, atmospheric deposition, and other factors.

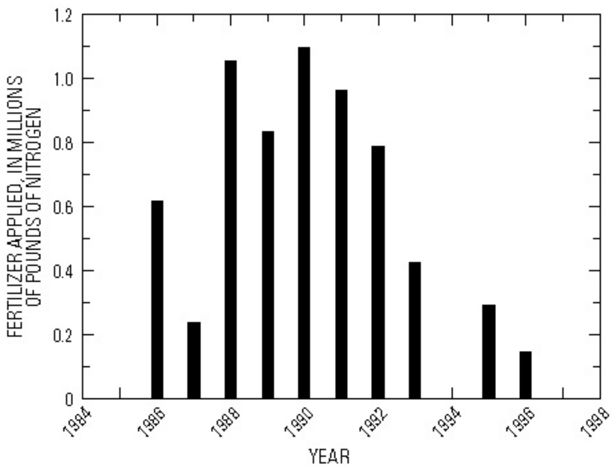

Figure 27. Fertilizer application in the Mount Hood National Forest in the Clackamas River Basin, Oregon, 1986–98. (Tom Rottman, U.S. Forest Service, written commun., 1999.)

The highest N concentrations in streams were typically found immediately after fertilizer application. Brief peaks in TKN concentrations up to 40,000 µg/L, from unintended direct application of fertilizer to streams and riparian areas, have been observed shortly after treatment (Binkley and others, 1999; Anderson, 2002). Elevated concentrations of NO_3^- have been observed as much as 2 years following fertilizer application, particularly during storm runoff (Fredricksen and others, 1975).

Anderson (2002) presents a conceptual model on the potential effects of forest fertilization on N concentrations in streams and algal growth. This model suggests that headwater streams may become enriched with N following fertilization, but that algal growth is not stimulated because of light limitation in these small streams (Lyford and Gregory, 1995), so excess nutrients are transported downstream. Greater light availability in downstream reaches, with additional nutrients from fertilizers, may stimulate algal growth in these reaches (Vannote and others, 1980). Large fluctuations in DO and pH levels and high algal biomass, such as those observed in the lower Clackamas River, could be one symptom of such nutrient enrichment.

Although forest management may play a role in increasing N concentrations in some Clackamas Basin streams, fire may also have had an effect (fig. 26). Wildfires have the potential to increase N in streams either directly by reducing the uptake of N by growing trees, or indirectly by allowing colonization of N-fixing species, including scotchbroom, snowbrush (*Ceanothus*), and red alder (*Alnus rubra*), which may colonize disturbed soils and increase nitrate concentrations in streams (Pojar and MacKinnon, 1994; van Miegroet and Cole, 1988). Vast stands of red alder occur throughout these basins, their abundance being due to a combination of factors, including anthropogenic disturbances (road construction and timber harvesting) and natural events (wildfires and floods). Fire histories in the North Fork Clackamas River and Eagle Creek Basins (U.S. Forest Service, 1995a; 1996a) include large stand-replacement fires (in the upper portions of the Eagle Creek Basin in the late 1800s) and several fires in the North Fork Clackamas Basin in the early 1900s. Afterwards, the North Fork Basin was salvage logged and grazed by sheep (Tom Horning, U.S. Forest Service, oral commun., 2001). The Clear Creek Basin also has experienced significant wildfires, such as the Hillockburn Fire in 1902, which burned the northern one-third of the basin (U.S. Bureau of Land Management, 1995).

Phosphorus—The positive relationship between the percentage of nonforest upland and TP concentrations in streams draining forested basins suggests that forest management, including timber harvesting and/or roads, may be transporting P to streams. However, because nonforest upland also includes areas of exposed rock (table 4), and considering that volcanic rocks may contain natural sources of P (Abrams and Jarrell, 1995; Wilson and others, 1999), dissolution of P from rocky outcrops in these watersheds also may contribute to this relationship. This possibility is supported by the positive relationship between silica and P (fig. 12), which suggests that much of the P is from a geologic source. However, the erosion of phosphorus-rich soils from harvest units and roads also could explain these associations.

The extensive network of roads and roadside ditches provides an efficient sediment delivery system (U.S. Forest Service, 1995c) by which soil bound P may be transported to streams. With the exception of the Roaring River watershed, which has 1.4 road-stream crossings per square mile of land (table 7), the remaining watersheds in the Mount Hood National Forest have between 9 and 16 road-stream crossings per square mile of land (Metro, 1997). About 490 miles of paved and dirt roads, used mostly for logging, dissect the upper basin (upstream of the confluence with the Collawash River), resulting in 377 stream crossings (U.S. Forest Service, 1995c), and road densities range from about 3 to 4 miles of roads per square mile of land (table 7).

From 1990 to 1995, most of the timber harvesting in the upper Clackamas and Oak Grove Fork Basins was on land classified as having a moderate to severe erosion potential (U.S. Forest Service, 1995c; 1996b). Debris flows from clear-cut units in the Upper Clackamas Basin have delivered sediment to streams (U.S. Forest Service, 1995c). Fish Creek, which drains a steep basin that has been extensively harvested (43% nonforest upland and regrowth forest), also experiences erosion problems such as high turbidity during winter storms. Fish Creek Basin has the highest road density (4 miles of road per square mile of land) and the highest number of road-stream crossings (16 per square mile of land) of any of the upper-basin watersheds (Metro, 1997). In February 1996, a 25-to-50-year flood (rain-on-snow event) occurred in Fish Creek, resulting in severe damage to the watershed. Post-flood surveys identified 236 landslides in the basin, with about three-quarters of the slides being associated with roads and harvest units (DeRoo and others, 1998).

Algal biomass—Algal biomass was generally low to moderate at tributary sites in forested basins, owing to the relative scarcity of light, N, P, or some combination. Low concentrations of N probably contributed to the low algal biomass at sites in the upper basin, despite the relatively high concentrations of P. Algal biomass was even lower at middle-basin tributary sites, where N concentrations were elevated, but P and light availability were lower than at the upper-basin sites (table 7). Whether the low nutrient concentrations resulted in low algal biomass at these sites, or alternatively, low nutrient concentrations were due to algal uptake of nutrients upstream from the sampling sites, is unknown. Other studies have shown that nutrient uptake by algae may significantly reduce nutrient concentrations in small streams (Mulholland and Rosemond, 1992; Peterson and others, 2001) and larger rivers (Tanner and Anderson, 1996).

Two sites with detectable levels of N and P, and moderate light availability (FISH and SFCLACK), had algal biomass values that were 1.5 and 2 times higher, respectively, than other sites in forested basins (tables 7 and 9). This suggests that N limits algal growth at upper basin sites, P and/or light limits algal growth at middle basin sites, and N and P, or some other factor (insect grazing or light), limits algal growth in Fish Creek and the South Fork Clackamas River. Nutrient addition experiments, such as those described later in this report, could be used to determine which nutrients limit algal growth in these forested streams.

Agriculture and Urban Development

A history of land conversion and development in the Clackamas River Basin is presented in Taylor (1999), detailing how the current landscape emerged from a once largely forested area. Euro-American settlement of the lower basin dates back to the early 1800s (Taylor, 1999). During the late 1800s and early 1900s, land was logged or burned, cleared, and drained for farming (Ecotrust, 2000). Dairy and subsistence farms were prevalent in the area until after World War II, when much of the land was subdivided for urban housing developments. Later in the 1970's, urban growth boundaries were established to curtail urban sprawl.

Nutrients—The highest concentrations of N and P occurred in streams draining a mixture of agricultural and urban land. One common source of nutrients from these land uses is chemical fertilizers, which are applied to field and nursery crops and landscaping, and to promote vegetation cover for erosion prevention. N fertilizer applications have steadily increased in the Willamette Basin, from about 2 million kg/year in 1945 to about 50 million kg/year in 1980 (Hinkle, 1997). Rinella and Janet (1998) found a significant positive correlation between NO_3^- concentrations in Willamette Basin streams and the percentage of agricultural land in each basin, a finding that has been reported nationally for streams and ground waters (Miller and Hamilton, 2001). Although the Clackamas Basin has, on average, less agricultural land than much of the Willamette Basin, the use of fertilizers for agriculture in the basin has likely increased. In the lower Clackamas Basin, nutrient enrichment in streams may be exacerbated by tile drains, which were originally installed by farmers to help drain excess water from the land (Ecotrust, 2000). These pipes efficiently deliver shallow ground water to streams, carrying soluble nutrients and minerals that have leached from the agricultural fields.

The highest nutrient concentrations (N and P) were found in Sieben Creek, which drains an area on the southeastern edge of Portland's urban growth boundary, where development has been rapid in the past 10 years. From 1990 to 2000, the population of Clackamas County increased 21% (U.S. Census Bureau, 2000); during this time, the area of urban development in the Sieben Creek Basin quadrupled from about 10% to 40%, with densities of up to 24,000 people per square mile in some residential developments.

Other studies have also found degraded conditions in Sieben Creek, including high concentrations of nutrients, sediment, and bacteria (KCM, Inc., 1995), and an impaired macroinvertebrate assemblage (Adams, 2001). The large area of impervious surface in the basin (36%, Dewberry and others, 1999) produces rapid increases in streamflow following storm runoff, and likely contributes to the degraded water quality in Sieben Creek.

In addition to the nutrient inputs that may occur from initial construction or fertilizer use from already developed areas, a large tract in the central portion of the Sieben Creek Basin contains a residential area that is not currently connected to sewers (Andrew Swanson, Clackamas County Department of Water Environment Services, oral commun., 1999), and contamination from septic wastewater may have contributed to the high nutrient concentrations measured in Sieben Creek. Some agriculture also occurs in the basin, however, including a few large nurseries, which also may contribute nutrients to streams.

Algae—Relatively high nutrient levels in the lower-basin tributaries fueled high algal biomass, reaching nuisance levels (>100–150 mg/m^2 chl *a*) in Rock, Sieben, and Deep Creeks. Algal biomass in Richardson Creek was lower, possibly due to the high abundance of grazers (primarily glossosomid caddis flies) that were observed at the time of sampling. Such high grazer densities were not observed, however, in Rock Creek, where a thick biofilm of high-nutrient-indicating diatoms (eutrophic taxa) were found. Many of the taxa found in Rock Creek are considered silt tolerant, and have adaptations for surviving in silty environments, such as the ability to move through sediments, thus preventing burial. Dewberry and others (1999) found macroinvertebrate assemblages to be "healthier" in Richardson Creek compared with Rock Creek, and concluded that the low diversity of aquatic insects in Rock Creek was due, in part, to habitat quality, which was judged to be marginal and moderately impaired by streambed sedimentation.

Algal assemblages at lower-basin tributary sites were largely dominated by *Melosira varians*, a eutrophic and N-heterotrophic diatom that can assimilate dissolved forms of organic nitrogen (van Dam and others, 1994). This alga was predictably abundant at sites where N concentrations also were high. In a study of small streams in agricultural and urban basins in the Willamette Basin, Carpenter and Waite (2000) found similarly high abundances of both eutrophic and N-heterotrophic diatoms, including *Melosira varians*, in association with N enrichment.

Despite the high nutrient concentrations, filamentous green algae, which also require large amounts of light (Biggs and others, 1998), were not prolific at the lower-basin tributary sites in 1998. This might be attributable to the sometimes-low light availability at these sites (canopy closure ranged from 43 to 85%). Therefore, the undesirable effects that filamentous green algae sometimes cause in streams, such as excessive algal biomass, low levels of DO, and high pH, might be avoided by promoting riparian vegetation and shading.

The impacts on water quality from urbanization will likely increase in the Clackamas Basin streams, particularly as more farmland is converted to urban development to accommodate an expanding urban growth boundary. Given current plans for future development, sediment and P loads in Rock and Richardson Creeks, for example, are predicted to increase six- and threefold, respectively (URS, 2000). Although not assessed in this study, urban runoff from these watersheds during storms likely contributes additional pollutants to the Clackamas River, including trace elements, volatile organic compounds, and pesticides.

Hydroelectric Projects

The hydroelectric projects in the basin (or their operation) have the potential to affect several fundamental controlling variables in downstream reaches, including streamflow, water temperature, and sediment transport. In addition to these effects, the projects also appeared to influence levels of DO, nutrient concentrations, and algal conditions during this study.

Water temperature—The hydroelectric projects affect water temperatures through water releases from the various impoundments, which, depending on the time of the year, may warm or cool downstream reaches. Cold water coming down the Oak Grove Fork that enters the upper Clackamas River via discharges through the Oak Grove Powerhouse (fig. 2) cooled the upper Clackamas River, especially during low-flow conditions in September, when powerhouse discharges accounted for nearly three-quarters of the flow in the upper Clackamas River. In late September, however, during the drawdown of Timothy Lake, water temperatures in the Oak Grove Fork increased by roughly 2°C.

A cumulative temperature increase of 4°C was observed in the Clackamas River through the main-stem hydroelectric projects in September. Longitudinal water temperature measurements collected in North Fork Reservoir in August 1997 indicated a 6°C increase in surface water temperature between the inflow to the reservoir and the log boom, with most of the warming occurring in the uppermost reaches of the reservoir (fig. 17). In the past 40 years, sediment deposition has reduced the volume of North Fork Reservoir by 30–40% (Robert Steele, Portland General Electric, written commun., 1998) and has created a long shallow reach near the inflow, producing ideal conditions for warming. Temperature increases in the main-stem projects in September (fig. 5) were about equally attributable to warming in North Fork Reservoir and the remaining impoundments (Faraday Forebay and Estacada Lake, fig. 2).

The longitudinal profile of water temperatures in the Clackamas River (fig. 5) shows that, while water temperatures upstream of the main-stem hydroelectric project decreased from July to September, water temperatures continued to increase downstream from the reservoirs. The warm surface layer that develops in North Fork Reservoir eventually becomes entrained in water releases from the reservoir as fall turnover, the process by which the reservoir is mixed due to the combined action of the wind and the cooling (and sinking) of surface waters during cold fall nights, begins. Such mixing of warm surface water, which in late September was about 4.5°C warmer than the inflowing water, ultimately results in warmer releases, thus altering the natural thermal regime in downstream reaches. The effects of these warmer water discharges may be significant on aquatic life in the river, especially if fall rains are delayed and high water temperatures persist. Changes in the thermal regime below dams, for example, are believed to affect macroinvertebrate assemblage species composition and diversity through eliminating important environmental cues required for egg development, hatching, and emergence (Lehmkuhl, 1972; Vannote and Sweeney, 1980; Munn and Brusven, 1991). These effects, however, were not evaluated during this study.

Dissolved oxygen—Timothy Lake often has low concentrations of DO in the bottom water during summer (Shulters, 1976; Portland General Electric, 1988). Low DO levels in the hypolimnion of Timothy Lake are likely a consequence of decomposing organic matter in the reservoir sediments, a process that consumes DO. The strong thermal stratification in the reservoir also acts to isolate bottom water from the surface, where aeration may increase DO levels. Additionally, the relatively long residence time of the reservoir (about 8 months) results in a slow exchange rate, which also likely contributes to the low DO. Because Timothy Lake is in a basin that was once a productive wetland (Timothy Meadows), the organic content of the sediments is probably high, especially given the history of sheep grazing in the meadow (Johnson and others, 1985), and the decomposition of this material would be expected to deplete DO in the overlying water. To increase concentrations of DO in water released from Timothy Lake, a special device called a Howell-Bunger valve has been fitted onto the powerhouse release pipe to aerate water exiting the reservoir. Although this did increase levels of DO downstream of Timothy Lake, concentrations of DO were still somewhat depressed (91% saturation) at OAK_BLTLK in July and September. Nonetheless, DO levels were much lower (50–60% saturation) at the water-release depth in the lake.

Nutrients—Over time, reservoirs collect organic material in the sediments from tributary inputs and from phytoplankton growth in the reservoir. At least some of the N that is fixed by blue-green algae in the Clackamas Basin reservoirs probably ends up in the bottom sediments. Upon decay, inorganic nutrients such as NH_4^+, NO_3^-, and SRP, which are available for algal growth, are released. In this sense, reservoirs with organic-rich sediments may effectively become "aquatic compost heaps" (Coats and Powell, 2000) generating nutrients to downstream communities, especially if water is released from the bottom of the reservoir (Marcus, 1980; Ward and Stanford, 1983; Anderson and Carpenter, 1998).

Lower DO and pH values and higher nutrient concentrations were sometimes observed near the bottom of both North Fork Reservoir and Timothy Lake, all indications that such processing of organic material was occurring in the reservoir sediments. During aerobic decomposition, DO is used and CO_2 is produced by bacteria, which lowers pH. The NH_4^+ released during decomposition may be converted into NO_3^- by nitrifying bacteria, a process that also consumes DO and lowers pH. The relatively high NH_4^+ concentration downstream from North Fork Reservoir in May (19 μg/L), in an otherwise severely N-limited system, suggests that appreciable decomposition was occurring in the reservoir. Although this was the only such detection of NH_4^+ downstream from North Fork Reservoir, NH_4^+ is the preferred form of N for algae

(Wetzel, 1983), and the high algal biomass downstream from the reservoir probably assimilated any NH_4^+ released by the reservoir in July and September. Additional studies, however, are needed to characterize important unknown factors such as the organic matter content of the sediments and decomposition rates, and perhaps more importantly, the relative effects of these processes on aquatic ecosystems within and downstream from the reservoirs.

Although concentrations of DIN were occasionally elevated downstream from the reservoirs (relative to upstream sites), DIN concentrations in the reservoirs were mostly low, and DIN concentrations downstream from the reservoirs were often below reporting limits. One possible explanation for this apparent contradiction is that nutrients released from decomposition in the reservoir sediments may migrate past the dams in seepage water and percolate up through the streambed downstream from the dams, where algae growing on the streambed can intercept nutrients before they enter the water column. Such a flow path for nutrient-enriched water might escape detection in water sampling. Additionally, low concentrations of N may result from nutrient uptake by algae growing on the streambed. Excessive growths of algae have been found in conjunction with low N concentrations downstream from other hydroelectric reservoirs in western Oregon, such as Toketee Lake and Soda Springs Reservoir in the North Umpqua Basin in southwestern Oregon (Anderson and Carpenter, 1998).

Phosphorus dynamics differed between North Fork Reservoir and Timothy Lake. North Fork Reservoir, which received a steady supply of SRP from the Clackamas River through the summer, supported phytoplankton growth that likely contributed to the observed decline in P concentrations and loads downstream of the main-stem reservoirs compared with upstream sites (figs. 9 and 11). Uptake of SRP by algae, suggested by the longitudinal decline in SRP concentrations in North Fork Reservoir (fig. 17), and subsequent settling of algal cells to the reservoir sediments may explain the declines in SRP and TP downstream from North Fork Reservoir. This decline is consistent with the observation that reservoirs generally act as sinks for P (Ward and Stanford, 1983).

In contrast, the SRP concentration downstream from Timothy Lake (at OAK_BLTLK) increased from 2 μg/L in July to 8 μg/L in September (table 8). Although the SRP concentration in Timothy Lake was only 1 μg/L, the reservoir sediments might be releasing phosphorus that is transported through seepage water. The P increase observed in September coincided with a decline in hypolimnetic DO from about 6 mg/L to 0.9 mg/L (fig. 22). Further, because the DO declined with depth, concentrations in the bottom sediments were probably even lower. Release of P from sediments occurs when the DO in overlying water is less than about 1 mg/L; above about 3 mg/L DO, P tends to sorb to sediment (Gachter, 1976). Movement of water from the reservoir through the bottom sediments and past the earthen dam is plausible given the relatively porous volcanic soils in the area and the hydraulic head generated by the reservoir depth (about 100 feet). The large number of seeps immediately downstream from the reservoir also supports this assertion.

Algae—Excessive growths of filamentous green algae were consistently observed immediately downstream from Timothy Lake, North Fork Reservoir, and Estacada Lake, particularly during July and September. The highest algal biomass value, 690 mg/m^2 chl *a*—more than 4 times higher than what is considered a nuisance—occurred in the upper Clackamas River downstream from the Oak Grove Powerhouse in September.

One alga that is notorious for reaching high biomass and producing nuisance conditions in streams is *Cladophora* (Dodds and Gudder, 1992; Biggs, 1996). This alga, although not found at upstream sites, was the dominant filamentous alga downstream from North Fork Reservoir in July (appendix 4). Much study has focused on the factors affecting the abundance and distribution of this widely occurring alga. In a review of the ecology of *Cladophora*, Dodds and Gudder (1992) stated that nuisance growths of *Cladophora* often result from nutrient enrichment, but that the alga may also reach high biomass in slightly eutrophic aquatic systems. The absence of *Cladophora* at all sites upstream from North Fork Reservoir suggests that some factor related to the reservoir or its operation might stimulate its growth, such as streamflow fluctuations (refer to Streamflows, p. 75) or lack of scouring high flows (Wootton and Power, 1993), which may allow algae to accumulate from one year to the next (Dudley and D'Antonio, 1991). Excessive growths of *Cladophora* have been reported downstream from other hydroelectric projects, such as those in the North Umpqua Basin in southwestern Oregon (Pacificorp, 1995; Anderson and Carpenter, 1998), where several reaches are currently listed on Oregon Department of Environmental Quality's 303(d) list of water-quality limited water bodies for high pH or low DO (Oregon Department of Environmental Quality, 2000). *Cladophora* has been observed in other streams draining the western Cascade Range, including the North Santiam, Sandy, and McKenzie Rivers (personal obs., 1996–99). Despite its reputation for causing water-quality problems in streams, *Cladophora* often hosts epiphytic diatoms that can be an important food resource for herbivorous macroinvertebrates living in the algal mats (Dodds and Gudder, 1992).

Streamflows—The high abundance of algae downstream from hydroelectric projects in Cascade Range streams, including the Clackamas, might be partly attributable to flow fluctuations from power peaking operations. Large proliferations of blue-green and filamentous green algae that were observed in the upper Clackamas River downstream from the Oak Grove Powerhouse might be explained by several hypotheses:

1. Fluctuating water levels provide an ideal habitat for macroalgae that can attain higher biomass, such as filamentous green and blue-green algae, because they may tolerate desiccation better than other types of algae. *Cladophora*, for example, tolerates repeated drying and often colonizes intertidal or splash zones around lakes (Dodds and Gudder, 1992; Blum, 1982) and certain blue-green algae, including *Nostoc*, produce a mucilaginous sheath that also resists desiccation. *Nostoc* occurred in the variable zone (where the stage fluctuated almost daily) in high densities along stream margins, primarily downstream of the Oak Grove Powerhouse. In July 1998, the cell biovolume of *Nostoc* was nearly twice as high below the Oak Grove Powerhouse at CR_3LYNX (3.0×10^7 $\mu m^3/cm^2$ [cell biovolume, in cubic microns per square centimeter]) compared with the upstream site (CR_UPPER), where the biovolume was 1.6×10^7 $\mu m^3/cm^2$.

2. Fluctuating discharge may stimulate algal growth downstream from the projects by providing alternating high and low water velocities. High water velocities deliver nutrients at faster rates than low water velocities, but lower velocities might result in less turbulence and greater light availability for algae growing on the streambed. Repeated discharge fluctuations would simulate small flood events, which might favor certain filamentous green algae that have holding structures that keep them attached to the stream bottom, while other algae may be washed downstream.

3. Fluctuating water levels might accelerate the death and decomposition of algal cells within already established algal populations because of increased exposure to air and direct sunlight during the day, or lower air temperatures during the night. Such accelerated decay might enrich stream margin areas (within the streambed or existing algal mats) with inorganic nutrients that may stimulate additional algal production in a positive feedback loop.

4. Insect grazing can be an important factor regulating filamentous green algae (Dudley and D'Antonio, 1991), and power peaking in the projects might negatively affect grazers that normally keep algal biomass low. During the July sampling, numerous dead caddis fly larvae were found stranded along the banks of the upper Clackamas River about 5 miles downstream from the Oak Grove Powerhouse, presumably from a recent sharp decline in streamflow. Changes in river stage may leave aquatic organisms stranded during periods of reduced streamflow, and abrupt increases in flow may flush organisms downstream. The decreased flows that often occur at night can adversely affect benthic invertebrate populations by reducing mayfly species abundance and richness (Malmqvist and Englund, 1996) or by shifting the invertebrate community toward a less diverse assemblage that may include large populations of tolerant species, such as chironomid midges (Munn and Brusven, 1991) and scuds, which were observed downstream of River Mill Dam. Although these hypotheses may help explain proliferations of algae in the Clackamas River, additional studies are needed to verify them.

Evaluation of Management Strategies to Improve Conditions

Despite the episodes of poor water quality that were occasionally observed in the Clackamas River and some of its tributaries, the river continues to support runs of wild salmon, steelhead, and trout, and provides reliable drinking water for a large population. Public education, management strategies, and restoration efforts could, however, help reduce contamination, restore natural processes, and return the high quality habitat that was once plentiful. Particular strategies aimed at reaching these goals are discussed next.

Nutrient Reduction Strategies

Nutrient enrichment can be a difficult process to reverse when high levels of nutrients also are present in ground water, as is the case in the Clackamas Basin. Precipitation events, common in the basin, help flush aquifers with large volumes of water upon infiltration. However, this is the same mechanism by which nutrients enter the ground water. Following are strategies aimed at reducing the transport of nutrients to streams and ground water such as fertilizer-use education, storm-water-runoff management, erosion control, and management of N-fixing plants.

Fertilizer use education—Raising public awareness about the effects of nutrient enrichment and the ways to reduce the runoff or leaching of fertilizers could help to reduce inputs from residential areas. One way to reduce nutrient transport to streams is to avoid overfertilization or fertilizer applications immediately prior to heavy rainfall and to employ buffer zones that may slow the runoff of excess fertilizer. Also, testing nutrient levels in soils to determine whether fertilization is necessary, and planting N-fixing cover crops (clover, for example) in lieu of using chemical fertilizer, could help reduce nutrient concentrations in streams and ground water.

Stormwater runoff and erosion management—Nutrients from fertilizers are often transported from the land surface to streams and ground water during storms. In the Clackamas Basin, some of the runoff to streams, especially those in the lower basin, is from impervious surfaces in urban and industrial areas. Innovative solutions to dealing with stormwater runoff, including constructed wetlands, sediment retention basins, and use of pervious paving materials might help reduce the runoff of nutrients and sediment to streams.

Controlling erosion should also decrease the transport of nutrients, particularly P, which often occurs bound to sediment (Fredricksen, 1971). Erosion control, however, is a challenging problem in the Clackamas Basin, given the large amounts of precipitation and heavy runoff (Uhrich and Wentz, 1999). There are numerous sources of soil erosion in the Clackamas Basin (presented in Nutrient Sources section); determining the relative contributions from each of these sources and implementing Best Management Practices, such as preserving the existing vegetative cover during construction of urban developments (Gerig, 1985), installing (and maintaining) erosion barriers where soils are exposed, and using conservation tillage techniques on farms, for example, could help reduce erosion. The positive correlation between P and SC in Clackamas Basin streams suggests that SC might be an inexpensive method to identify potential sources of P.

Removing invasive nitrogen-fixing plants—Many species of N-fixing plants are invasive and form extensive patches of growth in certain areas, and may be an important source of N in the basin. The removal of scotchbroom (*Cytisus scoparius*), an officially designated noxious plant, is ongoing (Robert Edgar, Oregon Department of Transportation, oral commun., 1997), but chemical methods, such as the use of herbicides, may cause other problems for aquatic life. Scotchbroom, red alder (*Alnus rubra*), and other N-fixing plants colonize open areas along roads, timber-harvest units, in riparian areas, and in locations where soils have been disturbed. Red alder is an active N-fixer and can be a significant source of N to Cascade Range streams (van Miegroet and Cole, 1988). Removal or thinning of red alder in riparian habitats and planting western red cedar (U.S. Forest Service, 1996c) might result in lowering concentrations of N in streams (Fenn and others, 1998). However, because alder provides shade and bank stability along streambanks, such manipulations should be evaluated along with the potential for increasing water temperature or accelerating erosion.

Habitat Restoration

Habitat restoration efforts, such as enhancing the natural functions of riparian zones and wetlands, and increasing stream complexity with the addition of large woody debris or boulders, could improve stream habitat and water quality. Fostering healthy riparian communities could improve stream habitat and water quality by intercepting sediment and soluble nutrients bound for streams (Gregory and others, 1991), providing stream cover, helping to reduce water temperatures, providing fish habitat, and possibly limiting algal photosynthesis through light limitation (Lyford and Gregory, 1995).

Wetland and backwater habitats have been reduced or lost in the Clackamas Basin, starting with the early settlers, who installed tile drains for farming (Ecotrust, 2000). Later, eradication of beavers, removal of large woody debris, and road construction activities contributed to the loss of wetland habitat and stream complexity. In 1956, an extensively braided segment of the upper Clackamas River was realigned and channelized during the construction of Forest Service Road 46 (U.S. Forest Service, 1995c), separating off-channel backwater areas from the primary channel. In recent years, the Forest Service has added logs, boulders, and culverts in this area to reconnect these backwater habitats and to increase stream complexity. Complex habitats contain abundant pools as well as riffles, benefiting fish and other aquatic organisms. Such restoration efforts would especially benefit fingerling coho salmon, which take refuge in backwater habitats during periods of high streamflow (Groot and Marcolis, 1991).

In addition to providing fish habitat (Fausch and Northcote, 1992), increasing channel structure helps to reduce water velocity. This allows for sediments and organic matter to settle in backwater areas. Here, nutrients from these materials can be processed, and denitrification, the process whereby bacteria convert NO_3^- to gaseous forms of N (which are lost to the atmosphere), can occur. Habitat complexity also increases the surface area to volume ratio in streams, which is important because biological films colonize surfaces and add significantly to nutrient retention (Tank and Winterbourn, 1995; Tank and Webster, 1998; Peterson and others, 2001). A lack of stream complexity may reduce interaction of surface water with subsurface (hyporheic) water and may contribute to other water-quality problems such as high (or fluctuating) pH and low DO levels (Powell, 1997) through decreased heterotrophic metabolism (Brunke and Gonser, 1997; Naegeli and Uehlinger, 1997; Fellows and others, 2001).

During watershed analysis, the U.S. Forest Service and Bureau of Land Management found a lack of large woody debris in portions of several watersheds, including the North and South Fork Clackamas Rivers, Eagle and Clear Creeks, and others, from a lack of wood recruitment due to timber harvesting, stream cleaning, road construction, and fires (U.S. Bureau of Land Management, 1995; U.S. Forest Service, 1995a, 1995b, 1996a, 1996b, 1997). Continued efforts to enhance stream complexity through large wood/boulder additions, and planting trees in riparian areas could have several benefits. Riparian vegetation intercepts sediment and nutrients bound for streams and helps maintain bank stability (Gregory and others, 1991). Undercut banks and overhanging vegetation from healthy riparian habitats provide cover for fish and also contribute to stream shading. Also, future recruitment of wood to streams, an important element of channel complexity (Gurnell and others, 2002) would be increased with riparian improvements.

Much of the wood that accumulates in North Fork Reservoir during the winter is burned at a site adjacent to the reservoir during springtime. Burning the wood creates soluble nutrients, which may stimulate algal growth in the reservoir. Proliferations of filamentous green algae were observed along the reservoir shoreline directly adjacent to the large burn pile during summer in 1997 and 1998, which might be attributable to leaching of nutrients from the ash piles. An alternative management option, transporting the large wood around the dam complexes and keeping the large wood in the Clackamas River to increase habitat and stream complexity, is under consideration during hydroelectric relicensing (John Elser, Portland General Electric, oral commun., 1999). Using the wood for habitat restoration, in lieu of burning, could have the added benefit of reducing nutrient inputs to North Fork Reservoir.

Water Temperature Reduction

The lower 23-mile reach of the Clackamas River, from River Mill Dam to the mouth, is currently considered water-quality limited (Clean Water Act, section 303(d) listed) because of high water temperatures during summer. High temperatures may be related to a variety of factors, including reduced stream shading, runoff from impervious surfaces, warm-water discharges from the reservoirs, and reduced inputs of cold ground water. Other factors, including reduced subsurface (hyporheic) flow due to channel scouring, reduced cover from loss of channel or bed structure, or increased solar warming from increases in stream width, also may be important in some areas.

Enhancing stream shading through riparian restoration and tree planting in areas affected by road building, logging, agriculture, urban development, and the construction of farm ponds, could help reduce water temperatures in the tributaries locally and downstream in the Clackamas River. Also, managing storm runoff from impervious surfaces in urban and industrial areas with constructed wetlands or other innovative methods may help reduce temperatures. Large areas of impervious surfaces exist in Richardson, Rock, and Sieben Creek Basins, ranging from 22 to 36% of the total land area (Dewberry and others, 1999), which sometimes produce pavement-warmed runoff instead of allowing rainfall to infiltrate into the ground where it can recharge aquifers.

Extensive development of ground-water resources, especially in the northern part of the basin, also may reduce ground-water discharges to the lower Clackamas River, a potential cooling mechanism, by lowering the water table. One indication that this is occurring is that reports of dry wells by area residents have increased in recent years (Bill Ferber, Oregon Department of Water Resources, oral commun., 1998). A decline in the water table could indirectly increase water temperatures in the Clackamas River simply by reducing the volume of cold ground-water seepage. However, more data on the importance of ground water in regulating water temperature in the Clackamas Basin are needed to verify this hypothesis.

Water releases from the hydroelectric project reservoirs also may contribute to high water temperatures in the Clackamas River, especially in the fall. From July to September, water temperatures in the upper Clackamas River decreased, but temperatures downstream from River Mill Dam increased, presumably in part from the release of water warmed in the reservoirs.

Although two of the reservoirs (North Fork Reservoir and Timothy Lake) have deep-water releases, water from the Faraday Diversion Dam and Forebay is taken closer to the surface, where the water may be warmed. One strategy to reduce warm-water releases from River Mill Dam, and possibly lower water temperatures in the lower Clackamas River, would be to bypass the Faraday Lake portion of the hydroelectric project during warm periods, although this could interfere with energy production goals.

Salmon Carcass Additions

The Clackamas River and its tributaries were once teeming with native anadromous fish, including spring Chinook salmon, fall Chinook salmon, coho salmon, and winter steelhead trout. These fish were important sources of marine-derived nutrients for food webs in streams (Bilby and others, 1996). Today, anadromous fish populations in Clackamas and other western rivers are declining (Nehlsen and others, 1991), spring Chinook and winter steelhead are listed as threatened by the National Marine Fisheries Service, and late-run Clackamas River coho salmon, the last remaining wild coho salmon stock in the Columbia River Basin, was listed as a candidate species in 1995 (Taylor, 1999).

For streams that are lacking in nutrients due to a reduction in the numbers of returning anadromous fish, the addition of salmon carcasses may enhance fish production (Wipfli and others, 1998). If nutrient amendments are made to streams, carcass additions are preferred over inorganic fertilizer because carcasses release organic nutrients slowly as they decompose over time. Inorganic chemical fertilizers are soluble and are immediately available for uptake by algae.

Although carcass amendments may stimulate stream productivity through direct ingestion by insects and juvenile fish, or indirectly via increases in primary production, caution should be exercised. As discussed previously, low nutrient concentrations in streams, which might be perceived as limiting stream productivity, also may be due to efficient uptake by algae. A moderate-biomass algal assemblage may become exacerbated to nuisance levels if additional nutrients from carcass additions are provided, especially in downstream reaches where additional light may be available for photosynthesis. Also, caution should be used to avoid spreading disease among native fish populations from carcass additions.

Controlling Phytoplankton Blooms

Phytoplankton require light, nutrients, and time in order to grow and multiply to produce bloom conditions. Positive correlation between TP and chl *a* suggests that P may be regulating the N-fixing blue-green algae in the reservoirs. Reducing the P availability through erosion control measures may therefore reduce the severity of algae blooms in the reservoirs. Another potential limiting factor for blue-green algae is time. The hydraulic retention time, or residence time, is one indication of how much time is available for phytoplankton to grow. The residence time for a reservoir is a function of the rate of inflowing water and the volume. Small-volume reservoirs with large inflows are not as conducive to growing algae because they flush more quickly and have shorter residence times compared with large-volume reservoirs with smaller inflows. Residence time has been used to explain the dominance of diatoms in rivers that move fast and why blue-green algae prefer slower rivers and reservoirs with longer residence times (Rickert and others, 1977).

One potential strategy to reduce the occurrence or severity of blue-green algae blooms in North Fork Reservoir, when they occur, is to use water from Timothy Lake to flush North Fork Reservoir. Higher flows through the reservoir would decrease the residence time and possibly reduce the severity of algae blooms. However, management goals, such as providing recreation or water supply needs, might be affected by early releases from Timothy Lake. Additionally, Timothy Lake is prone to algal blooms and periods of poor water quality (low levels of DO near the bottom or high pH at the surface), making routine monitoring in the reservoirs an important tool for managing the system as a whole.

Disinfection By-Products

As noted previously, toxic disinfection by-products are routinely detected in chlorinated drinking water from the Clackamas River drinking water treatment plants. The formation of disinfection by-products is related to the occurrence of organic matter in raw water supplies. Sources of organic matter include decaying leaves, woody debris, septic and animal manure waste, and other organic materials, including algae. In 1998, the quarterly maximum THM concentrations in finished drinking water (fig. 25) coincided with an algal sloughing event that increased the amount of organic matter in raw drinking-water supplies. This suggests that algae or its decomposition products may have been responsible for the observed increase in disinfection by-products.

Management strategies aimed at reducing disinfection by-product concentrations could include watershed enhancements, including previously presented nutrient reduction strategies aimed at reducing algal biomass, and mechanical modifications to drinking water treatment plants. Prior to filtration, most of the plants in the basin chlorinate raw water, which may contain relatively high levels of organic matter, especially during algal sloughing events. Other studies (Fram and others, 2001) have demonstrated that disinfection by-product concentrations may be reduced by as much as 50% by prefiltering raw water before chlorination. Reducing the concentration of organic matter by other means, such as settling basins or screens, also may help reduce by-product concentrations, depending on the specific characteristics of the material.

Information Needs and Potential Future Studies

This study documented current baseline water-quality and algal conditions in streams and reservoirs, generated hypotheses to explain the observed patterns in conditions, and evaluated management strategies that might improve conditions. Additional water-quality monitoring and focused follow-up studies could address specific factors that influence water quality and/or algal growth, so that management options can be developed and implemented.

Routine Monitoring

Sampling a network of sites on a routine basis or using continuous monitors could help detect changes in water quality and provide information on year-to-year variability necessary for identifying trends in water quality over time. Data collected at three main-stem sites by the Oregon Department of Environmental Quality's Ambient Monitoring Program, for example, have been used to detect for trends in water temperature, pH, DO, and nutrient concentrations in the Clackamas River; however, the spatial and temporal coverage of the Department's monitoring is insufficient to address many of the questions generated by this study, especially in the tributaries. Routine monitoring could quantify potential benefits of restoration activities and test or refine hypotheses presented in this report.

Determine compliance with water-quality standards—Instantaneous exceedances of water-quality criteria for temperature, pH, and DO were occasionally observed during this study, especially during the early morning and late afternoon, when extremes in these values occurred. As previously noted, however, determining compliance with water-quality criteria for temperature and DO require multiple-day observations: 7 days for temperature and 30 days for DO (table 5). Single point, instantaneous measurements, as were typically made for this study, cannot be used to indicate a violation of the standard or qualify a water body for listing on the 303(d) list of water-quality limited water bodies. Furthermore, the DO criteria also depend on the intergravel DO concentration measured in fish redds. Nevertheless, the pronounced fluctuations in water temperature, DO, and pH that were observed during this study may stress aquatic life. The USGS currently operates two continuous water-quality monitors in the lower Clackamas River, 0.25 miles downstream from River Mill Dam (RM 23.1) and near Oregon City (about RM 1.5), which will help determine the extent of such conditions. Definitive information on which reaches support fish spawning (or rearing), and when, is necessary for determining whether water-quality standards are being met.

Watershed Assessments and Focused Studies

Focused studies aimed at addressing particular issues could be used to further evaluate conditions, identify sources of nutrients, sediment, and contaminants, or test hypotheses regarding water or habitat quality. Some potential studies are evaluated next.

Watershed assessments—Watershed assessments aimed at characterizing and documenting baseline land-use, habitat, and water-quality conditions could provide a benchmark against which future studies may be compared. Such information could further understanding of how anthropogenic and natural influences affect watershed conditions.

Watershed assessments of public lands administered by the U.S. Forest Service and the U.S. Bureau of Land Management provide historical and current information on forest stand age and community structure, geology, soils and sediment, vegetation, and fire history at the watershed level, and relate these conditions to land management. Most of these reports, however, contain little information on water chemistry (although see U.S. Forest Service, 1995c; 1996b). Focused studies in the upper basin could, for example, address how dispersed camping and other forms of recreation, timber harvesting, fertilizer application, road construction, erosion, and other activities affect nutrient levels in forested streams.

The Clackamas River Basin Council recently sponsored a watershed assessment for Rock and Richardson Creeks and for Clear and Foster Creeks (Ecotrust, 2000). Future assessments of other tributaries, including Deep and Goose Creeks, and the lower main-stem Clackamas River, could help direct and focus restoration and other management efforts in the basin. Such assessments might include measures of streamflow variability, habitat complexity, and water-quality/algal conditions in smaller tributaries that would provide data at a more detailed scale.

Although satellites may provide land-cover data useful for examining landscape-level effects on water quality, land-cover data used for this study were 5–10 years old, and changes in land cover, especially in the lower basin, are occurring rapidly. Future watershed studies would benefit from up-to-date, small-scale, and field-verified information on the amount, condition, and distribution of urban/agricultural/forest land-cover and vegetation classes, along with other variables such as population density, road density, and areas or distribution of impervious surfaces. Such data might help identify particular sources of contaminants and strengthen conclusions regarding the effects of a particular land use on water quality or habitat conditions. Periodic updates in land-cover data could track changes in land use over time and might help explain future changes in water quality or habitat from restoration efforts.

Agricultural and urban land-use studies—Some water-quality issues related to land use, such as nutrient enrichment and contaminant occurrence in streams, may be addressed by "gradient" studies. By selecting sites that taken together represent a gradient or range of a particular condition, one can isolate the effects of one type of land use versus another. A study having sampling sites that represent the full gradient of the condition from 0 to 100% (for example, urban gradient studies [McMahon and Cuffney, 2000]) might identify thresholds for some response variable. For example, Dewberry and others (1999) found a decrease in the number of aquatic macroinvertebrate taxa in Clackamas Basin streams when the impervious surface area was greater than 15–25% of the basin area.

Disinfection by-products—The levels of disinfection by-products in finished drinking water supplied by the Clackamas River currently approach drinking-water standards at times. These compounds are formed during chlorination of water containing certain types of organic matter. Organic matter originates from human discharges (WWTPs), leaky septic tanks, and fish hatcheries), terrestrial inputs (leaves and wood, and their decomposition products), and aquatic sources (algae from reservoirs and streams). Monitoring the Clackamas River for organic carbon concentrations (SOC and DOC), suspended chl *a* concentration, ultraviolet absorbance, and the isotopic makeup of the carbon (in raw water and potential terrestrial and aquatic sources), could identify the relative contributions from each of these sources. This may help water managers predict when raw water supplies are most vulnerable to by-product formation. Additionally, identifying where in the treatment process such by-products are formed (during chlorination of raw water, for example), and modifying plant design or operations accordingly, may help reduce disinfection by-product concentrations in the future.

Algal toxin surveys—Although testing for algal toxins was not performed during this study, the types of algae known to produce them were found in both reservoirs. Future monitoring of water-quality and algal conditions in the reservoirs could include an evaluation of algal toxins, especially during blooms.

Effects of tides on the drinking-water supply—Water from the Willamette River can travel as much as 0.3 miles up the Clackamas River to the lowermost sampling site, where about one-third of the water sampled during low flow in September had characteristics of water from the Willamette River. This backwater condition, presumably caused by an unusual, but not uncommon, combination of flow conditions in the Clackamas, Willamette, and Columbia Rivers, could possibly reach the lowermost drinking-water intakes in the lower Clackamas River. Although it is unlikely that Willamette River water could regularly travel upstream to the intakes during low-flow conditions (because of riffles in the lower river), an abnormally high streamflow in the Willamette River, combined with receding streamflow in the Clackamas River, might produce a backwater condition that could occasionally reach drinking-water intakes. Continuous monitoring of SC at the lowermost intake, for example, could identify potential changes in SC that might correspond with tidal cycles or be used to indicate the presence of Willamette River water.

Effects of fluctuating water levels on aquatic biota—This study examined algal conditions in the upper Clackamas River and proposed hypotheses to explain the occurrence of excessive algae downstream from the hydroelectric projects, where power peaking results in fluctuating water levels. Future studies related to the operation of the hydroelectric projects could test hypotheses presented in this report and evaluate potential changes in project operations. A recent study of benthic macroinvertebrates in the project-affected reaches of the Clackamas River by Wisseman (2001) included multiple samples collected at various depths (distances from the stream margin) that may be useful for determining the effects of fluctuating water levels. The effects on algae, however, were not included in the study, nor were changes in nutrient cycling along stream margins.

Nutrient addition experiments—Although the data collected here suggest N limitation for some of the streams in the upper basin and P limitation in some of the middle-basin streams, uptake and recycling of nutrients, N fixation, and infusions of nutrient-rich ground water make conclusions about nutrient limitation based on nutrient concentrations alone dubious. To better define which nutrients, if any, are limiting algal growth in the Clackamas River, its tributaries, and the reservoirs, nutrient addition experiments could be conducted. Clay pots filled with agar containing N, P, or both are placed in streams (Fairchild and Lowe, 1984) and nutrients added to large plastic containers containing reservoir water (Carpenter, 1995) to test for algal growth over time. If a limiting nutrient is identified, reduction strategies to prevent its transport to surface waters can be developed and implemented.

Nutrients from point sources—This study found that point sources, including fish hatcheries and WWTPs, might be a significant source of N and P in the Clackamas Basin. Nutrient data was generally sparse for both of these sources, however, and additional data are needed to understand how plant operations, such as hatchery maintenance or methods of wastewater treatment, affect discharges. Treatment plant upgrades might be used to reduce nutrient inputs from these point sources, especially if eutrophication in the Clackamas Basin accelerates or if disinfection by-product levels begin to exceed drinking-water standards.

Nutrients from reservoirs—Nutrient concentrations were sometimes higher downstream from the reservoirs or in reservoir bottom water, suggesting that processing within the reservoirs, namely the decomposition and recycling of organic matter into soluble nutrients, was occurring. This probably contributed to the high algal biomass immediately downstream of the impoundments. Nutrient concentrations in water samples collected downstream of the reservoirs, however, sometimes did not match those in the reservoir. Additional studies that determine the source(s) of nutrients that are stimulating algal growth downstream of the reservoirs, such as evaluating the nutrient content of the sediments, decomposition rates, and flow paths through the sediments or past the dams, might help to explain the high algal biomass downstream from the dams.

Nutrients from forested basins—Concentrations of DIN at some forested sites in the middle basin were much higher than what the USEPA considers to be representative of minimally impacted, "reference" conditions. Further, DIN concentrations at these sites appeared related to the percentage of nonforest upland (clear-cuts and other areas without vegetation) in these basins. Other factors, however, besides timber harvesting may affect N concentrations in these streams. Post-harvest prescribed burning, fertilization, fire history, and N-fixing plants and trees also may be sources of N. Smaller-scale studies, including both streams and ground water, could help identify what sources are most important.

Concentrations of P at some high-elevation sites draining forested basins also exceeded the level USEPA suggests being representative of reference conditions. Again, P concentrations appeared to be related to the percentage of nonforest upland (mostly clear-cuts and other areas without vegetation) in these basins. The highest concentrations were found in the upper Clackamas River and in the Oak Grove Fork, both located in the Cascade Crest Montane Forest

Ecoregion, where young volcanic rock, and possibly naturally occurring P, might be found. Better information on the distribution of P concentrations in streams and ground water in these areas, along with information on geology and soils, might identify naturally occurring P deposits, which could help determine or refine reference conditions for the Clackamas Basin. Also, targeted erosion control may be used to reduce the transport of P to streams in certain areas. The significant correlation between TP concentrations and SC suggests that SC may be an inexpensive way to screen potential sites for nutrient sampling.

Nutrients in ground water—Ground water was found to contain relatively high concentrations of N and P, with shallow ground water yielding the higher concentrations of NO_3^- and deeper ground water containing the higher concentrations of P. The distribution of nutrient-rich ground water in the basin and the relative impacts that anthropogenic activities have on nutrient concentrations in ground water is not known, nor is the amount of ground water discharging to the lower Clackamas River, although data collected as part of the current study suggest that it might be significant. Additional seepage studies conducted during constant discharge from River Mill Dam are needed to verify actual inputs of ground water. Once gaining reaches are identified, naturally occurring isotopes of C or N may be used to identify particular sources of nutrients. Isotopes (in tissues or water) can sometimes help distinguish between natural and anthropogenic nutrient sources, such as sewage or chemical fertilizers, if the source produces a unique isotopic signature (McClelland and others, 1997).

Nitrogen from atmospheric deposition—The degree to which atmospheric deposition of N affects water quality and forest health in the Clackamas Basin is not known. Wet deposition data in the Bull Run Basin, about 20 miles north of the Clackamas Basin, show some high N concentrations: the average concentration of $NH_4^+ + NO_3^-$ in precipitation from May to September 1996–2000 was about 900 µg/L, and concentrations exceeding 1,000 µg/L occurred in nearly 15% of samples (National Atmospheric Deposition Program [NADP] web site, http://nadp.sws.uiuc.edu/nadpdata, accessed 5/28/2001). Monitoring for atmospheric deposition of N in the Clackamas Basin, particularly at mid-elevation sites, might help explain the relatively higher N concentrations in streams draining this area.

CONCLUSION

Despite the episodes of poor water quality that were occasionally observed during this study in the Clackamas River and its tributaries and reservoirs, the Clackamas River remains one of the highest quality waters in the State of Oregon, still supporting runs of wild salmon, steelhead, and trout. However, if the river is to continue to support other designated beneficial uses, such as providing high-quality drinking water, efforts are needed to reduce contamination and restore natural processes in order to reverse the symptoms of nutrient enrichment that are beginning to appear. Restoration efforts and future studies described here could improve habitat and water quality in the Clackamas Basin over time.

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APPENDIXES

APPENDIX 1. MINIMUM LABORATORY REPORTING LEVELS (MRLs) FOR CONSTITUENTS ANALYZED IN THE CLACKAMAS RIVER BASIN, OREGON, 1998

[µg/L, micrograms per liter; mg/m^2, milligrams per square meter, nutrient abbreviations are listed in glossary]

Nutrients	Chemical symbol	Minimum laboratory reporting levels [a]
Soluble reactive phosphorus	SRP	1 µg/L
Total dissolved phosphorus	TDP	1 µg/L
Total phosphorus	TP	1 µg/L
Ammonium - nitrogen	NH_4^+	2 µg/L
Nitrate + nitrite - nitrogen	$NO_3^- + NO_2^-$	5 µg/L
Dissolved Kjeldahl nitrogen	DKN	100 µg/L
Total Kjeldahl nitrogen	TKN	100 µg/L
Silicon dioxide (silica)	SiO_2	100 µg/L
Major ions		
Iron	Fe^{+2}	3 µg/L
Chloride	Cl^-	100 µg/L
Organic matter		
Chlorophyll *a* (phytoplankton)	Chl *a*	1 µg/L
Chlorophyll *a* (periphyton)	Chl *a*	1 mg/m^2
Ash-free dry mass	AFDM	1 mg/m^2
Dissolved organic carbon	DOC	100 µg/L
Suspended organic carbon	SOC	200 µg/L

[a] Nutrient and major ion MRLs reported on an atom-basis (as Phosphorus, for example).

APPENDIX 2. QUALITY-CONTROL SAMPLE RESULTS FOR NUTRIENTS IN WATER

[Site codes and nutrient abbreviations listed in glossary; chemical symbols as in appendix 1; µg/L, micrograms per liter; mg/L, milligrams per liter; <, less than minimum reporting levels (see appendix 1); nd, no data]

Blank samples

Site	Date	Time	NH_4^+ (µg/L)	NO_3^- (µg/L)	DKN (µg/L)	TKN (µg/L)	SRP (µg/L)	TDP (µg/L)	TP (µg/L)	SiO_2 (mg/L)
USGS_LAB [a]	5/13/98	12:00	<	<	<	<	<	1	<	<
USGS_LAB [b]	6/4/98	11:30	<	<	<	<	1	<	1	<
USGS_LAB [a]	9/1/98	14:10	<	<	<	<	<	<	<	0.18
USGS_LAB [a]	9/22/98	6:08	<	8	<	<	1	14	<	0.13
ROARING [b]	5/6/98	15:38	<	<	<	<	<	<	<	nd
ROARING [b]	7/7/98	15:08	<	<	<	<	<	6	<	nd
ROARING [c]	7/7/98	15:09	<	<	<	<	<	8	1	nd
NFKRES_1 [d]	6/3/98	12:38	<	<	<	<	1	<	1	<
TIM_LK [d]	7/1/98	17:08	<	<	<	<	<	<	4	nd
TIM_LK [d]	8/18/98	13:48	<	<	<	<	1	<	1	nd
TIM_LK [c]	8/18/98	13:49	<	<	<	<	<	<	<	nd

Standard reference samples

Sample	Date	Result	NH_4^+ (µg/L)	NO_3^- (µg/L)	SRP (µg/L)	TDP (µg/L)
1	05/13/98	expected	21	42	36	36
		reported	20	22	26	35
2	07/14/98	expected	10	21	9	9
		reported	3	7	6	6
3	09/01/98	expected	10	25	3	3
		reported	7	19	3	3
4	09/01/98	expected	10	25	3	3
		reported	6	18	2	3
5	09/22/98	expected	10	25	3	3
		reported	11	21	3	< 1

Replicate samples [e]

Site	Date	Time	NH_4^+ (µg/L)	NO_3^- (µg/L)	DKN (µg/L)	TKN (µg/L)	SRP (µg/L)	TDP (µg/L)	TP (µg/L)	SiO_2 (mg/L)
CR_3LYNX-A	05/06/98	10:50	<	<	<	<	7	10	16	nd
CR_3LYNX-B		10:52	<	<	<	<	7	19	14	nd
NFKRES_1-A	06/03/98	12:30	<	<	<	109	8	12	21	15.9
NFKRES_1-B		12:32	<	7	<	<	9	11	21	15.9
NKFKRES_1-A	07/02/98	11:00	<	<	106	<	7	11	17	18.1
NFKRES_1-B		11:02	<	<	<	<	8	11	17	nd
FISH-A	07/07/98	16:40	<	7	<	<	7	14	12	17.6
FISH-B		16:42	<	7	<	<	7	24	12	17.0
DEEP-A	07/10/98	11:40	3	1,045	167	161	68	78	78	18.7
DEEP-B		11:42	2	1,034	122	175	67	78	84	18.9
NFKRES_1-A	08/20/98	11:50	5	<	<	<	10	10	13	19.5
NFKRES_1-B		11:52	<	<	<	<	9	10	13	nd
CR_ABNFK-A	09/01/98	9:00	<	<	<	<	15	16	19	21.0
CR_ABNFK-B		9:02	<	<	<	<	15	17	18	nd
NFKRES_1-A	09/22/98	11:10	<	9	<	<	8	9	14	21.0
NFKRES_1-B		11:12	<	9	<	<	8	9	14	20.8

[a] Lab serial equipment blank (collection bottle, churn splitter, tubing, and filter).
[b] Field serial equipment blank (collection bottle, churn splitter, tubing, and filter).
[c] Certified inorganic blank water (non-equipment blank).
[d] Field Van Dorn sampler blank.
[e] A and B denote replicate samples.

Appendix 3A. Measures of algal abundance from true replicate samples

[Site codes are listed in the glossary; A and B denote independent samples collected and composited separately; g/m^2, grams per square meter; mg/m^2, milligrams per square meter; # cells/cm^2, number of cells per square centimeter; $\mu m^3/cm^2$, cubic micrometers per square centimeter]

Site	Month	AFDM [a] (g/m^2)	Chlorophyll *a* [a] (mg/m^2)	Abundance (# cells /cm^2)	Biovolume ($\mu m^3/cm^2$)
CR_BLNFK - A	May	83.7	213.7	2.57×10^6	5.00×10^9
CR_BLNFK - B	May	76.1	173.0	2.55×10^6	5.23×10^9
SFCLACK - A	July	25.5	149.1	5.50×10^6	1.33×10^9
SFCLACK - B	July	20.4	125.0	6.68×10^6	7.16×10^8
CR_99E - A	July	24.4	52.8	1.73×10^6	9.26×10^8
CR_99E - B	July	24.9	56.3	1.57×10^6	2.28×10^9
CR_ABNFK - A	September	15.4	60.8	7.45×10^5	7.07×10^8
CR_ABNFK - B	September	17.5	62.0	7.14×10^5	1.25×10^9

[a] Average of three replicates.

Appendix 3B. Percent similarity between true replicate samples analyzed by Bowling Green State University Laboratory

[Site codes are listed in the glossary]

Site	Month	Soft algae + Diatoms (relative abundance)	Diatoms (relative abundance)	Diatoms (relative biovolume)
CR_BLNFK	May	86.1	76.7	74.1
CR_99E	July	79.5	85.1	87.0
CR_BLNFK	July	69.8	76.9	70.5
CR_99E	September	77.6	76.7	74.1
CR_ABNFK	September	67.4	79.6	82.5

Appendix 3C. Percent similarity for diatom slide preparations analyzed by both algal contractors

[Site acronyms are listed in the glossary; A and B denote true replicate (i.e., separate samples, not split samples)]

Site	Month	Percent similarity
CR_MCIVER	May	60.7
CR_BARTON	May	66.7
CR_99E	May	65.2
SFCLACK - A	July	70.8
SFCLACK - B	July	62.1

APPENDIX 4. PERIPHYTON TAXA OCCURRENCE AT MAIN-STEM CLACKAMAS RIVER SITES, OREGON, 1998

[Algal taxa are ordered by major algal Division; site codes are listed in the glossary; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); some taxa are assigned to autecological guilds as follows: NF, nitrogen fixers; NH, facultative nitrogen heterotrophs; E, eutrophic taxa; O, oligotrophic taxa; A, alkaliphilic taxa; HP, halophilic taxa; HB, halophobic taxa; S, silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		Main stem sites, in downstream order																							
		CR_ UPPER			CR_ 3LYNX			CR_ ABNFK			CR_ BLNFK			CR_ MCIVER			CR_ BARTON			CR_ CARVER			CR_ 99E		
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	**Guild**	**M**	**J**	**S**	**M**	**J**	**S**	**M**	**J**	**S**	**M**	**J**	**S**	**M**	**J**	**S**	**M**	**J**	**S**	**M**	**J**	**S**	**M**	**J**	**S**
RHODOPHYTA (Red Algae)																									
Audouinella sp.												*				*								*	
CHLOROPHYTA (Green algae)																									
Ankistrodesmus sp.										*					*	*	*							*	*
Cladophora sp.												**									**	**	**	**	**
Crucigenia tetrapedia sp. # 1					*																				
Microspora sp.						**	**					*													
M*ougeotia* sp. # 2		**		**			**		*	*															
Scenedesmus dimorphus																					*				
Scenedesmus quadricauda																								*	
Scenedesmus sp. # 2																						*			*
Spirogyra sp.										**						**									
Staurastrum sp.																			*						
Stigeoclonium sp. # 1																		*					*	*	
Ulothrix sp. # 2																			*						
Ulothrix zonata		**					**	**			**							*							
Zygnema sp.					**				**	**															
CHRYSOPHYTA (Golden algae)																									
Tribonema sp.							*																		
Unidentified Chrysophyte filament				**																					
Vaucheria sp.		**					**																		
CYANOPHYTA (Blue-green algae)																									
Calothrix sp.	NF	*								*			*		*	*								*	*
Calothrix heterocysts	NF												*									*			
Ch*amaesiphon* sp.										*		*													
Lyngbya sp.						*				*	*		*	*	*				*					*	*
Nostoc sp.	NF	*	**	**	**	*	*	*	*	*		*	**		*	*		*	*			*			*
Nostoc sp. heterocysts		*			*	*	*		*	*			*		*	*			*						*
Nostoc akinete															*										
Oscillatoria sp. # 1		*	*		*		*		*		*	*	*	*	*	*	*	*	*			*	*	*	*
Schizothrix calcicola			*	*	*	*		*	*	*		*		*	*	*	*	*	*		*	*		*	*
Tolypothrix sp.	NF	**			**						*														
Tolypothrix heterocysts	NF	*			*																				
BACILLARIOPHYTA (Diatoms)																									
Achnanthes deflexa							*		*	*	*	*	*		*	*	**		*		*	*	*	*	*
Achnanthes hauckiana	O				*										*										
Achnanthes lapidosa			*			*																			
Achnanthes sp. # 2																					*				

[Algal taxa are ordered by major algal Division; site codes are listed in the glossary; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); some taxa are assigned to autecological guilds as follows: NF, nitrogen fixers; NH, facultative nitrogen heterotrophs; E, eutrophic taxa; O, oligotrophic taxa; A, alkaliphilic taxa; HP, halophilic taxa; HB, halophobic taxa; S, silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		Main stem sites, in downstream order																							
		CR_ UPPER			CR_ 3LYNX			CR_ ABNFK			CR_ BLNFK			CR_ MCIVER			CR_ BARTON			CR_ CARVER			CR_ 99E		
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	Guild	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S
BACILLARIOPHYTA (Diatoms) – Continued																									
Achnanthes suchlandtii	O, HB	*	*		*	*	*	*	*	*	*	*	*			*			*			*			
Achnanthidium minutissimum		*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*		*	*	*	*	*
Amphipleura pellucida	E, A									*			*		*										
Amphora ovalis	E, A													*										*	
Amphora perpusilla	NH													*			*		*			*			
Aulacoseira granulata	E, A									*		*	*			*						*			*
Aulacoseira sp. # 1			*		*	*	*	*				*		*								*		*	
Caloneis bacillum	A					*			*	*				*	*	*			*		*	*	*	*	*
Cocconeis klamathensis							*					**	*		*										*
Cocconeis pediculus	E, A			*	*		*			*			*	*		*			*			*			*
Cocconeis placentula	E, A	*	*		*	*		*	*		*	*		*	*		*	*			*		*	*	
Cyclotella meneghiniana	E, NH, A						*																		*
Cyclotella sp.								*																	
Cyclotella stelligera																					*				
Cymbella cistula	E, A							*																*	
Cymbella mexicana																	**								
Cymbella mexicana v. *janischii*		**	**			**		**		*		*			*	**						*			
Cymbella minuta sp. # 2		*	*	*	*		*	*	*	*	*	*		*	*	*	*	*	*		*	*	**	*	*
Cymbella minuta - like		*	**		*	**	*	*	*	*	*	*	*	*	*	*	*	*			*	*	*	*	*
Cymbella sp. # 2																								*	
Cymbella tumida	A																								*
Cymbella turgidula	A					*		*			*	*	*	*			*	*	*		*	*	*	*	*
Diadesmis confervacea	E, NH, HP								*						*										
Diadesmus perpusilla												*		*											
Diatoma hiemale	A, HB	*				*	*	*	*		*														
Diatoma hiemale v. *mesodon*	HB	*	*		*	*	*	*			*	*		*											
Diatoma tenue v. *elongatum*	HP															*									
Diatoma vulgare	E, A			*			*		*	*	*	*	*		*	**		**	*		**	**	*	**	**
Diploneis elliptica	A					*																			
Diploneis oblongella	A											*		*											
Epithemia adnata	NF, A	*	**	**			*	**	**	**		**	**		**	*		**	**			**	**	*	*
Epithemia sorex sp. # 1	NF, E, A					*			*	*		*	*		**	*		*	**		*	**		*	**
Epithemia turgida	NF, A														*										
Eunotia pectinalis v. *minor*	HB											*													
Eunotia perpusilla							*			*						*			*			*			*
Fragilaria construens v. *pumila*												*		*	*		*	*	*		*	*		*	*
Fragilaria crotonensis sp. # 2	A																	*							
Fragilaria vaucheriae	E, A	*	*		*	*		*	*		*	*		*	*		*				*		*	*	
Frustulia rhomboides v. *amphipleuroides*	O, HB					*				*		*		*	*				*		*				

APPENDIX 4. PERIPHYTON TAXA OCCURRENCE AT MAIN-STEM CLACKAMAS RIVER SITES, OREGON, 1998—Continued

[Algal taxa are ordered by major algal Division; site codes are listed in the glossary; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); some taxa are assigned to autecological guilds as follows: NF, nitrogen fixers; NH, facultative nitrogen heterotrophs; E, eutrophic taxa; O, oligotrophic taxa; A, alkaliphilic taxa; HP, halophilic taxa; HB, halophobic taxa; S, silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		Main stem sites, in downstream order																							
		CR_ UPPER			CR_ 3LYNX			CR_ ABNFK			CR_ BLNFK			CR_ MCIVER			CR_ BARTON			CR_ CARVER			CR_ 99E		
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	Guild	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S
BACILLARIOPHYTA (Diatoms) – Continued																									
Gomphoneis eriense v. *rostrata*		*	*					*			*	*		**				*					*	*	
Gomphoneis eriense v. *variabilis*		*	**		*	*	*	**	*	*	*	*	*	*	*	*	*	*	**			*	*	*	*
Gomphoneis herculeana			*		**	**	*	*	*		**	**		*	**	**	**	**	**		**	**	**	**	**
Gomphonema angustatum	E, A																*				*				
Gomphonema intricatum	E, A											**													
Gomphonema parvulum	E, NH													*	*										*
Gomphonema pumilum			*				*		*	*	*	*		*	*	*	*	*	*		*	*	*	*	*
Gomphonema quadripunctatum								*																	
Gomphonema sp. # 1		*			*			*	*																
Gomphonema sp. # 2			*	*		*	*	*	*	*	*	*	*		*			*	*		*			*	
Gomphonema sp. # 3		*									*						*						*		
Gomphonema sp. # 4																			*			*		*	*
Gomphonema subclavatum	O											*	*									*		*	*
Hannaea arcus	A, HB				*	*	*	*			**	*					*						*		
Hantzschia amphioxys	A						*							*											
Luticola mutica	E, HP, S													**											
Luticola sp. # 1	S														*										
Melosira varians	E, NH, A	*			*	**	**	*	*	*	**	**	**	**	**	**		**			*	*	**	**	*
Meridion circulare	E, A	*				*	*				*	*				*	*								
Meridion lineare												*		*	*										
Navicula capitata	A, S																						*		
Navicula capitata v. *hungarica*	A, S																*								
Navicula cincta	E, A, S														*			*							
Navicula confervacea	E, NH, HP, S															*			*						*
Navicula cryptocephala	E, A, S															*									
Navicula decussis	A, S						*														*	*			
Navicula gregaria	E, A, S													*											
Navicula menisculus	E, A, S									*									*		*			*	
Navicula minima Grun.	E, NH, A, S								*		*														
Navicula mutica v. *undulata*	NH, S												**												
Navicula radiosa	S		*						*			*			*		*				*	*			
Navicula radiosa v. *tenella*	S	*	*	*	*	*	*		*	**	*	*	*	*	*	*	*		*		*	*	*	*	*
Navicula salinarum v. *intermedia*	S														*										*
Navicula seminulum	E, NH, S							*			*														
Navicula sp. # 1	S						*					*		*								*		*	*
Navicula sp. # 2	S																	*							
Navicula tripunctata	E, NH, A, S																							*	
Navicula ventralis v. *chilensis*	S																				*				

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		Main stem sites, in downstream order																							
		CR_ UPPER			CR_ 3LYNX			CR_ ABNFK			CR_ BLNFK			CR_ MCIVER			CR_ BARTON			CR_ CARVER			CR_ 99E		
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	Guild	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S	M	J	S
BACILLARIOPHYTA (Diatoms) – Continued																									
Nitzschia sp. # 1	S						*	*											*						*
Nitzschia sp. # 2	S			*			*				*														
Nitzschia sp. # 3	S				*						*						*						*		
Nitzschia amphibia	E, NH, A, S																*								
Nitzschia angustata	S														*	*									
Nitzschia dissipata	E, A, S	*			*		*	*		*	*	*	*	*	*	*	*	*	*		*	*	*		*
Nitzschia frustulum	E, NH, A, HP, S		*	**		*	*	*	**	**	*	*	*	**	**	*	**	*	*		*	*	*	*	*
Nitzschia gracilis	HB, S			*												*	*					*			*
Nitzschia inconspicua	E, NH, A, HP, S				*			*	*		*			*	*	*	*		*		*	*	*	*	*
Nitzschia linearis	E, A, S			*	*	*						*					*					*			
Nitzschia palea	E, NH, S									*		*	*		*	*			*						*
Nitzschia recta	A, S						*														*				*
Pinnularia brebissonii									*												*				
Planothidium lanceolatum	E, A	*	*		*	*	*	*	*	*	*	*		*	*	*	*	*	*		*	*		*	*
Planothidium lanceolatum v. *dubium*											*	*										*			
Pseudostaurosira brevistriata	E, A					*	*		*	*	*	*		*	*	*		*			*	*		*	*
Reimeria sinuata								*				*					*		*		*			*	*
Rhoicosphenia curvata	E, A		*			*	*	*	*	*	*	*	*	*	*	*	**	*			**	*	*	*	*
Rhopalodia gibba sp. # 2	NF, E, A		*				*		*	*		*	*		*	*		*	**		*	*		*	*
Sellaphora pupula	E											*		*											
Staurosira construens	E, A				*																				
Staurosira construens v. *binodis*	A														*			*							*
Staurosira construens v. *venter*	A					*			*																
Staurosirella leptostauron	A					*						*			*			*							
Surirella angustata	E, A							*						*											
Surirella sp. # 1															*										
Synedra mazamaensis		*	*			*	*	*	*	*	*	*			*	*	*	*	*		*	*	*	*	*
Synedra parasitica	A																*								
Synedra rumpens v. *fragilariodes*					*						*			*		*	*								*
Synedra rumpens v. *rumpens*	O										*			*	*	*			*			*			
Synedra sp. # 1							*								*	*						*		*	
Synedra ulna	A	*	*	*	**	*	*	**	*	*	**	**	*	**	*	*	*	**	*		**	*	*	**	**
Synedra ulna v. *contracta*																					*			*	*

APPENDIX 5. PERIPHYTON TAXA OCCURRENCE AT TRIBUTARY SITES IN THE CLACKAMAS RIVER BASIN, OREGON, 1998

[Algal taxa are ordered by major algal Division; site codes are listed in the glossary; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); some taxa are assigned to autecological guilds as follows: NF, nitrogen fixers; NH, facultative nitrogen heterotrophs; E, eutrophic taxa; O, oligotrophic taxa; A, alkaliphilic taxa; HP, halophilic taxa; HB, halophobic taxa; S, silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		Tributary sites, in downstream order																							
		COLLA	COLLA	COLLA	OAK_BLTLK	OAK_BLTLK	OAK_BLTLK	OAK_RAIN	ROARING	ROARING	ROARING	FISH	SFCLACK	WINSLOW	FALL	NFCLACK	NFCLACK	NFCLACK	EAGLE_M	EAGLE_W	DEEP	RICHARDSON	CLEAR	ROCK	SIEBEN
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	**Guild**	M	J	S	M	J	S	J	M	J	S	J	J	J	J	M	J	S	J	J	J	J	J	J	J
RHODOPHYTA (Red algae)																									
Audouinella sp.		*					*							*	**										
CHLOROPHYTA (Green algae)																									
Ulothrix zonata		**	**				**				**							**							
Cladophora sp.																								**	
Stigeoclonium sp. # 1							**						*						*			*			
Zygnema sp.			**	**			**					**													
Spirogyra sp.				**																					
Mougeotia sp. # 2		**				**																			
Oedogonium sp.		*				*																		*	
Ankistrodesmus sp.				*								*													
Cosmarium sp.				*									*												
Crucigenia tetrapedia sp. # 1									*																
Draparnaldia (large cells)		**																							
Draparnaldia (small cells)		*						*																	
Microspora sp.						*			**											**					
Scenedesmus dimorphus																					*				
CYANOPHYTA (Blue-green algae)																									
Nostoc sp.	NF	*	**	*	*			*	*			*													
Nostoc akinete								*																	
Calothrix sp.	NF					*									*					*					
Chamaesiphon sp.														**	**	*									
Eucapsis alpina																**									
Lyngbya sp.		*	*	*		*								*	*					*	*		*		
Merismopedia sp.																*									
Oscillatoria sp. # 1		*		*	**	*	*	*	*	*		**	**	*	**	*	*	**	*	**	*	*	*		
Schizothrix calcicola		*	*	*	*			*	*	*	*	*	*	*	*	*	*	*	**	**	*	*	*		*
Tolypothrix sp.	NF					**	**			*															
Tolypothrix heterocysts	NF					*	*			*															
BACILLARIOPHYTA (Diatoms)																									
Achnanthes biasolettiana	A																							*	
Achnanthes deflexa			*				*	*				*	**	**	**	*	**	**	**	*	**	*	**	*	
Achnanthes hauckiana	O													*											
Achnanthes lapidosa									*																

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		Tributary sites, in downstream order																							
		COLLA	COLLA	COLLA	OAK_BLTLK	OAK_BLTLK	OAK_BLTLK	OAK_RAIN	ROARING	ROARING	ROARING	FISH	SFCLACK	WINSLOW	FALL	NFCLACK	NFCLACK	NFCLACK	EAGLE_M	EAGLE_W	DEEP	RICHARDSON	CLEAR	ROCK	SIEBEN
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	**Guild**	M	J	S	M	J	S	J	M	J	S	J	J	J	J	M	J	S	J	J	J	J	J	J	J
		BACILLARIOPHYTA (Diatoms) – Continued																							
Achnanthes sp. # 1					*			*																	
Achnanthes sp. # 2																					*				
Achnanthes sp. # 4															*										
Achnanthes suchlandtii	O, HB	*	*	*						*	*	*			*			*			*				
Achnanthidium minutissimum		*	*	*	*	*	**	**	*	**	**	*	**	**	*	*	**	*	*	**	*	**	*	*	*
Amphipleura pellucida	E, A		*	*		*																			
Amphora perpusilla	NH				*	*		*	*	*							*				*			*	*
Asterionella formosa	E, A							*																	
Aulacoseira distans	O, HB						*																		
Aulacoseira granulata	E, A				*			*																	
Aulacoseira sp. # 1								*									*								
Bacillaria paradoxa	E, A																				*				
Brachysira vitrea	A, O						*	*																	
Caloneis bacillum	A		*	*		*					*					*	*								
Cocconeis pediculus	E, A			**							*							*							
Cocconeis placentula	E, A	*	*		*	*			*	*		*	*	*	*	**	*		*	*	**	**	*	*	*
Cyclotella meneghiniana	E, NH, A																							*	
Cyclotella stelligera								*																	
Cymbella cistula	E, A	*																							
Cymbella mexicana					**	*			*		**		**								**			**	
Cymbella mexicana v. *janischii*						**																			
Cymbella microcephala sp. # 2	A						*																		
Cymbella minuta sp. # 2					*	*	*	*	*	*	*		*	*		*	*		*	*	*		*		
Cymbella minuta-like						**		*			*		*												
Cymbella prostrata	E, A																								**
Cymbella sp. # 2																			*						
Cymbella tumida	A												*				**	*							
Cymbella turgidula	A	*		*	*			*				*	*						*				*		
Diadesmis confervacea	E, NH, HP				*																				
Diadesmus contenta	A				*																				
Diadesmus perpusilla								*																	
Diatoma hiemale	A, HB				*																				
Diatoma hiemale v. *mesodon*	HB	*			*	*		*	**	**	*						*								
Diatomella balfouriana																							*		

APPENDIX 5. PERIPHYTON TAXA OCCURRENCE AT TRIBUTARY SITES IN THE CLACKAMAS RIVER BASIN, OREGON, 1998—Continued

[Algal taxa are ordered by major algal Division; site codes are listed in the glossary; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); some taxa are assigned to autecological guilds as follows: NF, nitrogen fixers; NH, facultative nitrogen heterotrophs; E, eutrophic taxa; O, oligotrophic taxa; A, alkaliphilic taxa; HP, halophilic taxa; HB, halophobic taxa; S, silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		Tributary sites, in downstream order																							
		COLLA	COLLA	COLLA	OAK_BLTLK	OAK_BLTLK	OAK_BLTLK	OAK_RAIN	ROARING	ROARING	ROARING	FISH	SFCLACK	WINSLOW	FALL	NFCLACK	NFCLACK	NFCLACK	EAGLE_M	EAGLE_W	DEEP	RICHARDSON	CLEAR	ROCK	SIEBEN
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	**Guild**	**M**	**J**	**S**	**M**	**J**	**S**	**J**	**M**	**J**	**S**	**J**	**J**	**J**	**J**	**M**	**J**	**S**	**J**	**J**	**J**	**J**	**J**	**J**	**J**
BACILLARIOPHYTA (Diatoms) – Continued																									
Diploneis elliptica	A				*																				
Entomoneis ornata	HB																							*	
Epithemia adnata	NF, A		**	**		**		**	*	**															
Epithemia sorex sp. # 1	NF, E, A		*					*																	
Epithemia turgida	NF, A				**			**																	
Eunotia pectinalis v. *minor*	HB																								*
Eunotia perpusilla				*			*				*														*
Fragilaria construens v. *pumila*							*	*		*															
Fragilaria vaucheriae	E, A	*	*		*	*		*	*	*		*	*	*	*	*					*		*		*
Frustulia rhomboides v. *amphipleuroides*	O, HB					*					*				**		**				*				*
Gomphoneis eriense v. *rostrata*						*																			
Gomphoneis eriense v. *variabilis*		**	*			*												*							
Gomphoneis herculeana		**			**				**			**	*						*		*				
Gomphoneis herculeana v. *septiceps*											**														
Gomphonema angustatum	E, A	*			*									*		*	*	*			*				
Gomphonema gracile													*												
Gomphonema parvulum	E, NH								*				*			**	*		*				*	*	*
Gomphonema pumilum			*	*		*		*	*	*	**	*	*	*		*	*	*	**	*	*	**	**		*
Gomphonema sp. # 1		*			*												*								
Gomphonema sp. # 2		*	**	*		*			*	*	*		*	*			*	*				**	*	*	
Gomphonema sp. # 3					*																				
Gomphonema sp. # 4													*									*			
Gomphonema subclavatum	O			*				*					*												
Gomphonema truncatum v. *capitatum*								*														*			
Hannaea arcus	A, HB	*			*		*	*	**	**	*	*	*				*			**		*			
Melosira varians	E, NH, A				**	*			*	*	*	**	**	**			**				**		**	**	**
Meridion circulare	E, A	*			*																				
Meridion lineare																	*								
Navicula accomoda	E, NH, A, S																								*
Navicula capitata	A, S																				*				
Navicula cincta	E, A, S				*																				
Navicula cryptocephala	E, A, S																	*			*				
Navicula cryptocephala v. *veneta*	E, A, S		*																						
Navicula gregaria	E, A, S									*				*											*

APPENDIX 5. PERIPHYTON TAXA OCCURRENCE AT TRIBUTARY SITES IN THE CLACKAMAS RIVER BASIN, OREGON, 1998—Continued

[Algal taxa are ordered by major algal Division; site codes are listed in the glossary; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); some taxa are assigned to autecological guilds as follows: NF, nitrogen fixers; NH, facultative nitrogen heterotrophs; E, eutrophic taxa; O, oligotrophic taxa; A, alkaliphilic taxa; HP, halophilic taxa; HB, halophobic taxa; S, silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		Tributary sites, in downstream order																							
		COLLA	COLLA	COLLA	OAK_BLTLK	OAK_BLTLK	OAK_BLTLK	OAK_RAIN	ROARING	ROARING	ROARING	FISH	SFCLACK	WINSLOW	FALL	NFCLACK	NFCLACK	NFCLACK	EAGLE_M	EAGLE_W	DEEP	RICHARDSON	CLEAR	ROCK	SIEBEN
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	**Guild**	**M**	**J**	**S**	**M**	**J**	**S**	**J**	**M**	**J**	**S**	**J**	**J**	**J**	**J**	**M**	**J**	**S**	**J**	**J**	**J**	**J**	**J**	**J**	**J**
BACILLARIOPHYTA (Diatoms) – Continued																									
Navicula lanceolata	E, HP, A, S		*																						
Navicula minima Grun.	E, NH, A, S				*					*						*									
Navicula radiosa	S			*		*	*	**													*	*			
Navicula radiosa v. *tenella*	S		*	**	*	*	*	*		*	*	*	*	*	*	*	*	*							
Navicula salinarum v. *intermedia*	S		*																						
Navicula seminulum	E, NH, S							*								*									
Navicula sp. # 1	S				*	*	*	*		*							*						*		
Navicula symmetrica	S																						*		
Navicula tripunctata	E, NH, A, S																			*					
Navicula viridula	E, A, S																							*	**
Nitzschia sp. # 1	S	*						*		*															*
Nitzschia sp. # 2	S		*		*				*	*		*													
Nitzschia sp. # 3	S		*		*					*															
Nitzschia amphibia	E, NH, A, S							*						*										*	*
Nitzschia angustata	S						*																		
Nitzschia dissipata	E, A, S	*	*	*	*	*	*		*	*	*		*	*		**	*	*		*	*			*	*
Nitzschia fonticola	E, A, S								*	*															
Nitzschia frustulum	E, NH, HP, A, S		*	*	*	*	*	*		**	*	*	*					**			*	*	*	**	**
Nitzschia gracilis	HB, S				*		*	*	*																
Nitzschia inconspicua	E, NH, A, HP, S		*	*					*	*	*	*									*	*		*	*
Nitzschia linearis	E, A, S					*							*				*				*				
Nitzschia palea	E, NH, S			*																	*			*	
Nitzschia recta	A, S					*		*						*										*	
Pinnularia acuminata v. *bielawskii*														*											
Pinnularia brebissonii																									*
Planothidium lanceolatum	E, A	*	*	*	*	*	*		*	*	*	*	*	**	*	**	*	*		*	**	*		*	**
Planothidium lanceolatum v. *dubium*		*										*													
Pseudostaurosira brevistriata	E, A				*		*	*	*															*	
Reimeria sinuata			*	*	*	*						*	*		*				*		*	*	*		*
Rhoicosphenia curvata	E, A	*	*	*	*	*			*	*	*	*	*	*	*		*	*	*		*	**	*	**	*
Rhopalodia gibba sp. # 2	NF, E, A		*					*																	
Sellaphora pupula	E						*																		*
Staurosira construens	E, A				*																				
Staurosira construens v. *binodis*	A							*																	

[Algal taxa are ordered by major algal Division; site codes are listed in the glossary; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); some taxa are assigned to autecological guilds as follows: NF, nitrogen fixers; NH, facultative nitrogen heterotrophs; E, eutrophic taxa; O, oligotrophic taxa; A, alkaliphilic taxa; HP, halophilic taxa; HB, halophobic taxa; S, silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		Tributary sites, in downstream order																							
		COLLA	COLLA	COLLA	OAK_BLTLK	OAK_BLTLK	OAK_BLTLK	OAK_RAIN	ROARING	ROARING	ROARING	FISH	SFCLACK	WINSLOW	FALL	NFCLACK	NFCLACK	NFCLACK	EAGLE_M	EAGLE_W	DEEP	RICHARDSON	CLEAR	ROCK	SIEBEN
		Sampling month (M) May, (J) July, and (S) September																							
Algal taxon	**Guild**	M	J	S	M	J	S	J	M	J	S	J	J	J	J	M	J	S	J	J	J	J	J	J	J
		BACILLARIOPHYTA (Diatoms) – Continued																							
Staurosira construens v. *venter*	A							*																	
Staurosirella leptostauron	A							*																	
Surirella angustata	E, A																							*	
Synedra delicatissima								*																	
Synedra mazamaensis		*	*	*	*						*														
Synedra rumpens v. *fragilariodes*		*	*		*	*		*																	
Synedra rumpens v. *rumpens*	O		*	*		*	*	*										*					*	*	*
Synedra sp. # 1					*																				
Synedra ulna	A	*	*	*	*		*	**		*		**	*				*	**					**	*	*
Synedra ulna v. *contracta*													*					*	**						
Tabellaria fenestrata	HB						*	*																	
Tabellaria flocculosa	HB							*							*										

APPENDIX 6. PHYTOPLANKTON TAXA OCCURRENCE IN NORTH FORK RESERVOIR, CLACKAMAS RIVER BASIN, OREGON 1997–98

[Algal taxa are ordered by major algal Divisions; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); B, NFKRES_B (site codes are listed in the glossary); sampling depths are given as follows: (1) surface, (2) thermocline, (3) depth of water release, and (4) 1 meter off the bottom; some taxa are assigned to autecological guilds as follows: (NF) nitrogen fixers, (NH) facultative nitrogen heterotrophs, (E) eutrophic taxa, (O) oligotrophic taxa, (A) alkaliphilic taxa, (HB) halophobic taxa, and (S) silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993]

Algal taxa	Guild	Reservoir station, year, month, and sampling depth																																					
		NFKRES_1																						NFKRES_2														B
		1997			1998																																	
		Sampling month and depth																																				
		July (1)	Aug (1)	Sep (1)	April (1)	May (1)	May (2)	May (3)	May (4)	June (1)	June (2)	June (3)	June (4)	July (1)	July (2)	July (3)	Aug (1)	Aug (2)	Aug (3)	Aug (4)	Sep (1)	Sep (2)	Sep (3)	Sep (4)	May (1)	May (2)	June (1)	June (2)	June (3)	July (1)	July (2)	July (3)	Aug (1)	Aug (2)	Aug (3)	Sep (1)	Sep (2)	Sep (3)	Sep (1)
CRYPTOPHYTA (Cryptophyte algae)																																							
Cryptomonas erosa v. reflexa						**		*		**	**			**	**	**	**	**	*	*		*	*		**	*	**	**		**	**	**	**	**	*	**	**	*	*
Rhodomonas minuta		**		**	*	*	*	*	*	**	**	**	*	**	**	**	**	**	**	*	**	**	*	*	*	**	**	**		**	**	**	**	**	*	**	*	*	*
DINOPHYTA (Dinophyte algae)																																							
Glenodinium sp.						*				*				**	**			*			**	*	*		*	**		*		**	**	**	*	**			*		
EUGLENOPHYTA (Euglenophyte algae)																																							
Euglena sp.						**													*			*			**	**													
Trachelomonas sp.														*			*																						
CYANOPHYTA (Blue-green algae)																																							
Anabaena circinalis	NF	*	**	**					*				*				**			**	**			*		*										**			
Anabaen circinalis heterocyst	NF		**	**													*			*	*															*			
Anabaena spiroides	NF																				*																		
Anabaena spiroides heterocyst	NF																				*																		
Anabaena akinete	NF		**																																		*	*	
Aphanothece sp.										*																	*												
Oscillatoria sp. # 2									**				*									**																**	
Schizothrix calcicola							*			*				*	**	*	*				*	*					*		*		*	*			*			*	
CHLOROPHYTA (Green algae)																																							
Ankistrodesmus sp.																	*			*	*	*	*										*				*		*
Chlamydomonas sp.									*				*	**				*			*	*				*													
Closterium sp.																										*			*										
Dactylococcus infusionum																		*																					
Dictyosphaerium sp.																							**																
Elakatothrix sp.																	**	**		*													**	**					
Eudorina sp.																						*																	
Mougeotia sp. # 1																																*	**						
Scenedesmus sp. # 1			**										*																										
Stigeoclonium sp. # 2														*																									
BACILLARIOPHYTA (Diatoms)																																							
Achnanthes deflexa								*																															
Achnanthes hauckiana	O							*																															
Achnanthes lapidosa								*																															
Achnanthes sp. # 2								*																															
Achnanthes sp. # 4								**																															

APPENDIX 6. PHYTOPLANKTON TAXA OCCURRENCE IN NORTH FORK RESERVOIR, CLACKAMAS RIVER BASIN, OREGON 1997–98—Continued

[Algal taxa are ordered by major algal Divisions; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); B, NFKRES_B (site codes are listed in the glossary); sampling depths are given as follows: (1) surface, (2) thermocline, (3) depth of water release, and (4) 1 meter off the bottom; some taxa are assigned to autecological guilds as follows: (NF) nitrogen fixers, (NH) facultative nitrogen heterotrophs, (E) eutrophic taxa, (O) oligotrophic taxa, (A) alkaliphilic taxa, (HB) halophobic taxa, and (S) silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993]

Algal taxa	Guild	Reservoir station, year, month, and sampling depth																																			
		NFKRES_1																						NFKRES_2														B
		1997			1998																																
		Sampling month and depth																																			
		July (1)	Aug (1)	Sep (1)	April (1)	May (1)	May (2)	May (3)	May (4)	June (1)	June (2)	June (3)	June (4)	July (1)	July (2)	July (3)	Aug (1)	Aug (2)	Aug (3)	Aug (4)	Sep (1)	Sep (2)	Sep (3)	Sep (4)	May (1)	May (2)	June (1)	June (2)	June (3)	July (1)	July (2)	July (3)	Aug (1)	Aug (2)	Aug (3)	Sep (1)	Sep (2)	Sep (3)	Sep (1)
BACILLARIOPHYTA (Diatoms) – Continued																																							
Achnanthidium minutissimum					*	*	*		*			*			*				*	*		*	**	*	*	*		*		*	*						*	*	*
Amphora sp.																					*											*							*
Asterionella formosa	E, A					**				*							*					**			**	*	*	*										*	**
Aulacoseira granulata	E, A																				**	**	**	**												**	**	**	**
Aulacoseira sp.						**							*				**	**	**						**	*													
Caloneis ventricosa																												*											
Cocconeis klamathensis																																			*				
Cocconeis placentula	A, HB					*			*				*			*			*	*		*	*	*	*	*		*				*			*		*	*	
Cyclotella sp.									*												*	*	*														*		
Cymbella microcephala sp. # 1	A												*																										
Cymbella minuta sp. # 1							*		*	*		*	*			*			**	**		*	*	*		*						*			*	*	*	*	
Cymbella sp. # 1												*																											
Diatoma hiemale	A, HB																											**									*		
Diatoma hiemale v. *mesodon*	HB				**		**		*				*							*									**								*		
Epithemia sorex sp. # 1	NF, E, A	**						**																									**						
Epithemia sp.	NF																																					*	
Eunotia sp.																													*			*							
Fragilaria crotonensis sp. # 2	A																				*																		**
Fragilaria sp. # 3																										**													
Frustulia rhomboides									*																														
Gomphoneis sp.					**		**	**	**	**		**	*														**	**	**			**			**		**		
Gomphonema sp.					**		*	**	**	*	**		**						*	**	**		*	*		*	*	*							**	*	*	*	
Hannaea arcus	A, HB				**				**		*	**	**															**	**									*	
Melosira varians	E, NH, A	**				**			*			*	*												**	*									**				
Meridion circulare	E, A					*				**			*												*		*												
Navicula aurora	S						**																																
Navicula salinarum v. *intermedia*	S		**				*																																
Navicula sp.	S			**	**	*	**	**	**	*		**	**	*		**	*		**	**	*	**	**	**	*	*	*	*	*	**					**	**	**	**	**
Nitzschia acicularis	S				*					*							*										*		*						*				
Nitzschia dissipata	E, A, S						*			*																	*												
Nitzschia sp.	S	*		**	*	*	*		*	*		*	**	**		**	*	**	**	*	*	*	**	**	*	*		*	*			**			*		**	**	*
Pinnularia sp.									*				*							*										**				**					
Planothidium dubium										*																	*		*										
Planothidium lanceolatum	E, A					*			*		*				**					*				*	*	*		*			**				*				
Rhoicosphenia curvata	E, A						*			*										*				**			**	*	*										

APPENDIX 6. PHYTOPLANKTON TAXA OCCURRENCE IN NORTH FORK RESERVOIR, CLACKAMAS RIVER BASIN, OREGON 1997–98—Continued

[Algal taxa are ordered by major algal Divisions; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); B, NFKRES_B (site codes are listed in the glossary); sampling depths are given as follows: (1) surface, (2) thermocline, (3) depth of water release, and (4) 1 meter off the bottom; some taxa are assigned to autecological guilds as follows: (NF) nitrogen fixers, (NH) facultative nitrogen heterotrophs, (E) eutrophic taxa, (O) oligotrophic taxa, (A) alkaliphilic taxa, (HB) halophobic taxa, and (S) silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993]

		Reservoir station, year, month, and sampling depth																																				
		NFKRES_1																						NFKRES_2														B
		1997			1998																																	
		Sampling month and depth																																				
Algal taxa	Guild	July (1)	Aug (1)	Sep (1)	April (1)	May (1)	May (2)	May (3)	May (4)	June (1)	June (2)	June (3)	June (4)	July (1)	July (2)	July (3)	Aug (1)	Aug (2)	Aug (3)	Aug (4)	Sep (1)	Sep (2)	Sep (3)	Sep (4)	May (1)	May (2)	June (1)	June (2)	June (3)	July (1)	July (2)	July (3)	Aug (1)	Aug (2)	Aug (3)	Sep (1)	Sep (2)	Sep (3)	Sep (1)
BACILLARIOPHYTA (Diatoms) – Continued																																							
Rhopalodia gibba sp. # 1	NF, E, A																																		**				
Sellaphora pupula	E																*			*	*																*		
Synedra delicatissima						*																*			*						**						*		
Synedra mazamaensis						*	*		*				*							*					*	*									*			*	
Synedra ulna	A	**				*	**		**	**	**	**	**			**				**	*		*	**	*	**	**	*	**						*		*	**	**

APPENDIX 7. PHYTOPLANKTON TAXA OCCURRENCE IN TIMOTHY LAKE, CLACKAMAS RIVER BASIN, OREGON 1997–98

[Algal taxa are ordered by major algal Divisions; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); site codes are listed in the glossary); sampling depths are given as follows: (1) surface, (2) thermocline, (3) depth of water release, and (4) 1 meter off the bottom; some taxa are assigned to autecological guilds as follows: (NF) nitrogen fixers, (NH) facultative nitrogen heterotrophs, (E) eutrophic taxa, (O) oligotrophic taxa, (A) alkaliphilic taxa, (HB) halophobic taxa, and (S) silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		TIM_LK																			
		1997			1998																
		Month and sampling depth																			
Algal taxon	Guild	May (1)	June (1)	July (1)	May (1)	May (2)	May (3)	June (1)	June (2)	June (3)	June (4)	July (1)	July (2)	July (3)	Aug (1)	Aug (2)	Aug (3)	Sep (1)	Sep (2)	Sep (3)	Sep (4)
CRYPTOPHYTA (Cryptophyte algae)																					
Cryptomonas erosa v. *reflexa* sp. # 1							*		*	*	*	*		*			*				
Cryptomonas erosa v. *reflexa* sp. # 2																		**	**	**	**
Rhodomonas minuta			*			*	*	**	**	**	**	*	*	*	*	**	**	**	*	**	**
DINOPHYTA (Dinophyte algae)																					
Glenodinium sp.					*			*			*				*	*					
Peridinium sp. # 1																			*		
Peridinium sp. # 2				**	**	**		*	*	*		*	**		**						
EUGLENOPHYTA (Euglenophyte algae)																					
Euglena sp.															*						*
Phacus sp.													**			*			*	*	**
Trachelomonas sp.											*	*									
CYANOPHYTA (Blue-green algae)																					
Anabaena circinalis	NF		**		**	**	**	**	**	*	*	**	**	**		**	**	*		**	*
Anabaena circinalis heterocyst	NF		**		*	**	*	*		*	*	*	**	*		*	**			*	
Anabaena akinete	NF		**					*													
Microcystis aerugenosa						*															
Schizothrix calcicola			**		**		**	**	**	**	**	**	**	**	*	**	*	*	**	*	*
CHLOROPHYTA (Green algae)																					
Carteria sp.		*															*				
Chlamydomonas sp.					**	*	*	*	*	*	*	*		**	**	*	**				
Crucigenia tetrapedia sp. # 1																		*	*	*	
Crucigenia tetrapedia sp. # 2															**	*					
Dactylococcus infusionum																	*				
Mougeotia sp. # 1						**															
Oocystis sp.															*						
Unidentified thick-walled oval cell		*																			
Unidentified thick-walled 4 unit			*			*									*	*					
BACILLARIOPHYTA (Diatoms)																					
Achnanthidium minutissimum				*														*			
Amphora sp.															*				*		
Asterionella formosa	E, A	**	**	**	**	**	**	**	**	**	**	*		**				**	**	*	
Aulacoseira granulata	E, A																			**	**
Aulacoseira sp.		**		**			**			**	*				**						

[Algal taxa are ordered by major algal Divisions; *, indicates taxon presence at a site; **, indicates 5 most abundant taxa at each site (based on % relative biovolume); site codes are listed in the glossary); sampling depths are given as follows: (1) surface, (2) thermocline, (3) depth of water release, and (4) 1 meter off the bottom; some taxa are assigned to autecological guilds as follows: (NF) nitrogen fixers, (NH) facultative nitrogen heterotrophs, (E) eutrophic taxa, (O) oligotrophic taxa, (A) alkaliphilic taxa, (HB) halophobic taxa, and (S) silt-tolerant taxa. Sources for autecological classification are from Patrick and Reimer, 1966, 1975; Schoeman, 1973; Lowe, 1974; van Dam and others, 1994; Tuchman, 1996; Lowe and Pan, 1996; Porter and others, 1993.]

		TIM_LK																			
		1997			1998																
		Month and sampling depth																			
Algal taxon	**Guild**	**May (1)**	**June (1)**	**July (1)**	**May (1)**	**May (2)**	**May (3)**	**June (1)**	**June (2)**	**June (3)**	**June (4)**	**July (1)**	**July (2)**	**July (3)**	**Aug (1)**	**Aug (2)**	**Aug (3)**	**Sep (1)**	**Sep (2)**	**Sep (3)**	**Sep (4)**
BACILLARIOPHYTA (Diatoms) – Continued																					
Cyclotella sp.		*		*													*				
Fragilaria crotonensis sp. # 1	A			**											**						
Fragilaria crotonensis sp. # 2	A																		*		
Fragilaria sp. #1		**																			
Fragilaria sp. #2																			**		
Gomphoneis sp.											**										
Navicula sp.	S	**				*	*											*	*		
Nitzschia dissipata	E, A, S										*					*					
Nitzschia sp.	S			**			*	*	*		*	**		*	*	*	*	*			
Sellaphora pupula	E			*																	
Staurosira construens	E, A	*								*					*	*					
Synedra delicatissima							**		**	**	**	**		**		**		**		**	**
Urosolenia sp.								**	*	*		**				**	**	**	**	*	

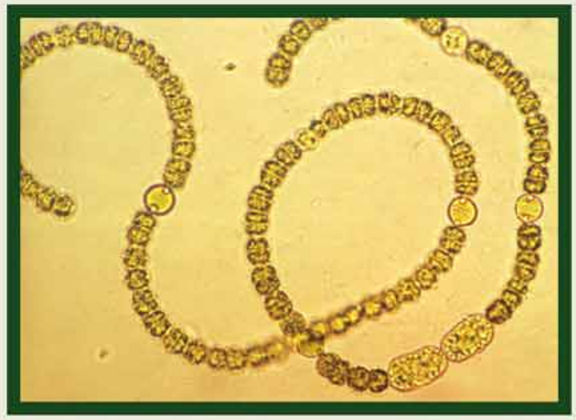
Back cover photographs, clockwise from lower left:

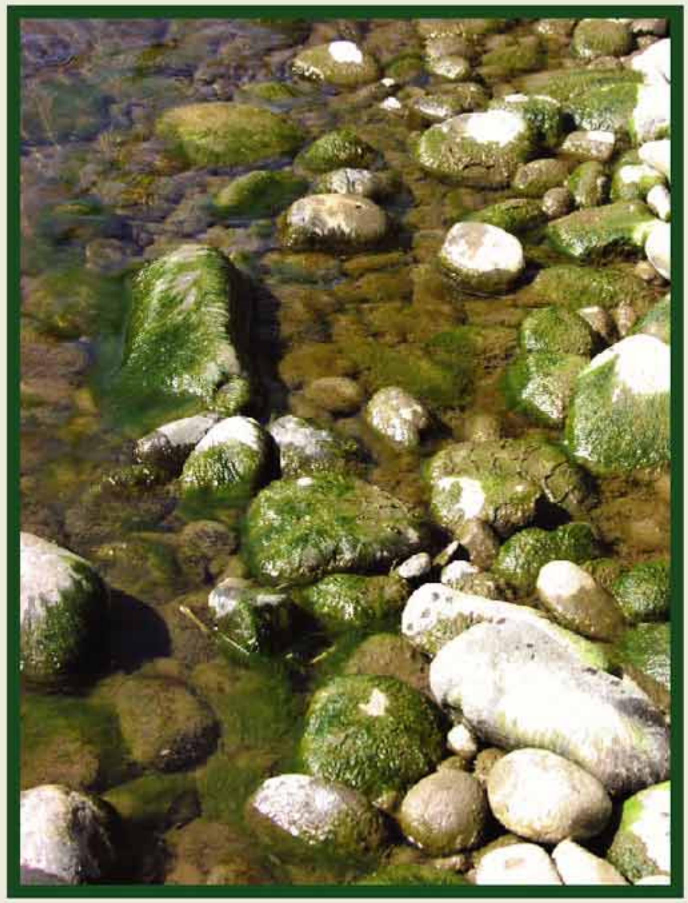
Growths of filamentous green algae often concentrate along the margins of some Clackamas Basin streams, as in this reach of the Collawash River.

Water exiting Timothy Lake is aerated at the powerhouse to boost oxygen levels in the Oak Grove Fork.

Blooms of the blue-green alga *Anabaena* in Clackamas Basin reservoirs can degrade water quality and contribute to taste and odor problems in the drinking water supply.

Another example of excessive algal growth, this one in the Clackamas River main stem upstream of Eagle Creek.





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