Assessment of Water Quality, Nutrients, Algal Productivity, and Management Alternatives for Low-Flow Conditions, South Umpqua River Basin, Oregon, 1990–92

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96–4082

Prepared in cooperation with
DOUGLAS COUNTY, OREGON

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

Cover photograph. South Umpqua River near Roseburg, Oregon (USGS files, 1981).

Assessment of Water Quality, Nutrients, Algal Productivity, and Management Alternatives for Low-Flow Conditions, South Umpqua River Basin, Oregon, 1990–92

By DWIGHT Q. TANNER and CHAUNCEY W. ANDERSON

U.S. GEOLOGICAL SURVEY
Water-Resources Investigations Report 96–4082

Prepared in cooperation with
DOUGLAS COUNTY, OREGON

U.S. DEPARTMENT OF THE INTERIOR
MARCH 3, 1849

Portland, Oregon
1996

U. S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
Gordon P. Eaton, Director

For additional information
write to:

District Chief
U.S. Geological Survey, WRD
10615 S.E. Cherry Blossom Drive
Portland, Oregon 97216

Copies of this report can be
purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286, Federal Center
Denver, CO 80225

CONTENTS

FIGURES

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply	By	To obtain
inch	0.3937	centimeter
inch	39.37	meter
foot (ft)	0.3048	meter
foot per second (ft/s)	0.3048	meter per second
cubic feet per second (ft^3 /s)	0.0283	cubic meter per second (m^3/s)
square foot (ft^2)	0.0929	square meter
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer
gallon	0.1337	cubic foot (ft^3)
million gallons per day	1.547	cubic feet per second (ft^3 /s)

Air and water temperatures are given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following:

°F = 1.8 (°C) + 32

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called Sea Level Datum of 1929.

Page Intentionally Blank

Assessment of Water Quality, Nutrients, Algal Productivity, and Management Alternatives for Low-Flow Conditions, South Umpqua River Basin, Oregon, 1990–92

By **Dwight Q. Tanner** *and* **Chauncey W. Anderson**

Abstract

This report is an evaluation of the effects of nutrient loading on water quality in the South Umpqua River Basin. The study was done by the U.S. Geological Survey in cooperation with Douglas County, Oregon. Five wastewater-treatment plants were shown to contribute less than 15 percent of the flow, but more than 90 percent of the nitrogen and phosphorus, in the South Umpqua River during low streamflows in summer. These nutrient inputs were associated with, and largely responsible for, the dense growth of periphytic algae that covered the rocky channel and produced biomass values as large as 340 grams of ash-free dry weight per square meter. The nighttime respiration of periphytic algae caused violations of the Oregon water-quality standard, which requires a dissolved oxygen concentration of at least 90 percent of saturation, at most sites along the South Umpqua River. Photosynthesis by algae during daylight resulted in many exceedances of the Oregon pH standard of 8.5.

Net productivity, calculated from hourly measurements of dissolved oxygen concentrations, was as much as 3.8 grams of oxygen per square meter per day. The magnitude of productivity increased with increases in dissolved inorganic nitrogen concentration and load. The large amount of nutrient uptake by algae resulted in lowered nutrient concentrations downstream from nutrient point sources.

Management alternatives for the South Umpqua River Basin include several methods to reduce nutrient concentrations and loads. The reduction of dissolved-inorganic-nitrogen and soluble-reactive-phosphorus loads from wastewater-treatment-plant effluent would reduce the frequency of violations of water-quality standards. Flow augmentation probably would decrease water-quality problems in the river, but it is difficult to predict the magnitude of the effects of increased velocity and decreased temperature on algal growth. Land application and storage of wastewater-treatment-plant effluent during the summer months would reduce the input of nutrients from point sources.

Three exceedances of the Oregon standard for fecal coliform of 200 colonies per 100 milliliters were associated with large streamflows, suggesting that nonpoint sources affect the river during periods of high runoff. Fecal-streptococcus counts were larger than historical values and require confirmation.

Ammonia from wastewater-treatment-plant effluent, high pH values, and high temperatures present a potential for chronic ammonia toxicity in the lower reaches of the South Umpqua River; however, actual violations of standards for chronic concentrations were not detected because of diel fluctuations in pH and water temperature.

INTRODUCTION

Water-quality problems in the South Umpqua River have been previously documented (Rinella, 1986). Along much of the river, daily metabolic cycles of the periphyton-dominated benthic community produces summertime pH values and dissolved oxygen (DO) concentrations that violate State of Oregon and U.S. Environmental Protection Agency (EPA) water-quality standards (U.S. Environmental Protection Agency, 1986; State of Oregon, 1992). Other water-quality concerns include bacteria and ammonia toxicity. Water-quality standards are intended to protect the beneficial uses of the river, including domestic water supply and the salmon fishery.

Many of the water-quality problems in the South Umpqua River Basin relate to low-flow and warm-weather conditions that generally occur from May through October. As the winter rains in southwestern Oregon cease, daily mean streamflow in the South Umpqua River decreases from about 1,000 ft^3/s (cubic feet per second) to less than 100 ft^3/s. Five wastewater-treatment plants (WWTPs) account for a large part of the dissolved nitrogen and phosphorus loading to the river during the summer. Periphyton filaments, nourished by dissolved nutrients and stimulated by light, sprout from overwintered basal fragments that are attached to rocks in the river channel. The periphyton, much of which is *Cladophora* (Anderson and others, 1994), grows prolifically in the lower reaches of the river. Periphyton respiration and photosynthesis can cause large diel (day–night) fluctuation in DO and pH. DO concentrations and pH values are at a diel minimum in early morning owing to overnight respiration of algae and other benthic organisms; in the afternoons, photosynthesis results in diel maxima of DO and pH. Violations of Oregon State standards for DO concentrations (minimum of 90-percent saturation) and pH (greater than 8.5) are frequent, occurring daily in many parts of the river owing to the diel metabolic cycle. In addition to causing water-quality problems, periphyton is a nuisance in the summertime along the South Umpqua River, hindering recreation and irrigation withdrawals and causing offensive odors as the algae decay.

In 1990, Douglas County entered into a cooperative agreement with the U.S. Geological Survey to assess nutrients, water quality, and algal conditions in the South Umpqua River. Data from that study have been published in two annual data reports (U.S. Geological Survey, 1992, 1993). In addition, the complete data set and methods of data collection have been published (Anderson and others, 1994). Information concerning stream velocity and reaeration coefficients also has been published (Laenen and Woo, 1994).

Purpose and Scope

This final report, an assessment of the effects of nutrient loading on the water quality of the South Umpqua River, quantifies the role of algal metabolism and presents management alternatives for improvement of water quality. Specific objectives of this study were to (1) define existing DO concentrations and pH values, (2) predict DO concentrations and pH values during alternate nutrient-management scenarios, and (3) evaluate current bacteria and ammonia toxicity.

This report includes an interpretation of the data collected by the U.S. Geological Survey during summer periods of low flow (June through October) from 1990 to 1992. Biological and chemical water-quality characteristics of streams and WWTP effluent in the South Umpqua River Basin were measured. Samples of periphytic algae were collected for species identification and analysis of biomass and nutrient content. Data on streamflow, channel characteristics, and incident light were collected at several sites.

Acknowledgments

The authors wish to express their gratitude to the following people and organizations: Douglas County Water Resources Department, for cooperative funding and logistical support; Douglas County Parks Department, for the use of land near Days Creek as a fixed station; and Dale Ritter and the staff of the Science Department at Umpqua Community College, for assistance in collecting and processing of wastewater-treatment-plant effluent samples. Special thanks go to the operators of wastewater-treatment plants in the South Umpqua River Basin for collecting effluent samples on a regular basis and at special times at our request— Dean Hunt and Jim Layton, Canyonville Department of Public Works; Eric Quinn, City of Riddle Wastewater Treatment Plant; Dick Schmidt, City of Myrtle Creek Wastewater Treatment Plant; Gary Gent, Douglas County Department of Public Works; and Jack O’Brien, Roseburg Urban Sanitary Authority.

In addition, we would like to thank the members of the Technical Advisory Committee who provided local knowledge, insights, and advice during this study. This committee included, at various times, the following individuals:

John Youngquist,
Douglas County Water Resources Department;

Kenneth Shumway,
Douglas County Water Resources Department;

Larry Spielbush, Douglas County Public Works;

Gary Gent, Douglas County Public Works;

Gary Ball, Oregon Water Resources Department;

Bob Baumgartner,
Oregon Department of Environmental Quality;

Bill Mularky,
Oregon Department of Fish and Wildlife;

Doyle Tankersly, Roberts Creek Water District;

Mark Andrews, OMI Inc., Roseburg;

John Keady, OMI Inc., Roseburg;

Steve Johnson, City of Myrtle Creek;

Richard Nelson, City of Myrtle Creek;

Lynn Herbert, Herbert Lumber Company;

Leonard Gondeck, Roseburg Forest Products;

Joe Merchep, Umpqua Fishermen Association;

Jerry Winterbotham, Umpqua Fishermen Association;

Jeff Kruse, Kruse Farms;

Webster Briggs, Webster Briggs Ranch;

Mikeal Jones, U.S. Forest Service;

Jeff Dose, U.S. Forest Service;

Joe Ross, Bureau of Land Management;

Scott Siegfried, Bureau of Land Management;

Steve Hofford, Bureau of Land Management;

Jim Vancura, Natural Resources Conservation Service
(formerly Soil Conservation Service);

Dave Zimmer, Bureau of Reclamation.

DESCRIPTION OF STUDY AREA

The South Umpqua River Basin of southwestern Oregon (fig. 1) has an area of 1,762 mi^2 (square miles) and ranges in elevation from about 6,800 feet above sea level in the eastern part to 380 feet above sea level at the mouth of the South Umpqua River. The South Umpqua River flows about 106 miles from its headwaters to the confluence with the North Umpqua River, northwest of Roseburg. From the headwaters to Tiller, the South Umpqua River flows southwestward for about 28 miles and drains the Umpqua National Forest. The river then flows westward from Tiller to Canyonville for 24 miles; the river valley gradually widens downstream from Days Creek. From Canyonville, the South Umpqua River flows north for 54 miles, at a reduced gradient, until joining the North Umpqua River. Hydrology, population, and land use in the Umpqua River Basin have been described by Rinella (1986).

Geology and Climate

The South Umpqua River Basin lies in three distinct geological provinces (Ramp, 1972). The eastern part of the basin (the part upstream from Tiller, which is mostly National Forest) is in the Western Cascades Province. The eastern part is underlain by Tertiary volcanic rocks that include silicic vent complexes, basaltic lava flows, tuffs, and Tertiary sedimentary and volcaniclastic rocks (Walker and MacLeod, 1991). The central part of the basin—the area between Tiller and Winston—is in the Klamath Mountains Province; lower Cretaceous and upper Jurassic sedimentary and volcanic rocks are prevalent. Ultramafic and related Jurassic rocks, locally altered to serpentine, form the site of a nickel mine near Riddle. The South Umpqua River Basin from Winston northward is in the Coast Range Province; rocks in this province include Tertiary marine sandstone, siltstone, and conglomerate, as well as some Tertiary volcanic and related rocks.

The climate in the South Umpqua River Basin generally is mild and characterized by dry summers and wet winters. The basin lies within the climatological division of Oregon’s southwestern valleys. The average annual precipitation for 1951–80 for the southwestern valleys was 35.78 inches; precipitation for those years averaged 5.97 inches (17 percent of annual precipitation) during the 5-month period from June through October. The June-through-October precipitation for the southwestern valleys during 1990, 1991, and 1992 was 6.88, 4.93, and 7.33 inches, respectively (National Oceanic and Atmospheric Administration, 1991, 1992, and 1993). Although the summer precipitation in 1990 and 1992 was greater than the 1951–80 average, the South Umpqua River Basin, as well as much of the State of Oregon, was in the sixth year of drought in 1992. Accordingly, streamflows were low in 1991 and 1992.

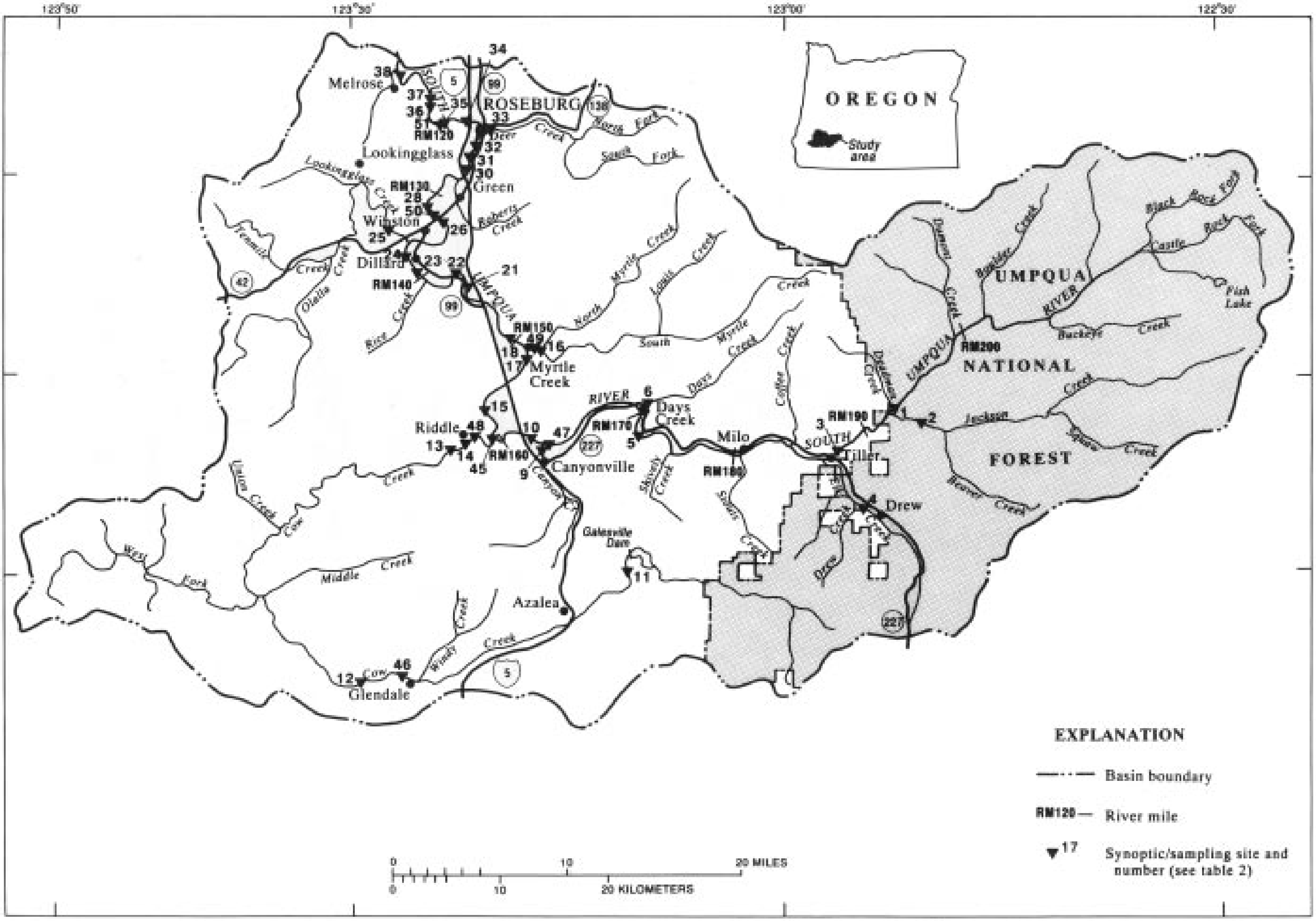

Figure 1. The South Umpqua River Basin, Oregon, and the location of synoptic sampling sites for 1990–92.

Hydrology

The hydrologic characteristics of the South Umpqua River Basin are illustrated by the 1992 hydrographs of the South Umpqua River at Tiller, Cow Creek near Riddle, and the South Umpqua River near Brockway (fig. 2). The streamflow-gaging station on South Umpqua River at Tiller measures flow from the upper part of the basin (upstream from Cow Creek), and the streamflow-gaging station on South Umpqua River near Brockway site measures flow from most of the South Umpqua River Basin drainage. Cow Creek is the largest tributary to the South Umpqua River. Cow Creek's contribution to streamflow in the lower South Umpqua River is especially important during drought years. Streamflow at the South Umpqua River near Brockway station ranged over three orders of magnitude in 1992, from less than 100 ft^3/s in August to more than 10,000 ft^3/s in December (U.S. Geological Survey, 1992, 1993).

The release of water from Galesville Reservoir in the summer of 1992 was important to the lower South Umpqua River (fig. 2). Beginning in early August, discharge in Cow Creek near Riddle remained nearly constant at approximately 50 ft^3/s, whereas discharge in South Umpqua River near Tiller continually decreased to a minimum of 27 ft^3/s. In August and September, the 50 ft^3/s supplied by Cow Creek accounted for over one-half of the flow (approximately 80 ft^3/s) in the South Umpqua River near Brockway. These data indicate that water-quality problems associated with low-flow conditions in the lower South Umpqua River could be even more severe without flow augmentation.

Land Use and Water Use

In the Umpqua River Basin, which includes the North Umpqua River Basin and the South Umpqua River Basin, the dominant category of land use is forest. According to the Oregon Water Resources Department (1978), forest constitutes 88.9 percent of the Umpqua River Basin in Douglas County. The next largest categories of land use are range (5.9 percent), and irrigated and nonirrigated agriculture (1.7 and 1.6 percent, respectively).

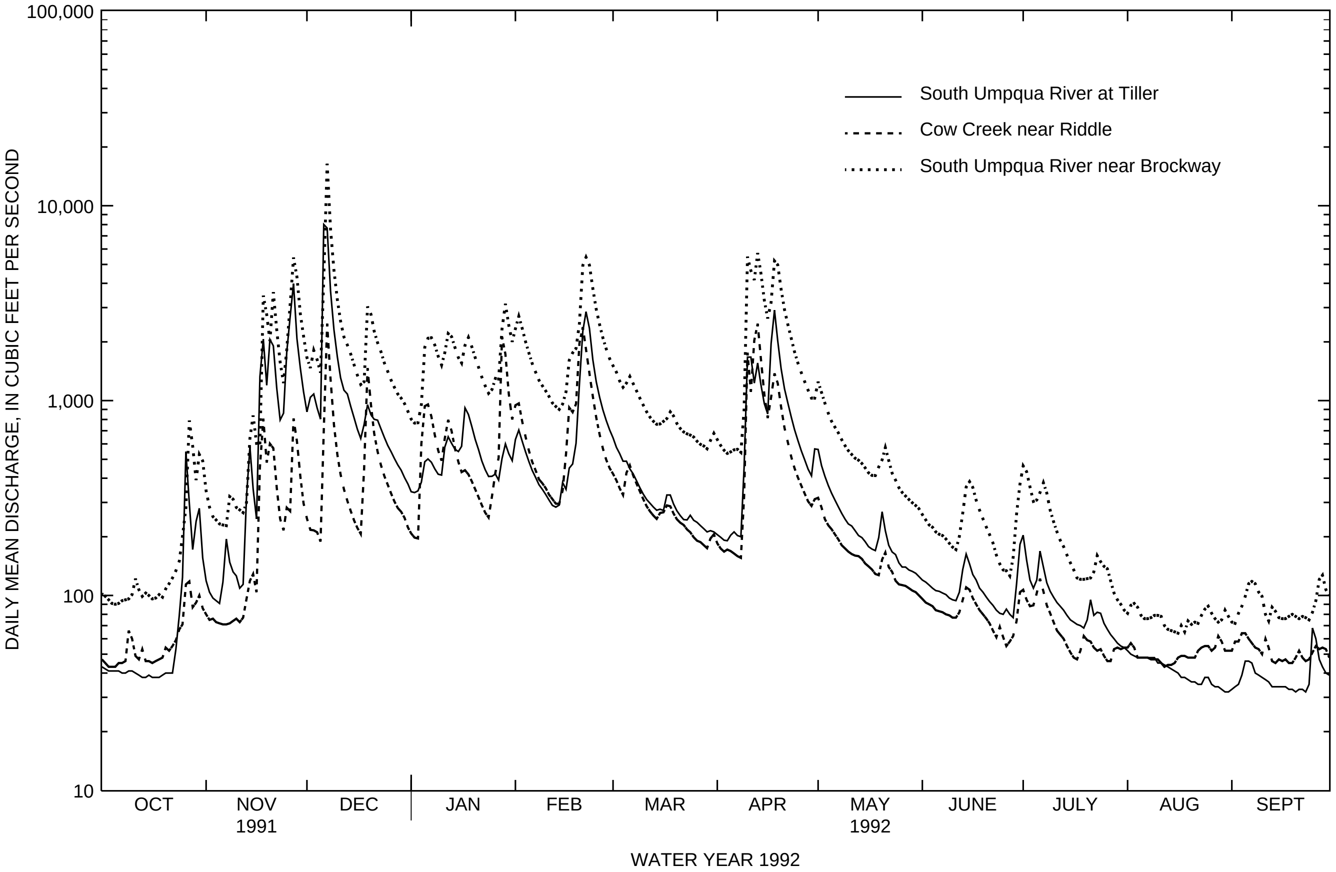

Figure 2. Daily mean discharge at three streamflow-gaging stations in the South Umpqua River Basin, Oregon, 1992.

Except for small areas of irrigated cropland and residential use, forest is virtually the sole category of land use in the South Umpqua River Basin east of Canyonville. West of Canyonville, irrigated agricultural land generally is found adjacent to the South Umpqua River and Cow Creek. According to T.M. Broad, U.S. Geological Survey (unpub. data, 1992), 8,300 acres in the South Umpqua River Basin are irrigated cropland. Much of the rangeland and nonirrigated cropland is located on rolling hills.

As of July 1, 1991, the population of Douglas County (which contains the North Umpqua River and Umpqua River Basins in addition to the South Umpqua River Basin) was 96,100 (Center for Population Research and Census, 1992). The largest towns in the South Umpqua River Basin are adjacent to either the South Umpqua River or Cow Creek. The largest town in the South Umpqua River Basin is Roseburg, with a population of 17,900. Other towns with populations over 1,000 are Winston (3,805), Myrtle Creek (3,100), Canyonville (1,225), and Riddle (1,140).

Water used in the South Umpqua River Basin is primarily surface water. Ground-water use is not prevalent because most of the basin is underlain by relatively impermeable aquifer units (Robison and Collins, 1978; Rinella, 1986). Total offstream withdrawals for 1990 were 21.41 Mgal/d (million gallons per day) (T.M. Broad, U.S. Geological Survey, unpub. data, 1992). Irrigation withdrawals were 13.83 Mgal/d, of which 98 percent was surface water. Domestic use was 6.85 Mgal/d and industrial use was 2.79 Mgal/d. In 1990, an estimated 99 percent of the 48,990 people who used public water supplies in the South Umpqua River Basin used surface water.

Wastewater-Treatment Plants

Eight WWTPs (Tiller Ranger Station, Milo Academy, Glendale, Canyonville, Winston-Green, Roseburg, Riddle, and Myrtle Creek) discharge effluent in the South Umpqua River Basin (table 1). The Tiller Ranger Station and Milo Academy facilities are small and have effluent discharges that constitute less than 0.5 percent of the summer low flow of the South Umpqua River. The Tiller Ranger Station WWTP uses tertiary treatment with alum (aluminum sulfate) for phosphorus removal. For these reasons, the WWTP sampling discussed later in this report did not include the Tiller Ranger Station or Milo Academy facilities. The Glendale WWTP, on Cow Creek, was sampled only once during a reconnaissance sampling trip in 1990, because the Glendale WWTP discharge was outside of the study area. Sampling near the town of Riddle provided adequate information regarding the quality of water discharged from Cow Creek to the South Umpqua River.

Table 1. Wastewater-treatment plants in the South Umpqua River Basin, Oregon

[River miles in Cow Creek and Myrtle Creek are measured from the mouths of the streams; Mgal/d, million gallons per day; RM, river mile; EACS, extended aeration with chemical and physical stabilization; AS, activated sludge with constant stabilization; RBC, rotating biological contactors; TF, trickling filter; ‘--’, missing data; source: Umpqua Regional Council of Governments, 1985]

Wastewater-treatment plant	Estimated service		Design			Receiving stream and river mile
	Population (1991)	Area (acres)	Capacity (population)	Dry weather flow (Mgal/d)	Type and year built	
Tiller Ranger Station	100	--	300	0.03	EACS-1972	South Umpqua (RM 187.2)
Milo Academy	325	--	450	.03	LG-1969	South Umpqua (RM 181.5)
Canyonville	1,225	326	2,700	.50	AS-1978	South Umpqua (RM 163.0)
Glendale	715	240	2,000	.39	AS-1977	Cow Creek (RM 41.0)
Riddle	1,140	387	2,500	.25	AS-1976	Cow Creek (RM 2.0)
Myrtle Creek	3,100	2,212	10,000	.96	AS-1973	Myrtle Creek (RM 0.1)
Winston-Green	8,000	2,302	10,000	1.60	RBC-1981	South Umpqua (RM 132.6)
Roseburg Urban Sanitary Authority	21,500	7,110	30,000	7.90	TF-1986	South Umpqua (RM 119.5)

The remaining five WWTPs (table 1) are the largest and discharge significant volumes of secondarily treated effluent—either directly into the South Umpqua River (Canyonville, Winston-Green, and Roseburg WWTPs) or immediately upstream from the mouths of South Umpqua River tributaries (Riddle and Myrtle Creek WWTPs). During the summers of 1991 and 1992, the Canyonville WWTP usually was operated to maximize nitrogen removal, thereby reducing the effluent concentrations of ammonia and nitrate (Jim Layton, City of Canyonville, oral commun., 1992). Nitrification also was maximized at the Riddle WWTP during the summer months (Eric Quinn, City of Riddle, oral commun., 1992). The Winston-Green WWTP used single-stage alum flocculation as a method for removal of materials that cause biochemical oxygen demand (BOD), (Gary Gent, Douglas County, oral commun., 1992), which also lowered the concentrations of phosphorus in the effluent. No other types of advanced (beyond secondary) treatment were used at any of the five largest WWTPs. Because the WWTPs in the South Umpqua River Basin are progressively larger downstream, in accordance with population patterns, the cumulative effects of their effluent discharges were a primary focus of this study. Most WWTPs do not operate to the full design capacities specified in table 1. For example, the median discharges in the summer of 1992 from the Canyonville, Winston-Green, and Roseburg WWTPs were approximately 0.14, 0.83, and 3.5 Mgal/d, respectively.

APPROACH AND METHODS

The purposes of this study included the assessment of nutrient loading and algal metabolism and of their effects on water quality in the South Umpqua River. Achieving this goal involved several tasks that are described herein and detailed by Anderson and others (1994). Reconnaissance by canoe provided data on stream morphology and algal habitat and aided in the selection of sites used for water-quality sampling. DO, pH, and bacterial populations were measured to assess the spatial and temporal variability of each. Nutrient data were used to indicate point and nonpoint sources in the South Umpqua River Basin and to quantify nutrient loading and mass balance of nutrients. Hourly DO measurements were used to quantify aquatic-community metabolism. The relations between aquatic-community metabolism and nutrients, in turn, were used to evaluate the possible effects of nutrient reduction on DO and pH in the South Umpqua River Basin.

Sample Collection and Analysis

Sites for water-quality sampling, as well as selected tributaries and point sources, are listed in table 2 and shown in figure 3. Latitude and longitude for sampling sites were determined from USGS 7-1/2-minute-series topographic maps (scale 1:24,000). River miles (RM) for sampling sites were taken from the Columbia Basin Inter-Agency Committee (1966) and from Oster (1972).

Water-quality samples were collected for (1) synoptic surveys (fig. 1), (2) fixed-station sampling (fig. 4), and (3) diel inflow/outflow sampling (fig. 5). Synoptic surveys involve sampling many sites within a brief period of time to provide a “snapshot” of basin conditions. Synoptic surveys were done in the South Umpqua River Basin during steady-state flow conditions in order to calculate mass balance of water-quality constituents and to identify problem areas relative to DO and pH. Fixed stations included (1) streamflow-gaging stations, (2) sites with recording multiparameter monitors, (3) sites sampled weekly or biweekly in the summer of 1992, and (4) WWTPs sampled twice weekly for effluent in the summer of 1992. Estimates were made of temporal variability of streamflow and water quality by using data from fixed stations. Diel inflow/outflow sampling was conducted over 24-hour periods to determine day-night fluctuations in water quality, DO, and other parameters. Sites selected for diel inflow/outflow sampling were upstream and downstream from point sources in three 5- to 10-mile-long reaches of the South Umpqua River.

Three types of biological data were collected for this study: (1) periphytic-algae samples for biomass, species identification, and nutrient content, (2) water samples for fecal-streptococcal and fecal-coliform bacteria, and (3) samples for the identification and enumeration of macroinvertebrates.

The methods used for collection and analysis of water samples, biological samples, and streamflow data followed standard USGS techniques. Water samples were collected using the equal-width-increment (EWI) technique to obtain depth- and width-integrated water samples (Edwards and Glysson, 1988).

Table 2. Sampling sites in the South Umpqua River Basin, Oregon, 1990–92

[Map reference number is sampling location (see figures 1, 4, and 5); °, degrees; ’, minutes; ", seconds; RM, river mile, measured from mouth; S, synoptic site; D, diel inflow/outflow site; F, fixed station; G, State of Oregon streamflow-gaging station]

Map reference number	Station number	Station name	Latitude	Longitude	River mile	Site use code
1	14307698	South Umpqua River above Jackson Creek near Tiller	42°58’12"	122°52’42"	192.8	S
2	14307700	Jackson Creek near Tiller	42°57’15"	122°49’40"	192.6	S
3	14308000	South Umpqua River at Tiller	42°55’50"	122°56’50"	187.3	S, G
4	14308500	Elk Creek near Drew	42°53’25"	122°55’00"	187.0	S, G
5	14308600	South Umpqua River at Days Creek	42°58’03"	123°09’59"	170.0	S, F, D, G
6	14308700	Days Creek at Days Creek	42°58’23"	123°10’13"	169.9	S
7	14308730	South Umpqua River below Packard Gulch near Days Creek	42°58’02"	123°13’29"	166.8	D
8	14308740	South Umpqua River above Morgan Creek near Canyonville	42°57’02"	123°14’13"	165.3	D
9	14308905	Canyon Creek at Hamlin Road at Canyonville	42°56’04"	123°16’38"	162.9	S
10	14308910	South Umpqua at Canyonville	42°56’38"	123°17’03"	162.6	S
11	14309000	Cow Creek near Azalea	42°49’30"	123°10’40"	158.9	S
12	14309300	Cow Creek at Reuben	42°44’07"	123°29’30"	158.9	S
13	14310000	Cow Creek near Riddle	42°55’25"	123°25’40"	158.9	S, F, G
14	14310510	Unnamed tributary to Cow Creek at Riddle	42°57’00"	123°21’28"	158.9	S
15	14310550	South Umpqua River at Missouri Bottom Bridge at Tri City	42°58’24"	123°20’46"	156.0	S, D
16	14311100	Myrtle Creek at Myrtle Creek	43°01’24"	123°17’18"	150.7	S
17	14311105	South Umpqua River at Myrtle Creek	43°01’21"	123°17’46"	151.3	S, F, D
18	14311110	South Umpqua River near Myrtle Creek	43°01’50"	123°18’57"	149.7	S, D
19	14311115	South Umpqua River at Ruckles	43°03’32"	123°20’04"	146.6	D
20	14311120	South Umpqua River below I-5 Bridge near Ruckles	43°03’52"	123°21’32"	145.2	D
21	14311140	South Umpqua River above Mary Moore Bridge near Round Prairie	43°04’49"	123°22’00"	143.3	S, D
22	14311160	South Umpqua River at RM 141.5 near Dillard	43°04’51"	123°23’07"	141.5	S
23	14311170	South Umpqua River at Dillard	43°06’10"	123°26’00"	138.7	S
24	14311172	Effluent, Roseburg Forest Products, near Dillard	43°06’13"	123°26’03"	138.6	S

Table 2. Sampling sites in the South Umpqua River Basin, Oregon, 1990–92—Continued

Map reference number	Station number	Station name	Latitude	Longitude	River mile	Site use code
25	14311500	Lookingglass Creek at Brockway	43°07’50"	123°27’50"	137.0	S, G
26	14312000	South Umpqua River near Brockway	43°08’00"	123°23’50"	132.8	S, F, D, G
27	14312002	South Umpqua River below Treatment Plant near Brockway	43°08’18"	123°24’18"	132.3	D
28	14312005	South Umpqua River near Winston	43°08’39"	123°24’57"	131.6	S, D
29	14312010	South Umpqua River at Happy Valley Road near Roseburg	43°09’38"	123°23’40"	130.0	D
30	14312060	South Umpqua River at Shady near Roseburg	43°10’31"	123°21’40"	126.8	S
31	14312070	South Umpqua River at Oaks near Roseburg	43°10’44"	123°22’05"	126.6	S, D
32	14312150	South Umpqua River at Roseburg	43°12’45"	123°20’50"	123.4	S
33	14312210	Deer Creek at mouth at Roseburg	43°12’54"	123°20’31"	123.0	S
34	14312251	South Umpqua River at Stewart Park at Roseburg	43°12’58"	123°22’34"	121.6	S
35	14312258	South Umpqua River above sewage-treatment plant at Roseburg	43°12’45"	123°23’36"	119.6	S
36	14312260	South Umpqua River near Roseburg	43°13’20"	123°24’45"	118.0	S, F
37	14312261	South Umpqua River at Melrose Road	43°14’26"	123°24’46"	116.6	S
38	14312350	South Umpqua River near Melrose	43°15’45"	123°26’25"	112.2	S
39	4256451232025	South Umpqua River near Riddle	42°56’45"	123°20’25"	158.5	G
40	4259191232025	South Umpqua River at RM 154 near Riddle	42°59’19"	123°20’25"	154.9	D
41	4259351231936	South Umpqua River at RM 154 near Tri City	42°59’35"	123°19’36"	154.0	D
42	4304111232212	South Umpqua River near Boomer Hill Road	43°04’11"	123°22’12"	147.8	D
43	4303531232041	South Umpqua River at RM 146 above I-5 Bridge near Ruckles	43°03’53"	123°20’41"	146.0	D
44	4309061232434	South Umpqua River above Happy Valley Road near Winston	43°09’06"	123°24’34"	130.9	D
45	425640123201400	Cow Creek at mouth near Riddle	42°56’40"	123°20’14"	158.9	S
46	424436123254401	Wastewater Treatment Plant, Glendale	42°44’36"	123°25’44"	158.9	S
47	425602123165701	Wastewater Treatment Plant, Canyonville	42°56’02"	123°16’57"	163.0	S, F
48	425705123212001	Wastewater Treatment Plant, Riddle	42°57’05"	123°21’20"	158.9	S, F
49	430117123174701	Wastewater Treatment Plant, Myrtle Creek	43°01’17"	123°17’47"	150.7	S, F, D
50	430812123240101	Wastewater Treatment Plant, Winston-Green	43°08’12"	123°24’01"	132.6	S, F, D
51	431233123234301	Wastewater Treatment Plant, Roseburg	43°12’33"	123°23’43"	119.5	S, F

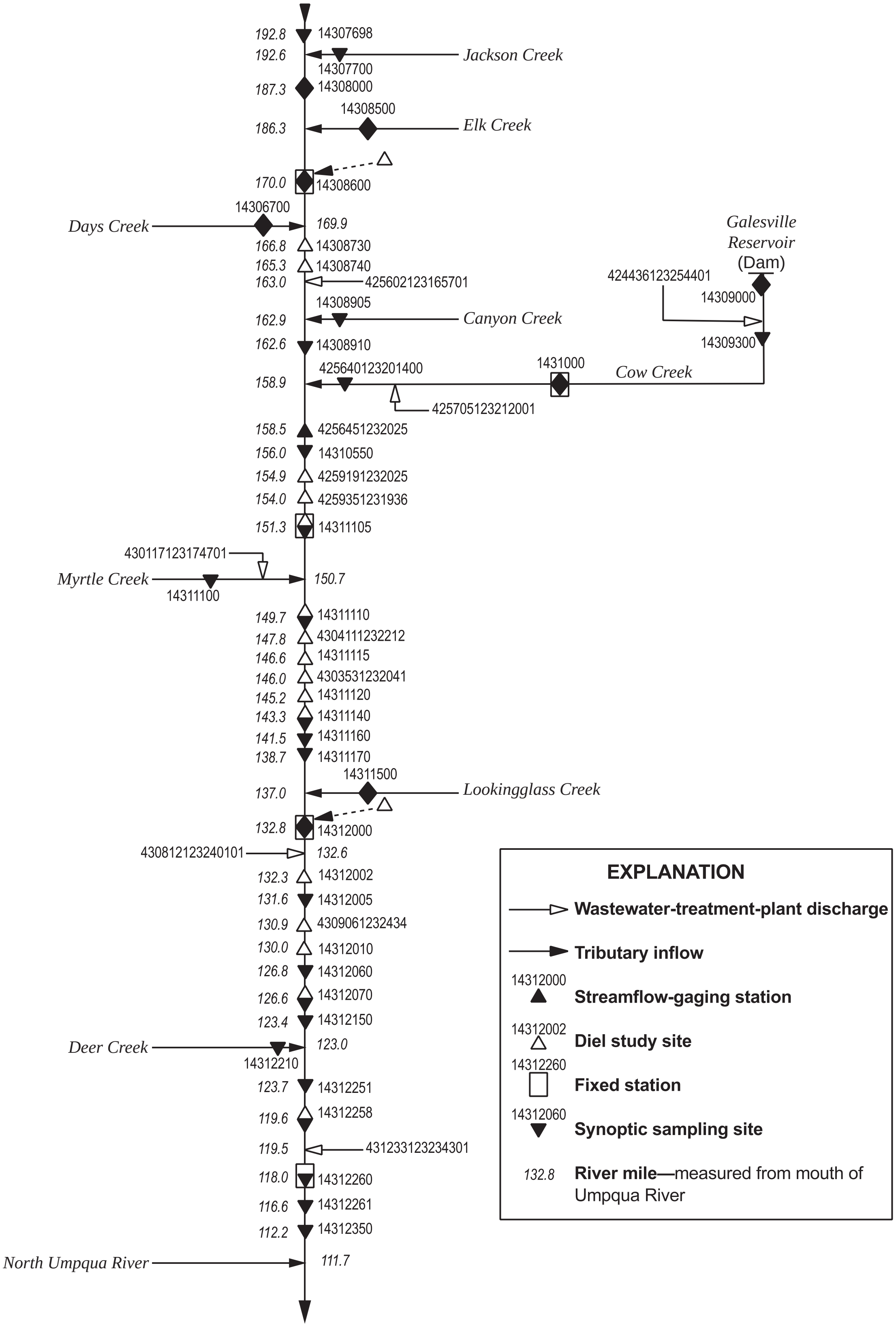

Figure 3. Relative positions of selected tributaries, sampling sites, and selected point sources in the South Umpqua River Basin, Oregon, 1990–92. (See table 2 for site description.)

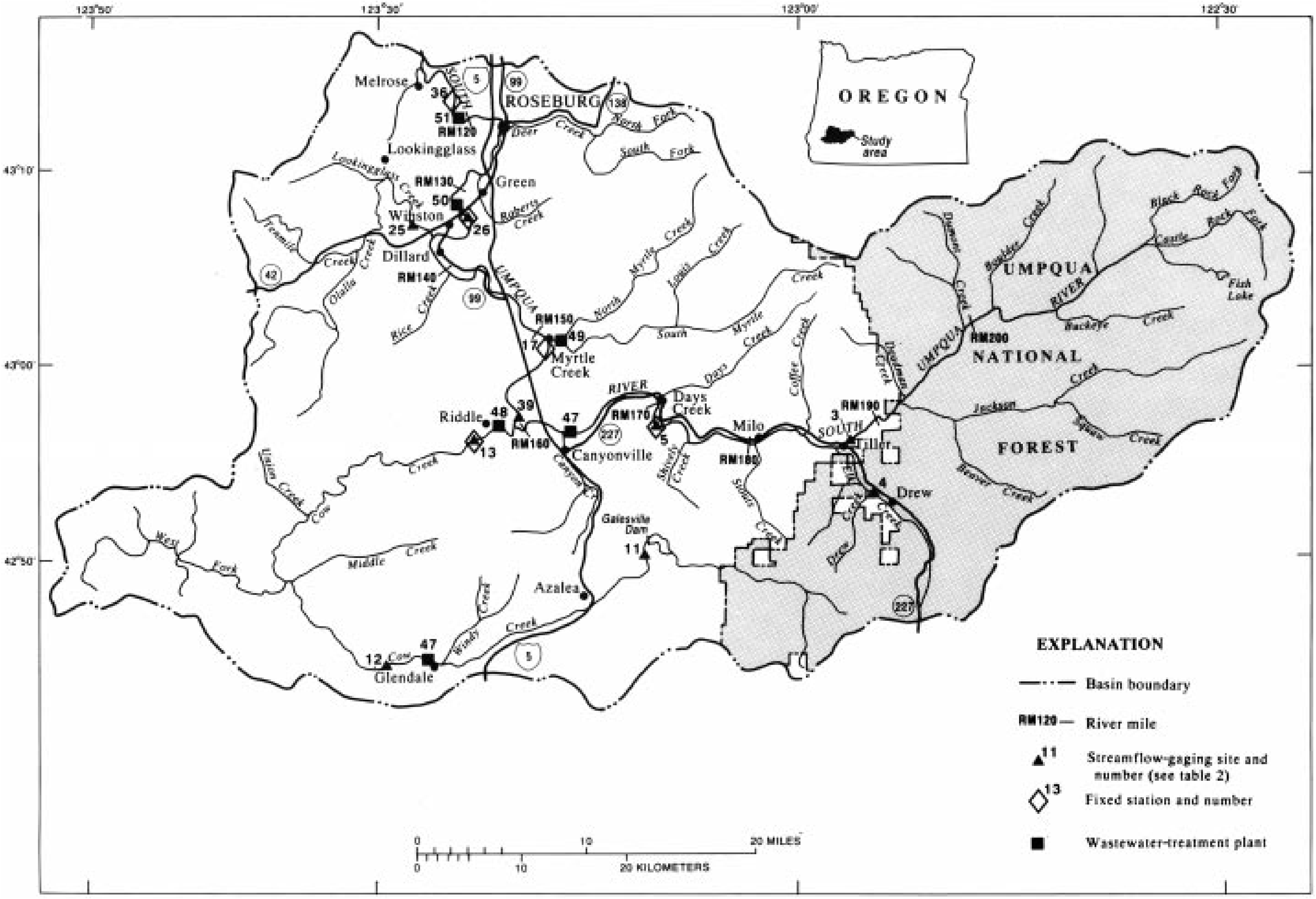

Figure 4. Fixed stations, wastewater-treatment plants, and streamflow-gaging stations, South Umpqua River Basin, Oregon, 1990–92.

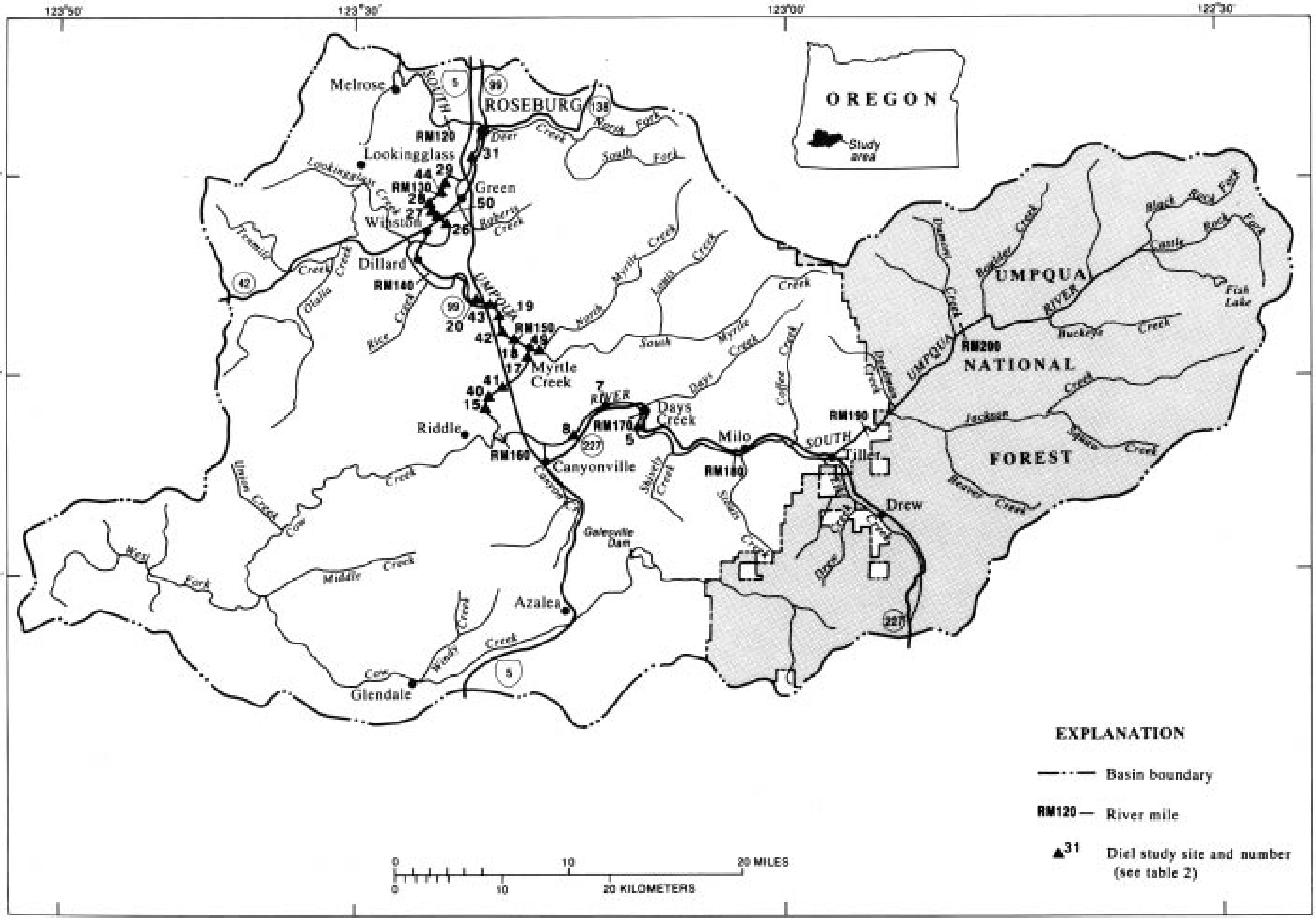

Figure 5. Diel sampling sites, South Umpqua River Basin, Oregon, 1990–92.

Water-quality samples were analyzed at the USGS National Water Quality Laboratory in Arvada, Colorado, according to techniques described by Fishman and Friedman (1989). Biological samples were collected and analyzed according to Britton and Greeson (1987). Streamflow was measured according to the guidelines in Buchanan and Somers (1984). The methods of Kennedy (1983) were used to develop datum shifts for continuously collected streamflow and water-quality data at fixed stations.

Because Oregon DO standards are for percent saturation (State of Oregon, 1992), DO concentrations are expressed in percent saturation in this report. To compute DO in percent saturation, water temperature, DO (in milligrams per liter), and barometric pressure were measured whenever possible. During diel surveys and at the monitors near Roseburg and Days Creek, water temperature, specific conductance, pH, and DO were recorded continuously. Barometric pressure was not measured continuously.

An equation based on elevation and water temperature was used for computing the 100-percent saturation value for oxygen in water when barometric pressure was not measured (Duke and Masch, 1973, p. 91):

$$C_s = [(14.62 - 0.3898*T) + (0.006969*T^2) - (5.897*10^{-5}*T^3)]*[1 - (6.97*10^{-6}*E)]^{5.167} \quad (1)$$

where

C_s = the concentration of DO at 100-percent saturation, in milligrams per liter;
T = the water temperature, in degrees Celsius; and
E = the elevation, in feet above sea level.

Percent saturation of DO for field measurement was then computed as the ratio of the measured value and C_s, multiplied by 100. Percent saturation values calculated in this way were verified with percent DO saturation values determined from barometric pressure over a range of barometric pressures, elevations, water temperatures, and DO values (n = 476). The difference in percent saturation as determined by the two methods ranged from -2.14 to 2.16 percent, with a mean difference of 0.64 and a standard deviation of 0.64 percent. Using elevation data to determine percent saturation of DO, therefore, was considered an acceptable alternative.

Water-quality data were measured only in the actively flowing parts of the channel and, therefore, were not representative of the water quality in all microhabitats of the South Umpqua River. DO, pH, water temperature, and specific conductance were measured at equidistant points across the actively flowing stream cross section using a portable instrument, and the values were averaged. In many cases, mats of aquatic plants along the edges of the river slowed the flow. Within a mat, afternoon values for DO, pH, and water temperature frequently were elevated relative to other parts of the cross section. For example, the following measurements were made in a mat of aquatic plants at RM 151.3 on September 18, 1991, at 1320 hour: DO, 9.2 mg/L (milligrams per liter); pH, 8.5; and temperature, 22.9°C (degrees Celsius). The average values of nine measurements in the actively flowing part of the same station at RM 151.3 were DO, 8.1 mg/L; pH, 8.1; and temperature, 21.3°C. Small diffusion gradients near the photosynthesizing plants probably were responsible for high values of DO and pH; decreased velocity combined with the heat storage capacity of the plant mass probably caused the higher temperatures of the water. Conversely, early morning values for DO and pH in the mats were, at times, lower than in the main channel. Therefore, ranges of DO, pH, and water temperature in individual microhabitats may be more extreme than those of the average values reported.

Quality Assurance

Quality-assurance data were published in tables 33 and 34 of Anderson and others (1994). Split (replicate) samples were used to assess laboratory precision. Field blanks and laboratory blanks were used to assess potential contamination in the field and laboratory, respectively. Reference samples provided an indication of the accuracy of laboratory determinations.

Split samples are subsamples taken from the same composited water sample as the environmental subsample. Differences between environmental and split samples, therefore, reflect the combined precision of sample processing in the field and analysis in the laboratory. Forty-eight split samples (23 from streams or rivers and 25 from WWTPs) containing a wide range of nutrient concentrations were submitted for most analytes. To evaluate the precision of data from split samples, a relative standard difference (rsd) was calculated. Because the environmental sample value and the split sample value have no inherent distinctions, the absolute value of the difference was compared to the mean of the values:

$$rsd = |(environmental\ value) - (split\ value)| / \{[(environmental\ value) + (split\ value)]/2\} \times 100. \quad (2)$$

In figure 6, the rsd's are plotted against the means of the environmental and the split values for total phosphorus (TP), soluble reactive phosphorus (SRP), dissolved nitrite plus nitrate ($NO_2^- + NO_3^-$), dissolved nitrite (NO_2^-), dissolved ammonia ($NH_4^+ + NH_3$), and total ammonia plus organic nitrogen (total Kjeldahl nitrogen [TKN]). Analytical precision generally was less at concentrations near the lower level of detection. The graphs for TP, SRP, and $NO_2^- + NO_3^-$, indicate that trend. For those three analytes, rsd values more than 100 percent were near the lower limit of detection.

For NO_2^-, ammonia, and TKN, there was one rsd for each that was greater than 100 percent for a concentration that was not near the lower limit of detection (fig. 6). Each of these samples was from Roseburg WWTP effluent, which frequently had large concentrations of several analytes. The three anomalous data values were not used in subsequent calculations of nutrient loadings. Each anomalous point represents only about 2 percent of the total number of split samples.

For most analytes, precision was generally within the 1 mg/L range. A frequency distribution of the absolute difference between the concentration in the environmental sample and the concentration in the split sample was analyzed. The 95th percentile of these differences for each analyte, in milligrams per liter, was as follows: TP, 0.4; SRP, 0.4; $NO_2^- + NO_3^-$, 1.0; NO_2^-, 0.1; ammonia, 0.4; and TKN, 3.8.

Data from the analysis of field blanks and laboratory blanks were used to assess potential sample contamination. Distilled-deionized water was used for both types of blanks. Water for the field blanks was subsampled, filtered, and preserved in the field in the same manner as a water-quality sample.

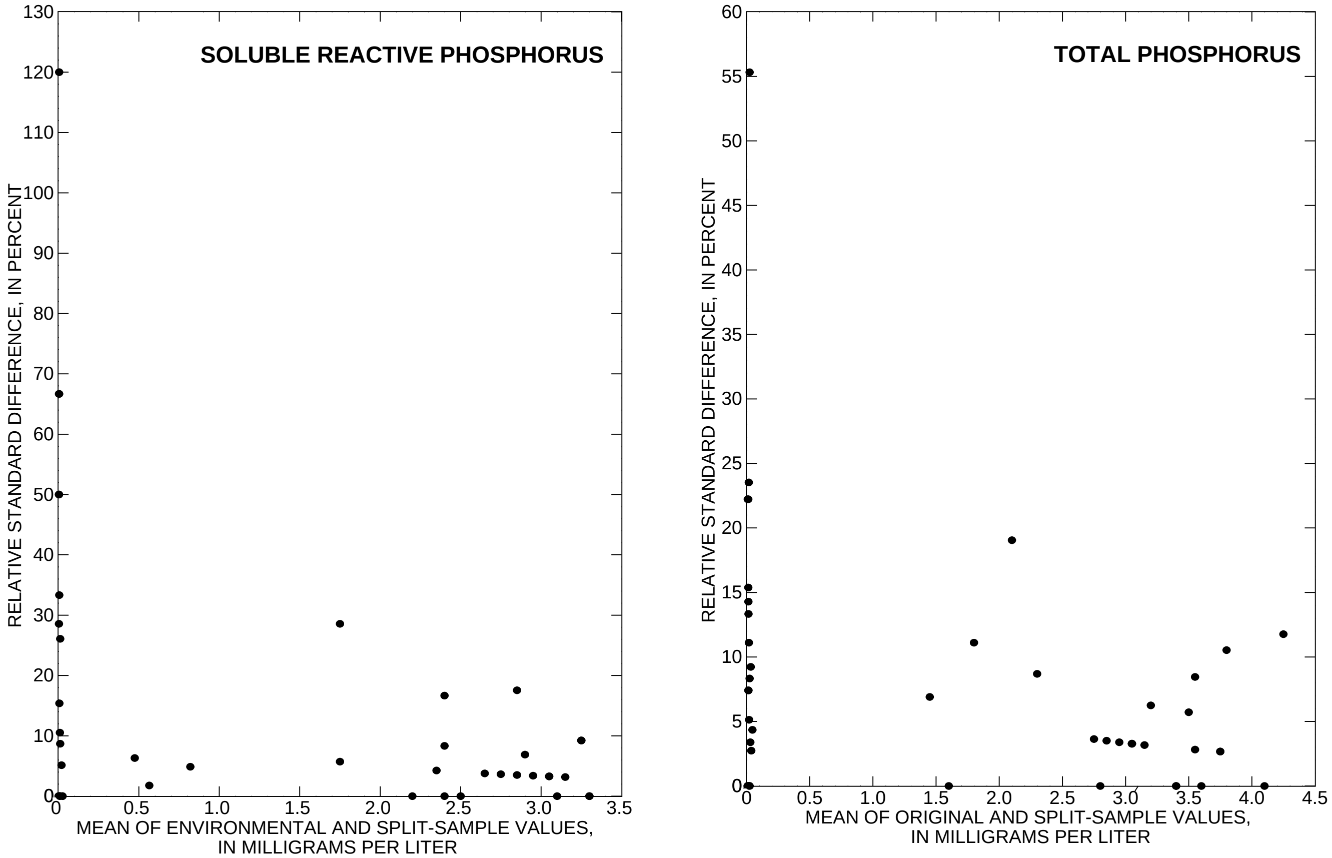

Figure 6. Nutrient quality-assurance data. (Sample size equals 48.)

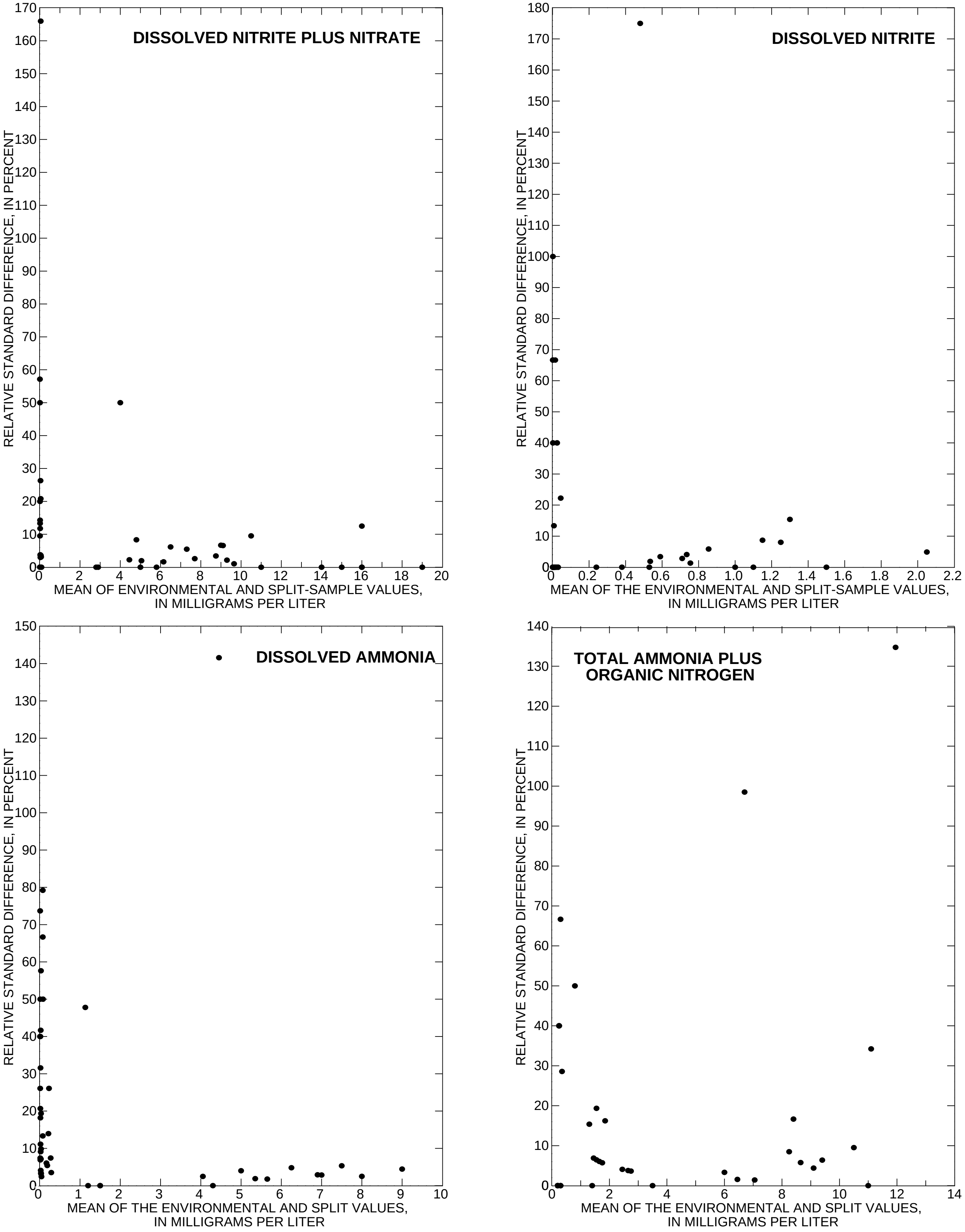

Figure 6. Nutrient quality-assurance data—Continued.

Water for laboratory blanks was transferred to sample bottles in the U.S. Geological Survey Oregon District laboratory and preserved. Any detection of an analyte in these samples would indicate contamination from either the field techniques, the National Water Quality Laboratory, or the distilled-deionized water source. Eight field and five laboratory blanks were run for most analytes. One analyte, ammonia, was detected in more than one-half of the field and laboratory blanks; blanks for the other analytes had no significant contamination. All 8 field blanks and 3 of the 5 laboratory blanks had detectable ammonia. The minimum reporting limit for ammonia is 0.002 mg/L as nitrogen (N). The highest concentration of ammonia detected in a field blank was 0.015 mg/L, and the highest concentration of ammonia in a laboratory blank was 0.014 mg/L. The consistent detection of ammonia in field and laboratory blanks possibly was due to impurities in the distilled-deionized water or to contamination at the National Water Quality Laboratory.

A total of 14 reference samples were prepared and submitted to the National Water Quality Laboratory in 1991 and 1992. The reference samples contained known concentrations of nutrients that were within the range of values reported by the National Water Quality Laboratory for water samples from the South Umpqua River Basin, including WWTP-effluent samples. For the reference samples, the rsd was calculated as:

$$rsd = [(measured\ value) - (expected\ value)] / expected\ value \times 100 \qquad (3)$$

The median rsd for each analyte was as follows: $NO_2^- + NO_3^-$, -3.09 percent; ammonia, 1.72 percent; TKN, 0 percent; TP, -2.13 percent; dissolved phosphorus, 2.04 percent; and SRP, -4.60 percent. The rsd's for two analytes in one reference sample were larger than 100 percent or smaller than -100 percent. These were ammonia (rsd = 942 percent) and TKN (rsd = 250 percent). Because these two results were from the same reference sample, it is possible that a sample mix up or dilution error occurred for that sample.

In summary, quality-assurance data indicated that water-quality data collected for this study was of acceptable quality for the range of analyte concentrations found in the South Umpqua River Basin. Exceptions were single anomalies in split samples for NO_2^-, ammonia, and TKN. Most field and laboratory blanks had small but detectable concentrations of ammonia that may have resulted from using contaminated distilled-deionized water. Single anomalies were detected for standard reference samples for ammonia and for TKN.

OVERVIEW OF ECOLOGICAL CONDITIONS

As the South Umpqua River descends from its headwaters in the Umpqua National Forest, it changes from a narrow stream in a steep canyon to a broad river running through agricultural and urban areas. During low-flow periods, releases of water from Galesville Reservoir on Cow Creek may supply 50 percent or more of the flow in the lower South Umpqua River (fig. 2). The hydrological and ecological dynamics of the river change with the topography and land use. The river ecosystem also changes seasonally and with river discharge, especially during summer low flows.

There is a downstream continuum of increasing algal growth and eutrophication during summer as the South Umpqua River flows from the Umpqua National Forest towards the mouth near Roseburg. The headwaters generally are clear, attached algal growth in most places is limited, concentrations of nutrients are low (SRP frequently less than 0.01 mg/L), and water temperatures are cool. In contrast, nearer to the mouth of the South Umpqua River there are large and pervasive mats of periphyton, large amounts of sloughed and decaying algae drifting downstream, and warm water temperatures. Urban areas are progressively larger in a downstream direction and, correspondingly, water-quality conditions in the river become increasingly eutrophic. In the South Umpqua River, there are few natural controls on algal growth. Grazing by native and introduced fish on periphyton is not significant (D.W. Loomis, Oregon Department of Fish and Wildlife, oral commun., 1994).

The patterns of violations of Oregon water-quality standards for DO and pH in the South Umpqua River essentially mirror each other; with few exceptions, the locations where DO concentrations were below the 90-percent saturation standard were the same locations where the pH values exceeded the standard of 8.5 (fig. 7). Furthermore, a large deviation from the DO standard usually was associated with a large deviation from the pH standard.

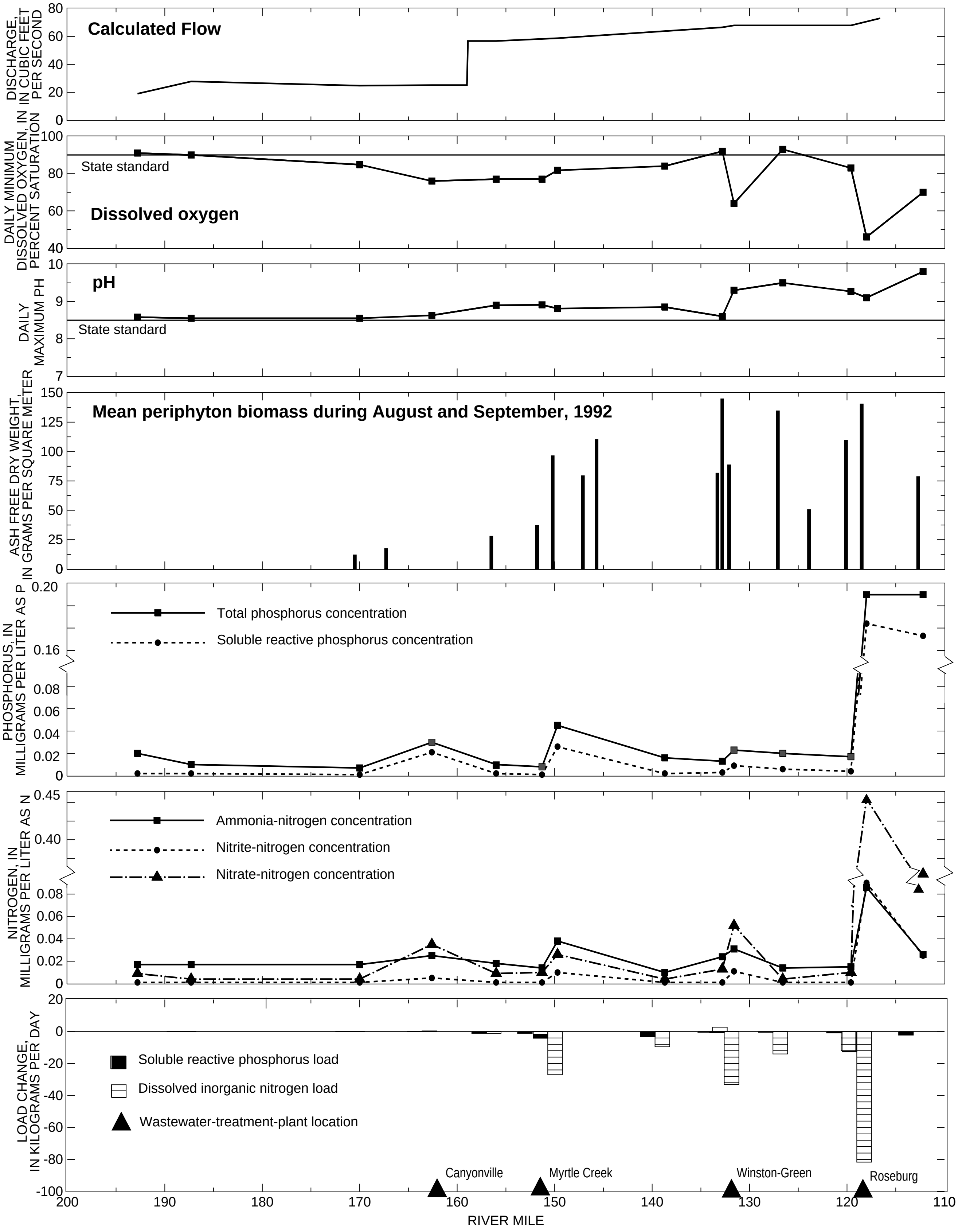

Figure 7. Calculated discharge, dissolved oxygen concentration (DO), pH, biomass, nutrient concentration, and changes in nutrient load in the South Umpqua River, Oregon, August 31–September 2, 1992. (Load change is measured from the site upstream of a given location; negative values indicate a sink; positive values indicate a source. Dissolved inorganic nitrogen is calculated as the sum of the concentrations of dissolved nitrate + nitrite and dissolved ammonia.)

Exceedances of the DO and pH standards occur and large mats of periphytic algae extend almost throughout the entire 80-mile length of the South Umpqua River, from the Umpqua National Forest upstream from Jackson Creek at RM 192.8 to the confluence with the North Umpqua River near Roseburg at RM 111.7. These conditions were unexpected, because the absence of known point sources of nutrients led to the initial expectation that algal growth upstream from Tiller would be minimal or nonexistent and that there would be no exceedances of the DO and pH standards at these sites. The broad distribution of algae and the impairment of water quality prevented the establishment of a reference site which was needed to define natural background conditions in the river.

Sites with significant growths of periphytic algae generally had exceedances of DO or pH standards at some time during the day (fig. 7). In some reaches of the river, the primary controls on DO and pH are physical factors such as temperature and stream reaeration, with a secondary effect from periphytic algae; in other reaches, the diel and seasonal patterns of DO and pH cycling probably are controlled almost entirely by the metabolism of the local benthic community (including periphyton). Other influences on the DO regime of the river, such as BOD and nitrification, have minimal control in most locations.

There are seasonal effects on the timing of DO and pH problems. Although figure 7 shows elevated pH and depressed DO throughout most of the length of the river, the values for these constituents typically are less extreme earlier in the summer, minimizing the occurrence and magnitude of exceedances. Seasonal effects include flow, water temperature, light availability, onset and the length of the algal growing season, nutrient-source variability, and algal-growth dynamics.

The water in the South Umpqua River is clear, allowing effective light penetration. Measurements of photosynthetically available radiation (PAR) (wavelength = 400 to 700 nanometers) were made in the river at a depth of about 2 feet at RM 132.3 and in the air at the Winston-Green WWTP at RM 132.6. These data were nearly identical; a regression of values taken over a 24-hour period had a correlation coefficient of 0.99 and a slope of 1.01. PAR values were published in Anderson and others (1994, tables 26 and 27).

The data on light available for photosynthesis, along with the large width of the South Umpqua River and lack of canopy cover, indicate that light availability probably does not significantly limit periphyton growth in the summer. Limitation of periphyton growth by light may occur sporadically where the canopy cover is extensive, as in the headwaters, or when periphyton mats are self-shading.

Periphyton act as an effective sink for nutrients entering the South Umpqua River. Nutrient input causes a distinct increase of algal activity immediately downstream and results in the transfer of nutrients from the water column to storage in algal tissue. Consequently, in the first few miles below a nutrient source, concentrations and loads of nutrients in the water column decrease markedly. Assuming that algal growth is nutrient limited, biomass and net productivity of the benthic community are expected to decline in conjunction with decreasing nutrient loads. Where nutrient loads do not limit algal growth, the nutrient profile may decrease over the length of the reach until nutrient uptake reduces loads to limiting levels, even though plant biomass and productivity remain relatively steady. Successive nutrient uptake by downstream periphyton mats further decreases nutrient loads, gradually limiting overall biomass, net productivity, and magnitude of exceedances of the DO and pH standards. This pattern is repeated for each occurrence of a new nutrient source (fig. 7).

The first significant point source for nutrients downstream from Elk Creek is the Canyonville WWTP at RM 163.0 (fig. 7); algal conditions immediately downstream (at RM 162.6) were not considered to be at nuisance levels. Exceedances of Oregon State standards for DO and pH have been recorded at RM 162.6 on numerous occasions, however, indicating that even small amounts of algae may adversely affect DO and pH. Nuisance algal conditions were first observed downstream from the mouth of Cow Creek (RM 158.9) and increased in severity below Myrtle Creek and the Myrtle Creek WWTP (RM 151.3). The final 2 miles of Cow Creek, downstream from the Riddle WWTP, also were affected.

Large mats of filamentous periphyton were prevalent downstream from Myrtle Creek (RM 150.7). The reach from Myrtle Creek to the Dillard area (RM 138.0) also had been affected; by late summer of 1992, periphyton coverage of the riverbed near Brockway (RM 132.8) was almost 100 percent. This longitudinal extension of the affected reach may have been due to decreased algal uptake or growth rates or to regeneration, all of which would allow the downstream transport of larger nutrient loads and thereby increase the potential for growth as far downstream as the Brockway site. Excess growth at the Brockway site is noteworthy because the bed material is composed almost entirely of gravel and fine-grained substrates that normally are considered unsuitable for periphyton growth owing to the instability of the stream bed. The occurrence of large algal mats at the Brockway site probably resulted from slow and stable water velocity and abundant light and nutrients.

Between the Winston-Green WWTP (RM 132.6) and the mouth (RM 111.7), the South Umpqua River bed was almost completely covered with algae. In places, photosynthetically produced oxygen bubbles support floating algal mats that are from 75 to 100 feet wide (Anderson and others, 1994, tables 3, 4, and 5). Daytime water temperature, DO, and pH are higher in these mats than in the center of the river. Nutrient levels decrease between the Winston-Green WWTP and the Roseburg WWTP (RM 119.5) but still support a large amount of periphyton. The Roseburg WWTP discharge further elevates nutrient concentrations to the highest levels measured in the river. Subsequent nutrient uptake, resulting from the proliferation of algal mats downstream from Roseburg, reduces nutrient concentrations. Nutrient concentrations continue decreasing to RM 111.7—where the nutrient-poor waters of the North Umpqua River join the South Umpqua River and form the Umpqua River (fig. 7).

WATER-QUALITY CONDITIONS OF CONCERN

Along much of the South Umpqua River, daily metabolic cycles of the periphyton-dominated benthic community produced summertime pH values and DO concentrations that did not meet water-quality standards of the State of Oregon (State of Oregon, 1992) and the EPA (U.S. Environmental Protection Agency, 1986). Because of algal growth during the low-flow months (June through October), DO concentrations frequently were less than the State standard of 90 percent of saturation and the pH was frequently greater than the State standard of 8.5 pH units (see, for example, fig. 8).

Bacteria also are a concern for water managers of the South Umpqua River Basin. Disease-producing bacteria can be associated with fecal contamination from warm-blooded animals, including humans. Fecal-coliform bacteria and fecal-streptococcal bacteria are biological indicators of the disease-producing potential of water that is used for drinking or recreation. The presence of indicator bacteria usually is interpreted as a potential health hazard.

Ammonia, often present in WWTP effluent, is a soluble, biologically active compound commonly present in natural waters as a biological degradation product of nitrogenous organic matter. Ammonia can be toxic to aquatic life, and ammonia toxicity generally increases as pH and temperature increase.

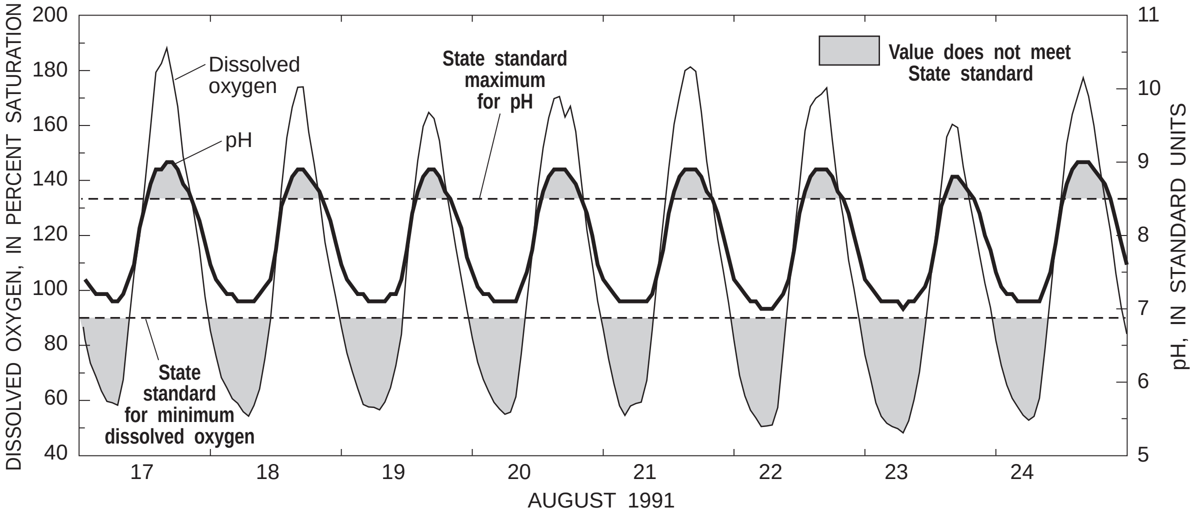

Figure 8. Daily changes in dissolved oxygen concentration and pH from August 17 through August 24, 1991, South Umpqua River near Roseburg, Oregon. (Because continuous barometric pressure data were not available, percent saturation of dissolved oxygen was calculated based upon elevation.)

In the South Umpqua River Basin, ammonia toxicity is primarily of concern downstream from the WWTPs, because effluent from these WWTPs contains elevated concentrations of ammonia and because algal productivity can elevate pH.

During the summer, the high temperatures of the South Umpqua River may adversely affect some aquatic life. Water temperatures as high as 30°C were measured during June, July, and August of 1992 in the South Umpqua River. The spatial distribution of these elevated temperatures was widespread, extending from RM 170.0 to RM 116.6.

Dissolved Oxygen

DO is vital to most aquatic life, including fish and aquatic microorganisms responsible for aerobic degradation of organic matter. The equilibrium concentration of DO in a stream is equivalent to 100-percent saturation and is a function of water temperature and barometric pressure. The EPA DO criterion for the early stages of cold-water aquatic life permits a 1-day DO minimum of 8.0 mg/L (U.S. Environmental Protection Agency, 1986). Oregon State standards for the protection of freshwater aquatic life in the Umpqua River Basin specify that “*** dissolved oxygen concentrations shall not be less than 90 percent of saturation at the seasonal low [State of Oregon, 1992].”

Sources of DO in a stream include photosynthesis and physical reaeration by atmospheric oxygen. DO can be depleted by plant and animal respiration, aerobic degradation of organic matter by bacteria, and nitrification. Nitrification is the oxidation of ammonia to nitrite and, ultimately, to nitrate. In the South Umpqua River Basin, the extreme daily fluctuations of DO indicate that photosynthesis is an important process. DO concentrations can change as much as 10 mg/L over the course of several hours at South Umpqua River near Roseburg (RM 118.0) (fig. 8).

Photosynthesis and respiration by aquatic plants can play important roles in controlling DO in surface waters (Wetzel, 1983; Welch, 1992). Photosynthesis (eq. 4) produces maximum DO values in the late afternoon. Overnight respiration by aquatic plants, bacteria, and animals consumes oxygen, causing early morning minima of DO. Carbon dioxide (CO_2), which is involved in the carbonate equilibrium (eq. 5), affects the pH.

$$6\,CO_2 + 6\,H_2O \underset{respiration}{\overset{photosynthesis}{\rightleftharpoons}} C_6H_{12}O_6 + 6\,O_2 \tag{4}$$

$$CO_2 + H_2O \longleftrightarrow HCO_3^- + H^+ \longleftrightarrow CO_3^{2-} + 2H^+ \tag{5}$$

Daily minima for DO were measured between 0500 and 0900 hours. (Ninety-seven percent of the diel measurements made in 1991–92 indicated that DO minima occurred between 0500 and 0900 hours.) In addition to daily fluctuations, DO also varied seasonally and spatially. Minima and maxima of percent saturation of DO from synoptic surveys in 1990–92 are shown in figure 9.

The longitudinal profiles in figure 9 indicate that DO concentrations for much of the South Umpqua River did not meet the Oregon State standard of 90-percent saturation during the summer. The magnitude of the violation was dependent on time of year, flow, and location. In early summer, algal growth was insufficient to cause significant violations of DO standards. During synoptic surveys in early summer (June 1991 and May 1992), when flows were relatively high, DO saturations of less than 90 percent were observed only above Myrtle Creek (RM 151.3) and below the Roseburg WWTP (RM 119.5). Below Roseburg, DO concentrations were as low as 72 percent of saturation, even in early summer.

As stream discharge decreased during the summer, the affected area increased until, by August and September of 1990, 1991, and 1992, DO in most of the river downstream from Cow Creek (RM 158.9) was less than the 90-percent saturation standard (fig. 9). Because of drought in 1992, DO violations occurred even at the Days Creek reach in June, August, and September. The minimum saturation recorded during a synoptic survey was 46 percent at the South Umpqua River near Melrose Bridge site (RM 116.6). Data from the continuous monitor at South Umpqua River near Roseburg (RM 118.0), however, indicate that DO downstream from the Roseburg WWTP dropped to as low as 8.5 percent saturation on July 31, 1992, and declined to levels of less than 40 percent on a daily basis from July 27 to August 19, 1992 (fig. 10).

Although DO was not less than 90 percent of saturation in most of the upper South Umpqua River Basin (upstream from RM 151.3) in the early summer, many of the early morning observations were close to 90 percent, even at Tiller (RM 187.3) and in the Umpqua National Forest (RM 192.8) (fig. 9).

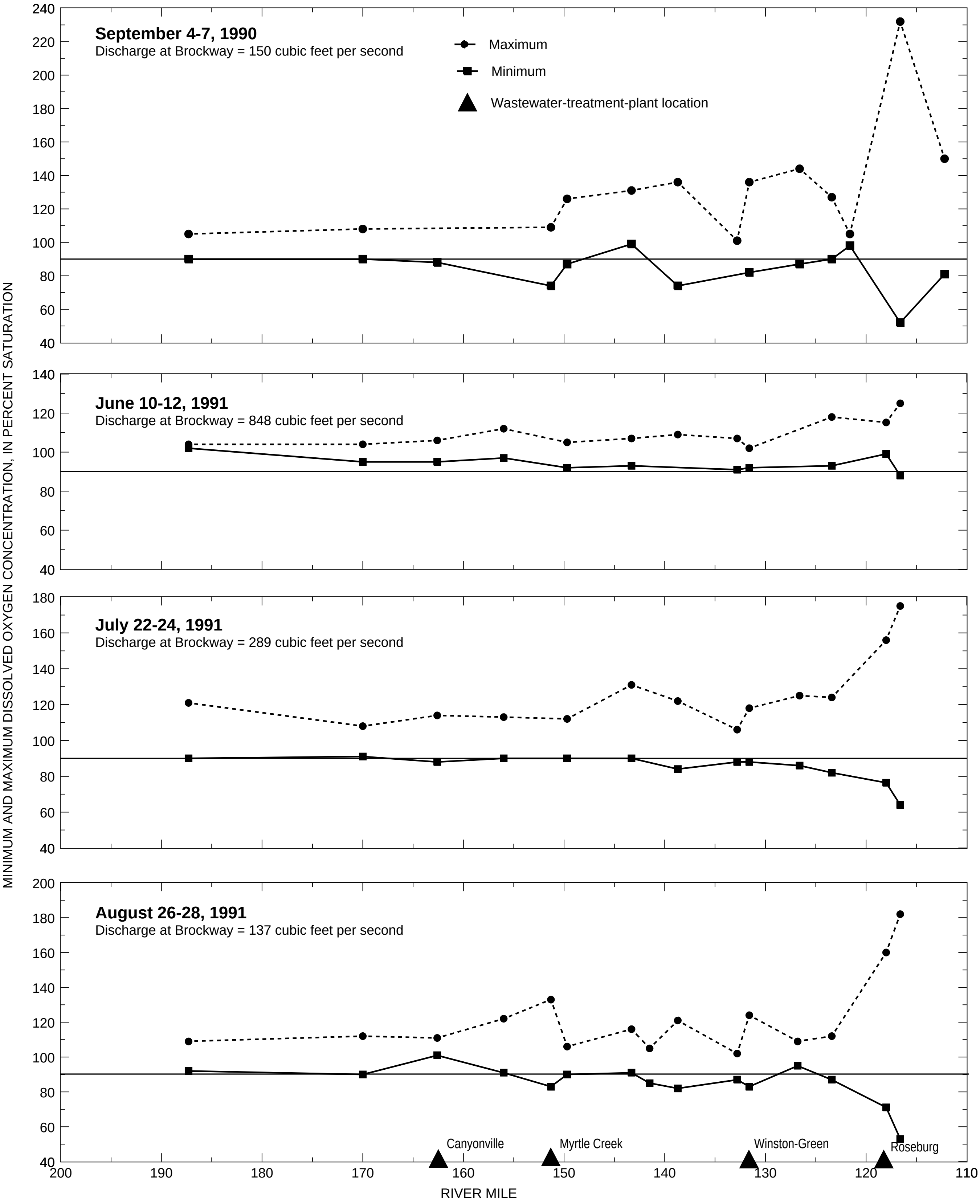

Figure 9. Daily minimum and maximum dissolved oxygen concentrations for synoptic surveys in the South Umpqua River, Oregon, during 1990–92. (The Brockway gaging station is located at river mile 132.8.)

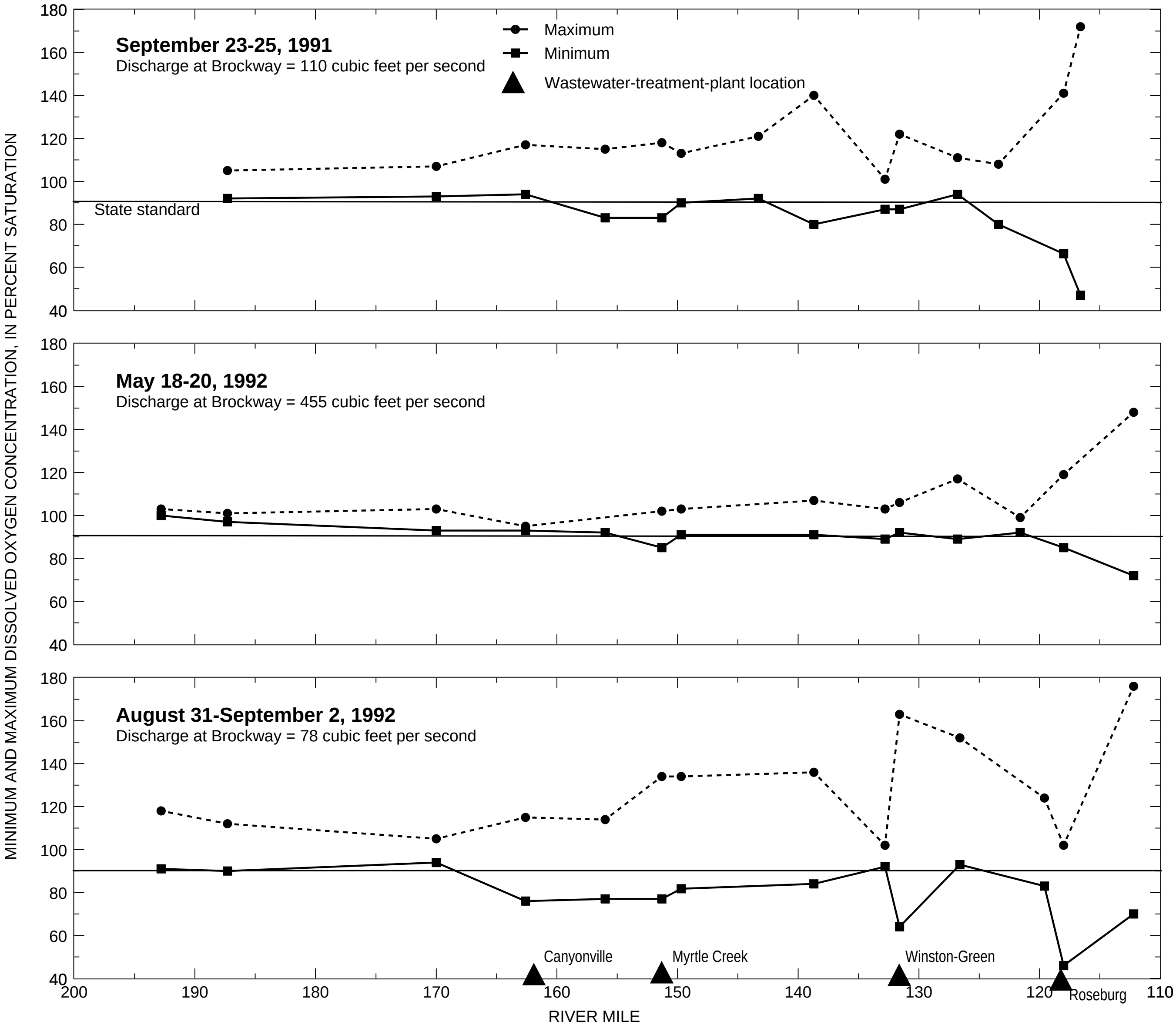

Figure 9. Daily minimum and maximum dissolved oxygen concentrations for synoptic surveys in the South Umpqua River, Oregon, during 1990–92—Continued.

It is probable that DO violations occurred in these upstream reaches in early summer, even though the violations were not observed. During synoptic surveys, the median value of DO saturation minima observed was 80.5 percent; 95 percent of the observations were less than 92-percent saturation. Therefore, the Oregon State standard of 90-percent saturation probably was not met consistently, except in a few locations.

One exception was at the South Umpqua River near Myrtle Creek site (RM 149.7), where minimum DO was usually greater than 90-percent saturation. This site, located downstream from Myrtle Creek and the effluent of the Myrtle Creek WWTP, lies within a reach of the South Umpqua River significantly affected by nuisance algae. Extensive areas of the riverbed are frequently covered by thick, bubbly mats of periphytic algae, even in the early summer; however, DO lower than 90-percent saturation was observed only during the diel surveys in August and September 1992.

The higher concentrations of DO near Myrtle Creek may have been caused by the steep gradient of the reach (18.5 feet per mile of river), compared with the gradient of the reach immediately upstream (4.9 feet per mile from South Umpqua River near Missouri Bottom to South Umpqua River at Myrtle Creek) and the gradient of the reach downstream (9.9 feet per mile from South Umpqua River near Myrtle Creek to South Umpqua River at Ruckles) (Oster, 1972).

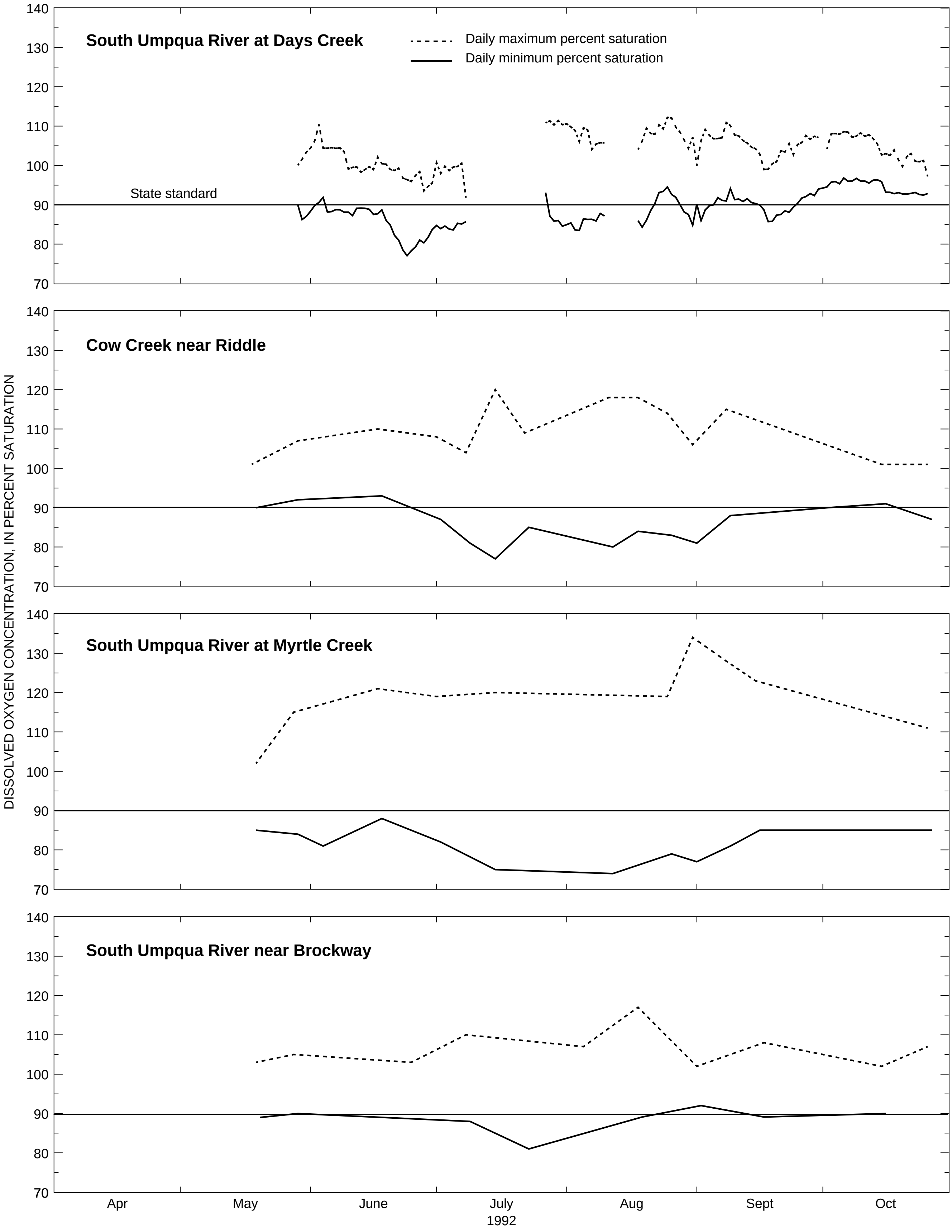

Figure 10. Daily minimum and maximum dissolved oxygen concentrations at five sites in the South Umpqua River Basin, Oregon, 1992.

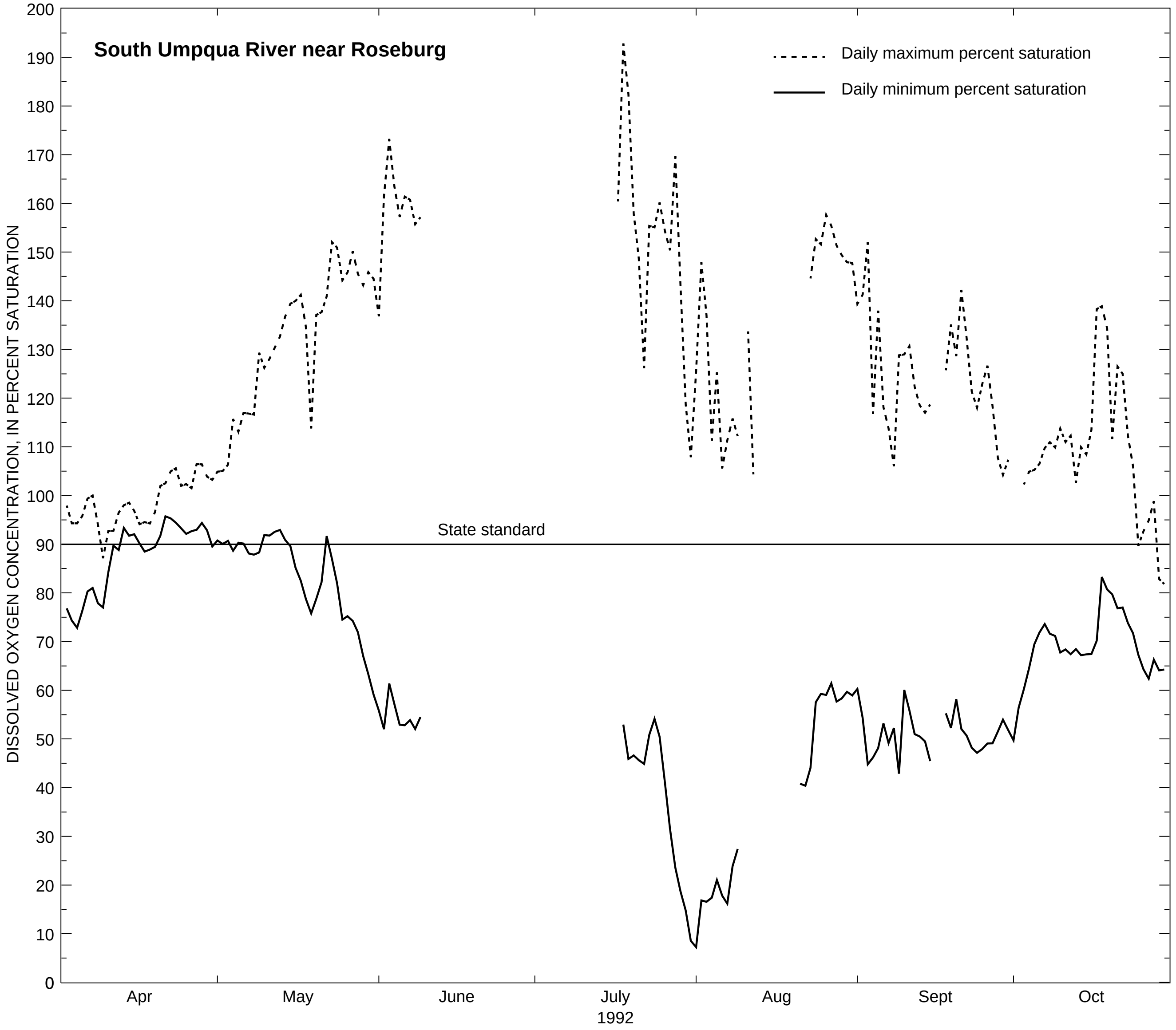

Figure 10. Daily minimum and maximum dissolved oxygen concentrations at five sites in the South Umpqua River Basin, Oregon, 1992—Continued.

The steep gradient increases the number of riffles (Anderson and others, 1994, table 3), causing reaeration to be greater than in pools (Kilpatrick and others, 1989; Laenen and Woo, 1994) and helping maintain higher concentrations of DO.

Seasonal change in DO saturation for five fixed stations is shown in figure 10. Data for the South Umpqua River at Days Creek and near Roseburg were from unmanned recording instruments from which barometric pressure was not available; therefore, percent-saturation data for these graphs were calculated by using equation 1. Other measurements were made weekly or biweekly. Daily minima and maxima were determined as described above for synoptic surveys.

At the South Umpqua River at Days Creek site, after reaching a minimum in late June, daily minimum and maximum percent saturation of DO gradually increased. These changes may have been due in part to the decreasing water temperature after June 26, 1992 (Anderson and others, 1994), which would allow more oxygen to dissolve. Daily minimum water temperature for Days Creek was highest on June 24, 1992, reaching 25°C; the minimum DO at Days Creek for the entire summer was 76 percent of saturation on June 26, 1992. Although DO at Days Creek was rarely less than 85 percent of saturation and did not have significant seasonal changes, minimum DO was less than 90 percent of saturation for a significant part of the summer in 1992.

At the Days Creek site, which has a small amount of periphyton, water temperature apparently exerts some control on DO concentrations. The periphyton community at this site is characterized by diatoms, which have lower levels of primary productivity than filamentous green algae (Anderson and others, 1994, table 29).

At Cow Creek near Riddle, daily minimum DO was less than 90 percent of saturation most of the summer in 1992 (fig. 10). The addition of effluent from the Riddle WWTP and the resulting periphyton growth immediately downstream from Riddle further decreased DO. During synoptic surveys in 1991, percent saturation of DO was consistently reduced downstream from Riddle, and Cow Creek was significantly undersaturated where it entered the South Umpqua River. In late summer, Cow Creek supplies a significant part of the flow to the lower South Umpqua River as a result of releases from the Galesville Reservoir. In the late summer, therefore, Cow Creek contributes to oxygen deficits downstream from its confluence with the South Umpqua River at RM 158.9.

Daily minimum percent saturation of DO at the South Umpqua River at Myrtle Creek site (RM 151.3), just upstream from Myrtle Creek, was less than 90 percent each time the river was sampled (figs. 9 and 10). Minimum DO was less than 80 percent of saturation six times in 1992 and as low as 74 percent on August 5, 1992. The South Umpqua River at Myrtle Creek site is in the reach immediately downstream from Cow Creek, and DO in the river at the Myrtle Creek site may be influenced by Cow Creek. The travel time from Cow Creek to the Myrtle Creek site is greater than 14 hours at flows of 100 ft^3/s (Laenen and Woo, 1994); therefore, it is not clear to what extent oxygen-depleted water is transported through the reach.

The South Umpqua River near Brockway (RM 132.8) is located immediately upstream from the Winston-Green WWTP and at the end of the longest reach between known nutrient point sources in the lower half of the river (17.9 miles from the Myrtle Creek to Winston-Green WWTPs). Like the South Umpqua River at Myrtle Creek, the Brockway site was visited twice each month during the summer of 1992. Minimum DO saturation was lower than the State standard of 90 percent at only one sampling time, when the saturation was 81 percent (fig. 10). The streambed at Brockway is composed primarily of gravel and loose rocks, which are unfavorable for periphyton attachment; consequently, no large mats of periphyton were observed at the Brockway site until late summer of 1992. In addition, nutrient loads remained low at this site most of the summer. Despite the lack of periphytic algae, large beds of macrophytes (*Elodea* and *Potamogeton*) grew along the edges of the river at the Brockway site.

The most downstream fixed station in 1992 was on the South Umpqua River near Roseburg (RM 118.0), where an electronic monitor recorded water temperature, specific conductance, DO, and pH every hour. Owing to equipment problems, DO measurements were unreliable during several periods in 1992. (One recurring problem was the clogging of pump intakes by algal mats in the summer.) Large daily fluctuations in DO are evident in figure 10, which shows extreme maximum and minimum percent DO saturations of 192 and 8.5 percent, respectively. The shape of the DO minimum and maximum curves indicate that the algal growing season below Roseburg started as early as April 1992 and continued until late October. Minimum DO was less than 90 percent every day from May 15 until after the first significant rainstorm on November 8, 1992.

Because of river dilution, BOD attributable to point sources probably does not contribute significantly to DO problems in the South Umpqua River. Using average effluent-flow rates from 1991 and assuming, conservatively, that the effluent BOD concentration is 10 mg/L (the permitted amount) for each WWTP, the increases in BOD in the South Umpqua River (at a river discharge of 100 ft^3/s) from the Canyonville, Myrtle Creek, Winston-Green, and Roseburg WWTPs would be 0.08, 0.1, 0.1, and 0.54 mg/L, respectively. Even in the case of the Roseburg WWTP, the potential BOD contribution is barely sufficient to produce a significant decrease in DO in the river; prorated over a 5-day period, it causes only about a 0.2 mg/L decrease in DO.

Measurements of 5-day BOD (BOD_5) taken in the South Umpqua River by the Oregon Department of Environmental Quality (ODEQ) during the summers of 1988–90 (after the beginning of operation of Galesville Reservoir and the reconstruction of the Roseburg WWTP) indicated that BOD_5 concentrations ranged from 0.5 to 2 mg/L at several locations between Days Creek (RM 170.0) and Melrose Road (RM 116.6) (Greg Petit, Oregon Department of Environmental Quality, written commun., 1992).

Although BOD contributes to decreased DO in the South Umpqua River, the relative amount of DO lost due to BOD is probably less than the decreases caused by daily cycles of periphyton respiration. During the study, daily DO fluctuations ranged from as high as 2 to 5 mg/L in the middle reaches of the river and increased in the vicinity of Roseburg and downstream. The maximum DO on August 18, 1992 at the South Umpqua River near Brockway site was 9.2 mg/L (117-percent saturation). The minimum DO was 7.2 mg/L (89-percent saturation) the following morning. BOD_5 values provided by ODEQ for 17 analyses between 1986 and 1989 at the same site averaged 1.1 mg/L; BOD_5, measured twice by the USGS in September 1992, ranged from 0.5 to 0.7 mg/L. The DO loss caused by BOD at South Umpqua River near Brockway, therefore, is probably about 0.1 to 0.2 mg/L on a daily basis, which is 5 to 10 percent of the daily DO cycle observed in August 1992. At the South Umpqua River near Melrose site, which might constitute a “worst-case” scenario with respect to BOD due to its short distance downstream from the Roseburg WWTP, BOD_5 analysis indicated a possible value as high as 2 mg/L, or 0.4 to 0.5 mg/L per day; at that site, average summer daily DO range was 6.5 mg/L. In summary, probably less than 10 percent of the lost DO is caused by BOD.

It is still possible, however, that at certain times and locations, BOD contributes significantly to DO problems in the South Umpqua River. If an additional 10 percent of the daily DO decrease attributed to BOD were sufficient to cause violations of the State DO standard or to impair fish habitat at a particular site, then reducing BOD loads to the river would help improve water quality. Periphyton is a potential instream source of BOD. Dying algal mats, which slough off tissue, would contribute organic matter to the river’s BOD load and decrease DO concentrations to below levels caused by plant respiration. Periphytic mats also may provide substrates for attachment by nonphotosynthetic, respiring bacteria that, in turn, could reduce DO in the river and contribute to BOD.

Nitrification, the oxidation of ammonia to NO_2^- and subsequently to NO_3^-, also can reduce DO in river water. Nitrification is a component of BOD and frequently is referred to as nitrogenous biochemical oxygen demand. Nitrification is a bacterially mediated, two-step process that can consume large quantities of DO—4.3 grams of oxygen are consumed for every gram of nitrogen oxidized (Velz, 1970). Nitrification can greatly reduce DO concentrations in streams that receive sewage effluent, particularly when the sewage effluent has high concentrations of ammonia (Hines and others, 1977). NO_2^-, which is usually oxidized quickly to NO_3^-, may be found in higher concentrations than expected in river systems where nitrification is an important DO sink.

Evidence that nitrification contributes significantly to decreased DO in the South Umpqua River is sparse. Uptake of dissolved inorganic nitrogen (DIN), either as ammonia or as NO_3^-, probably occurs too rapidly for nitrification to be an important process in most of the river. Data for ammonia, NO_2^-, and NO_3^- (Anderson and others, 1994) do not indicate that unexplained increases in either NO_2^- or NO_3^- were occurring at the same location or time as decreases in ammonia. In most cases, there were losses of all three types of DIN, indicating possible uptake by algae and bacteria. Some occurrences of slightly elevated concentrations of NO_2^- occur immediately downstream from some WWTP inputs, implying that nitrification may be occurring; however, even in those instances, decreases in concentrations of ammonia are accompanied by decreases in concentrations of NO_2^-. Therefore, the effect of nitrification probably is minor when compared to DO depletions caused by algal respiration and probably is limited to areas immediately downstream from WWTPs that discharge large amounts of ammonia.

The profile of decreasing NO_3^- concentrations, which generally parallels ammonia profiles downstream from point sources, indicates that algae in the river may be nitrogen limited. Because ammonia is the preferred form of inorganic nitrogen for consumption by algae (due to considerations of energetics), if NO_3^- is consumed by algae, it must be reduced to ammonia before incorporation into biochemical pathways (Grady and Lim, 1980; Welch, 1992, p. 71). Therefore, a decrease in NO_3^- loads suggests that there is a scarcity of the more efficient nitrogen source, ammonia.

Comparison of the daily minimum and maximum DO values recorded by the monitor near Roseburg (RM 118.0) to flow information from the nearest gaging station near Brockway (RM 132.8) provided evidence that periphyton sloughing and decay may have contributed to BOD in the river. Data for the first fall storms that produced measurable flow increases in 1991 and 1992 were considered. Such sudden flow increases generally increase channel scour.

Large and sudden decreases in minimum and maximum DO were observed at the Roseburg monitor soon after the first fall rainstorms. In the fall, the flow increased from 152 ft^3/s on October 29, 1992 to more than 3,000 ft^3/s by November 2, 1992. Daily minimum DO decreased from about 6 to 7 mg/L (58- to 68-percent saturation) to less than 0.5 mg/L (5-percent saturation) from November 1 to November 5, 1992. In addition, the daily maximum DO decreased to less than 2 mg/L (20-percent saturation) during this event. The discharges were measured at South Umpqua River near Brockway, almost 15 miles upstream from the monitor. (The delay between the flow increase and the DO decrease may have been a result of travel time.) Such extreme lows in DO, resulting from decay of sloughed or scoured algae, could affect anadromous fish populations in the South Umpqua River during fall spawning seasons.

pH

The pH of a solution is a measure of its hydrogen-ion activity. In most natural waters, the carbonate system (which includes CO_2, H_2CO_3, HCO_3^-, and CO_3^{2-}) controls pH. The pH of a solution affects the degree of dissociation of acids and bases. The toxicity of many compounds, including ammonia, is dependent on the pH of the water containing the compound. Oregon State standards specify that pH values in the Umpqua River Basin shall not fall outside the range of 6.5 to 8.5 (State of Oregon, 1992).

Similar to the daily cycle of DO in relation to photosynthesis (eqs. 3 and 4), the pH of surface waters can be controlled primarily by the metabolism of aquatic plants. Consumption of CO_2 by photosynthesis raises pH, causing late afternoon maxima; overnight respiration produces CO_2, causing early morning pH minima. This cycle is repeated daily (fig. 8) and is a function of the productivity of the aquatic-plant community.

Daily pH minima and maxima measured during synoptic surveys from 1990 to 1992 are shown in figure 11. Daily pH maxima in the South Umpqua River Basin had distinct spatial and seasonal patterns. Daily maxima for pH occurred between 1530 and 1900 hours in 30 of 34 diel measurements made in 1991 and 1992.

The seasonal patterns of DO and pH exceedances of State standards generally are the same. Much of the South Umpqua River meets the State standard for maximum pH of 8.5 during spring and high-flow conditions but is in violation during summer and low-flow conditions (fig. 11).

During spring and high-flow conditions, such as in June 1991 and May 1992, maximum pH values greater than 8.5 were observed only downstream from the Roseburg WWTP (RM 119.5 and RM 116.6) and between Winston and Roseburg (RM 123.4 in June 1991 and RM 126.6 in May 1992). Maximum pH values also were greater than 8.5 at Days Creek (RM 170.0) in May 1992 and at Tiller (RM 187.3) from July to September 1991 and September 1992. The pH at Melrose Road (RM 116.6) was as high as 9.4 during this study.

Despite the small number of exceedances during May 1992, daily maximum pH values were high at many sites, indicating that algal growth began earlier in the spring. Considering the extreme low flows and unusually warm and sunny spring weather, the early algal growth was not surprising. A sudden, heavy rainstorm, which occurred during the synoptic survey in May 1992, may have contributed to the lower pH values observed in the middle reaches of the South Umpqua River (from Cow Creek at RM 158.9 to Winston at RM 131.6) through dilution effects and suppression of algal photosynthesis.

During the low flow of warm summer months, the daily maximum pH value commonly exceeded 8.5 throughout much of the South Umpqua River. The pH problems extended upstream from the town of Canyonville and as far as the Umpqua National Forest above Tiller. During synoptic surveys, the South Umpqua River at Days Creek consistently had daily maximum pH values of less than 8.5 (fig. 11); however, diel surveys made just downstream from Days Creek (RM 170 to 165.3) indicated that pH exceeded 8.5 (fig. 11). The reasons for the high values of pH (and presumably, large algal productivity in Days Creek) are unclear, but the possibility of nonpoint loading of nitrogen exists in this reach.

The South Umpqua River at Brockway (RM 132.8), where maximum pH values of less than 8.5 frequently were recorded, also had DO problems that were less severe than at most other sites.

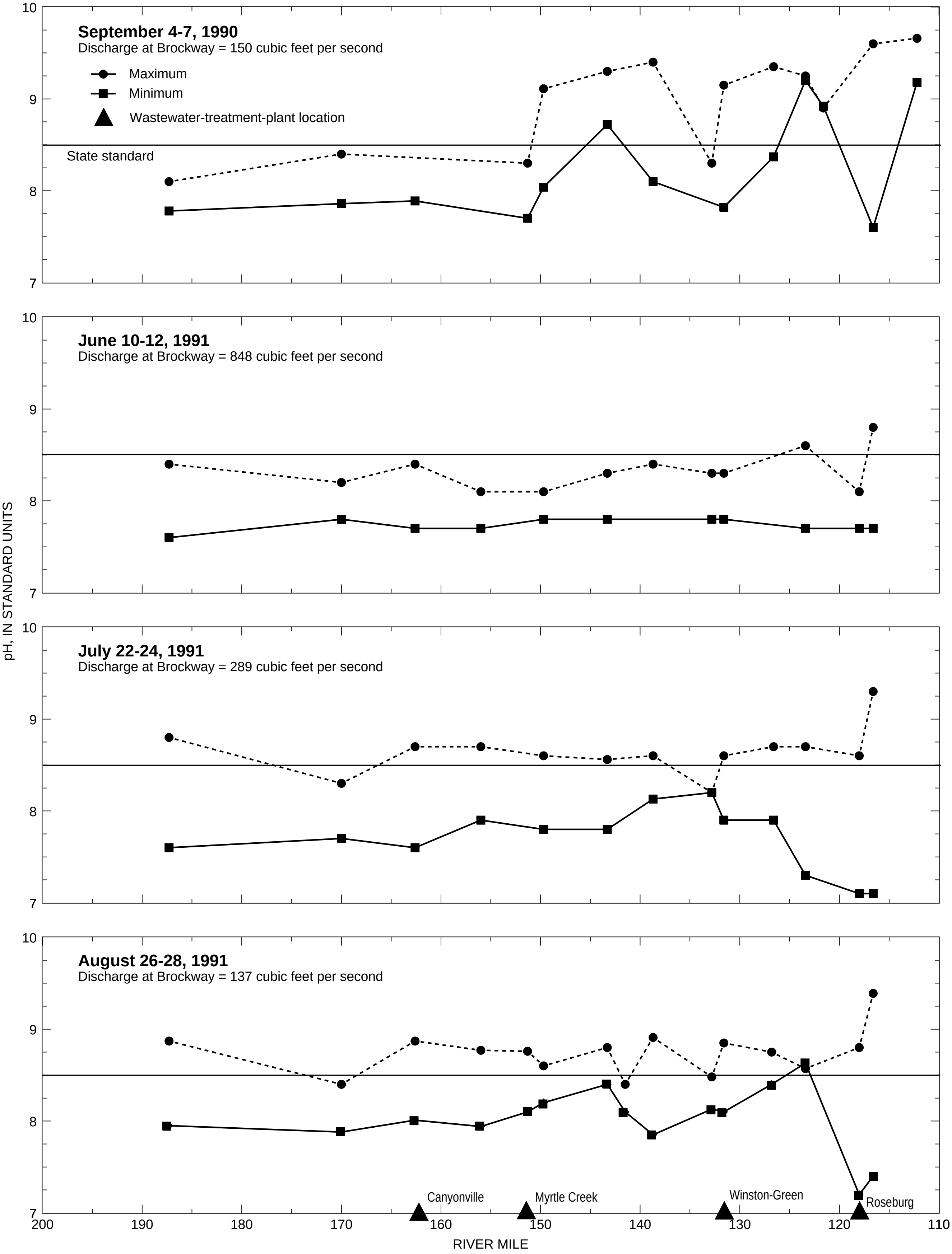

Figure 11. Daily minimum and maximum pH in the South Umpqua River, Oregon, 1990–92. (The gaging station at Brockway is located at river mile 132.8.)

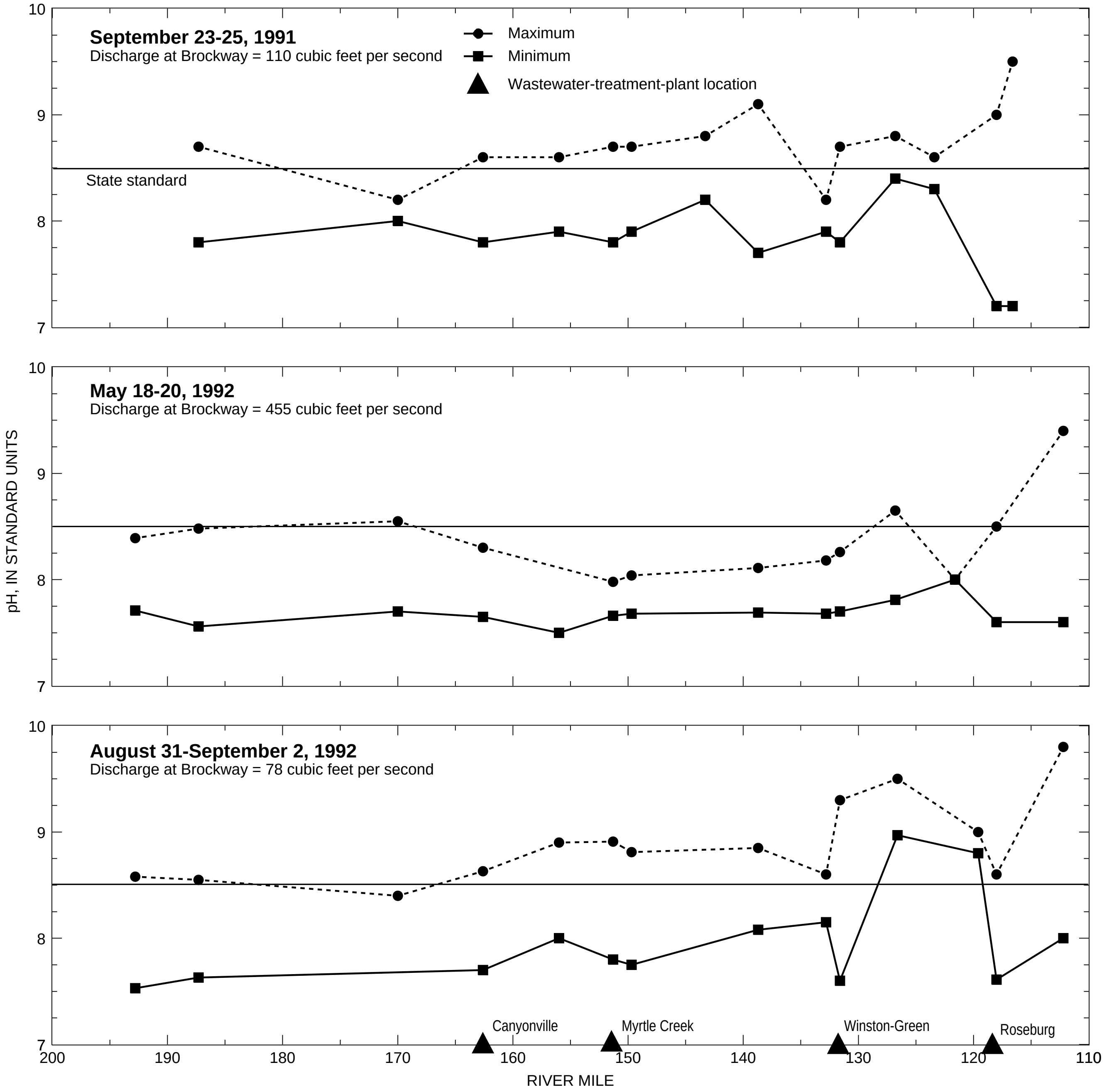

Figure 11. Daily minimum and maximum pH in the South Umpqua River, Oregon, 1990–92—Continued.

Both phenomena probably were due to low algal biomass, which is attributable to low nutrient content in water and the gravelly, unstable riverbed. The low nutrient concentrations and loadings observed at Brockway (RM 132.8) probably were the result of the distance between that downstream site and the Myrtle Creek WWTP (17.9 miles), because most of the nutrient load had been consumed by the benthic community before reaching Brockway site.

Despite the conditions limiting algal growth at the Brockway site (RM 132.8), extensive coverage of the riverbed by periphytic algae occurred by late summer in 1991 and 1992, resulting in the higher maximum pH values observed at this site (fig. 11). Several factors may have contributed to the higher values of pH. In the upstream reach, maturation, sloughing, and senescence of the algal community may have reduced the demand for nutrients, thereby elevating nutrient concentrations in the water column farther downstream and extending the length of the reach that might be affected by algal growth. Furthermore, the instability of the substrate was potentially negated, because depressed flows caused by the drought decreased water velocity.

One South Umpqua River site, just downstream from the Myrtle Creek WWTP (RM 149.7) had anomalous DO values. Because of reaeration, that site seldom had DO of less than 90 percent of saturation, despite large nutrient loads. There was no such anomaly for pH, which was frequently greater than 8.5 and sometimes represented an increase in pH from the South Umpqua River at Myrtle Creek site (RM 151.3), just upstream from the Myrtle Creek WWTP (fig. 11). This was the case during the synoptic survey in September 1990 and during the diel surveys in August and September 1992. The increase in maximum pH value indicates that increased algal activity was sufficient to overcome the apparently large amount of reaeration between the two sites. The ratio of the rates of atmospheric exchange of CO_2 and DO due to physical reaeration is 0.894 (Tsivoglou, 1967), indicating that CO_2 does not exchange with the atmosphere as rapidly as DO. Therefore, a decrease in pH due to reaeration (representing an increase in CO_2 saturation in water) would not be expected to occur as rapidly as an increase in the percent saturation of DO for the same river reach.

Daily minimum pH values greater than 8.5 occurred at several sites located almost exclusively downstream from the Winston-Green WWTP, with the exception of a measurement at the South Umpqua River at Mary Moore Bridge site (RM 143.3) in September 1990 (fig. 11). Minimum pH values greater than 8.5 were observed only in late summer and when the discharge at the gaging station near Brockway was less than 150 ft^3/s. Minimum pH values greater than 8.5 occurred most frequently between the Winston-Green WWTP and the Roseburg WWTP at the following sites: South Umpqua River near Oaks (RM 126.6), South Umpqua River at Roseburg (RM 123.4), and South Umpqua River above Roseburg WWTP (RM 119.6). In September 1990, minimum pH values were greater than 9.0 at two sites (fig. 11).

Temporal trends in daily minimum and maximum pH for four fixed stations in 1992 are shown in figure 12. Daily maximum pH values at the South Umpqua River at Days Creek site (RM 170.0), a site originally chosen to represent background conditions, were greater than 8.5 only during the early summer of 1992 and decreased as the summer progressed. Daily minimum pH values showed little evidence of significant trends during the course of the summer. The fact that pH values peaked in early summer may indicate that the algal community achieved its maximum growth rate early at this site, and the biomass did not substantially increase after late June.

The seasonal patterns of late afternoon pH values in 1992 at the two fixed stations between Cow Creek and Roseburg was similar (fig. 12) and consistent with previous findings for DO. The afternoon pH values were higher than 8.5 from late June through early September at the South Umpqua River at Myrtle Creek site (RM 151.7). The Brockway site (RM 132.8) had maximum pH values higher than 8.5 for approximately the same time period, although several pH values in July and August were less than 8.5. Although unexpected, the pattern of high values of pH at the Myrtle Creek site (RM 151.7) was consistent with the low saturations of DO in the mornings (fig. 10) and potential inputs of high-pH water from Cow Creek.

Daily maximum pH values, recorded by the continuous monitor at South Umpqua River near Roseburg (RM 118.0), typically were higher than 8.5 from early May until late October 1992. Although maximum pH values exceeded 9.0 on many occasions, the minimum pH was as low as 7.0. High values of pH at this site, which is downstream from the largest WWTP in the South Umpqua River Basin (Roseburg WWTP), may contribute to ammonia toxicity in the river.

The temporal and spatial patterns of maximum pH (figs. 11 and 12) were similar to temporal and spatial patterns of minimum DO (figs. 9 and 10). That pH and DO commonly fluctuated together (fig. 8) is consistent with the hypothesis that photosynthetic activity is primarily responsible for DO and pH variations throughout most of the South Umpqua River during the summer.

Bacteria

The transmission of disease-producing bacteria can be caused by fecal contamination from warm-blooded animals, including humans. Fecal-coliform and fecal-streptococcal bacteria are indicator organisms used to evaluate the potential health hazards of water used for drinking or recreation. Unless the source of the indicator bacteria has been determined by species identification to be nonfecal, the presence of indicator bacteria is usually interpreted as a potential health hazard.

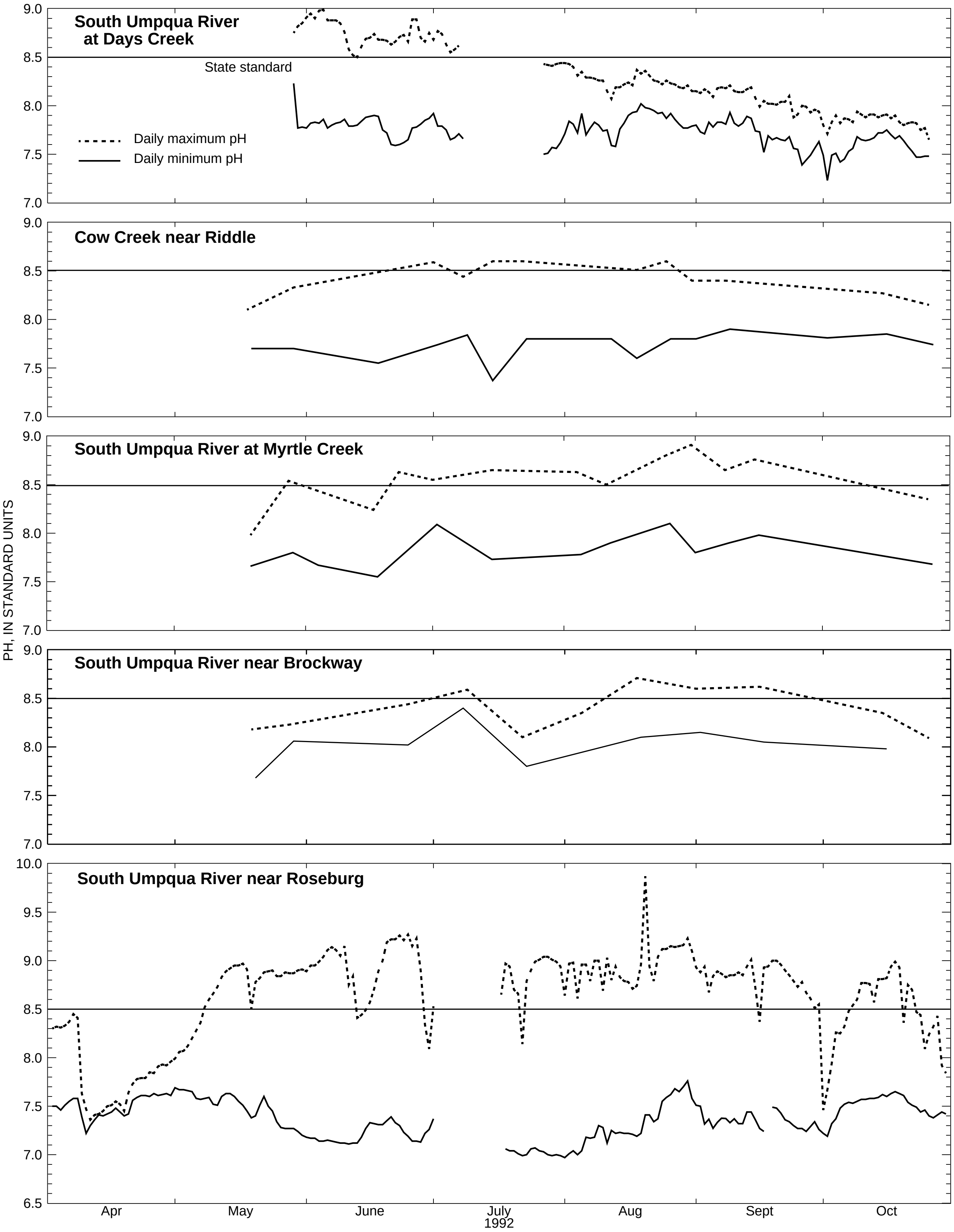

Figure 12. Daily minimum and maximum pH at four sites on the South Umpqua River, Oregon, 1992.

Oregon State standards for the South Umpqua River require that colony counts of fecal-coliform bacteria should not exceed a log mean of 200 colonies per 100 milliliters of sample, based on a minimum of 5 samples in a 30-day period, and that no more than 10 percent of the samples in a 30-day period exceeding 400 colonies per 100 milliliters (State of Oregon, 1992). There is no State standard for fecal streptococci.

Grab samples for bacteria were collected in sterilized bottles and analyzed by membrane filtration (Britton and Greeson, 1987). The data collected on September 1 and 15, 1992, at several sites throughout the South Umpqua River Basin illustrate the spatial distribution of fecal-coliform and fecal-streptococcus counts (table 3). All counts for fecal-coliform bacteria on these dates were less than the State standard of 200 colonies per 100 milliliters. However, fecal-streptococcus counts were larger than they had been historically. Blank samples, processed at the time of sampling, indicated no evidence of contamination. The fecal-streptococcus data from September 1 and 15, 1992, were not published in Anderson and others (1994) but are shown in table 3 with the qualification that the high values require confirmation.

The South Umpqua River near Roseburg (RM 118.0) was sampled monthly as part of the USGS National Stream Quality Accounting Network (NASQAN) program, which provided most of the bacterial data. Counts of fecal-coliform bacteria ranged from less than 1 to 670 colonies per 100 milliliters at the Roseburg station from January 1990 to December 1992 (table 3). Three samples with 200 colonies or more per 100 milliliters (collected January 3, 1990; February 6, 1990; and November 12, 1991) were associated with high streamflows. The smallest streamflow for fecal-coliform samples with values of 200 colonies or more per 100 milliliters was 272 ft^3/s on November 12, 1991. The direct relation between increased fecal-coliform bacteria and increased streamflow suggests that contaminants from nonpoint sources, such as livestock waste, urban stormwater, or WWTP bypass, are being carried into the South Umpqua River during periods of runoff. Small counts of fecal-coliform bacteria were associated with low runoff in summer.

At Roseburg, fecal streptococci usually were more numerous during the summer low flow than during higher flows (table 3). Fecal-streptococcus counts larger than 500 colonies per 100 milliliters (an arbitrary level for purposes of comparison) occurred on August 9, 1990; August 13, 1991; and September 15, 1992. The largest streamflow associated with these sampling dates was 179 ft^3/s on August 13, 1991. An inverse relation between fecal-streptococcus counts and streamflow suggests that the bacteria emanate from a point source upstream, the discharge of which is diluted by high streamflow. The sampling site is 1.5 miles downstream from the Roseburg WWTP—the largest point source discharging to the South Umpqua River, and the fecal streptococci at Roseburg sampling site may have been associated with WWTP effluent. However, other potential sources, including an urban stream known as Deer Creek, exist in the Roseburg area upstream from the Roseburg sampling site.

Ammonia

Simultaneous data on dissolved ammonia, pH, and temperature are available for 250 water samples collected from main-stem South Umpqua River sites from September 1990 to September 1992. None of these samples had concentrations that exceeded the criterion for acute ammonia toxicity that is used when salmonid fish and other cold-water fish species are present. Un-ionized ammonia (NH_3) is toxic to aquatic life; for any given total ammonia ($NH_3 + NH_4^+$) concentration, the proportion of un-ionized ammonia increases as pH increases. Ammonia criteria set by the State of Oregon (State of Oregon, 1992) are the same as EPA standards (U.S. Environmental Protection Agency, 1986). The criteria for acute ammonia toxicity (1-hour average conditions) and for chronic toxicity (4-day average conditions) are based on equations using ammonia concentration, water temperature, and pH to calculate a maximum allowable concentration of un-ionized ammonia (European Inland Fisheries Advisory Committee, 1970).

Evidence of potential exceedances of the chronic-concentration criterion for ammonia toxicity was found. The ratio of the measured concentration of un-ionized ammonia to the maximum un-ionized ammonia allowed by the chronic-concentration criterion was calculated for the same set of 250 samples (fig. 13).

Table 3. Bacteria in streams of the South Umpqua River Basin, Oregon, at selected sites, 1990–92
[ft^3/s, cubic feet per second; 0.7 UM-MF, 0.7 micron millipore filter; Cols./100 ML, colonies per 100 milliliters;
K, nonideal colony count; '--', missing data or data not collected]

Station name and number	Date	Time	Discharge instantaneous (ft^3/s)	Coliform, fecal 0.7 UM-MF (Cols./100 ML)	Streptococci, fecal KF AGAR (Cols./100 ML)
South Umpqua River at Days Creek 14308600	SEP 1992				
	01...	1220	--	K6	1,400
	15...	0710	--	25	K1,500
Cow Creek at mouth, near Riddle 425640123201400	SEP 1992				
	01...	0700	--	35	900
	15...	0810	--	21	980
South Umpqua River at Myrtle Creek 14311105	SEP 1992				
	01...	0930	--	K16	860
	15...	0830	--	K16	K2,800
South Umpqua River near Myrtle Creek 14311110	SEP 1992				
	01...	0940	--	K5	2,000
	15...	0845	--	K11	500
Lookingglass Creek at Brockway 14311500	SEP 1992				
	01...	1025	--	34	1,400
	15...	0920	--	58	1,200
South Umpqua River near Winston 14312005	SEP 1992				
	01...	1045	--	170	2,100
	15...	0935	--	30	2,200
South Umpqua River near Roseburg 14312260	JAN 1990				
	03...	1030	600	K200	56
	FEB				
	06...	0930	4,460	K500	170
	MAR				
	20...	0930	3,340	K2	49
	APR				
	10...	1000	1,090	K16	K8
	MAY				
	16...	0930	475	K18	K6
	JUN				
	13...	0930	864	22	K12
	JUL				
	11...	1400	244	K9	120
	AUG				
	09...	1200	90	K9	840
	30...	1430	227	33	57
	OCT				
	17...	0930	156	K14	21
	NOV				
	07...	0930	844	K33	57
	DEC				
	05...	1330	1,600	39	37

Table 3. Bacteria in streams of the South Umpqua River Basin, Oregon, at selected sites, 1990–92—Continued

Station name and number	Date	Time	Discharge instantaneous (ft^3/s)	Coliform, fecal 0.7 UM-MF (Cols./100 ML)	Streptococci, fecal KF AGAR (Cols./100 ML)
South Umpqua River near Roseburg 14312260–Continued	JAN 1991				
	15...	1400	10,500	41	40
	FEB				
	27...	1000	1,360	K18	K12
	MAR				
	26...	0930	3,210	36	55
	MAY				
	01...	1330	1,890	K33	K3
	30...	1430	1,710	23	K7
	JUN				
	25...	1130	536	20	K5
	JUL				
	25...	1000	280	K1	53
	AUG				
	13...	1400	179	<1	K510
	SEP				
	04...	1400	126	K20	31
	OCT				
	17...	0930	99	K14	190
	NOV				
	12...	1345	272	670	22
	DEC				
	11...	0915	2,630	53	88
	JAN 1992				
	14...	1330	1,850	26	K15
	FEB				
	12...	1130	972	K13	K6
	MAR				
	09...	1330	1,030	K10	K2
	APR				
	09...	0930	606	K10	55
	MAY				
	04...	1130	857	K13	K2
	JUN				
	09...	1130	187	K2	740
	JUL				
	15...	1200	149	K14	960
	AUG				
	17...	1600	75	K9	K420
	SEP				
	01...	1110	--	55	4,400
	08...	1300	116	21	39
	15...	0955	--	29	4,200
	OCT				
	21...	1330	144	K1	70

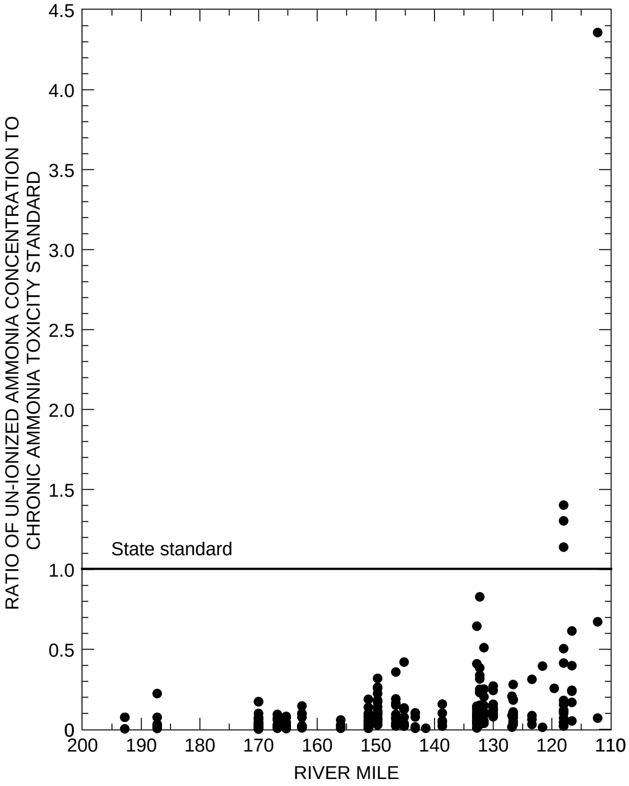

Figure 13. The ratio of un-ionized ammonia to the Oregon State standard for chronic ammonia toxicity in the South Umpqua River, Oregon, between September 1990 and September 1992.

Any ratio larger than 1.0 represents a potential violation. For actual violations to have occurred, the instantaneous values of dissolved ammonia concentrations, temperature, and pH also would have to be representative of the average conditions for 4 consecutive days. Temperature and pH values are extremely variable, especially during late summer in the lower reaches of the South Umpqua River. Dissolved ammonia concentrations can be expected to vary considerably downstream from WWTPs, because of daily changes of ammonia concentration and load in the effluent and because of uptake by the benthic community. Figure 13 may not, therefore, be representative of chronic conditions and can be considered only as an indicator of locations at which chronic ammonia toxicity may occur.

The four potential exceedances of the chronic-concentration criterion for ammonia toxicity occurred downstream from the Roseburg WWTP (RM 119.5) (fig. 13). The Roseburg WWTP is the most significant point source of nutrients on the South Umpqua River; in the lower reaches of the river, the temperature and pH values are often high. Several samples, collected downstream from the Winston-Green WWTP (RM 132.6), contained dissolved ammonia concentrations that approached the level of chronic ammonia toxicity; however, no chronic or acutely toxic conditions were detected during this study.

In summary, ammonia from WWTP effluent, combined with high values of pH and high temperatures, created the potential for exceedances of the chronic-concentration criterion for ammonia toxicity in the lower reaches of the South Umpqua River. For exceedances of the criterion actually to have occurred, the instantaneous values of dissolved ammonia concentrations, temperature, and pH would have to have represented the average conditions for 4 consecutive days.

NUTRIENT SOURCES AND CHARACTERISTICS

In eutrophic water such as that in South Umpqua River, major nutrients are typically nitrogen, phosphorus, and carbon. The dissolved forms of ammonium, nitrate, nitrite, and orthophosphate are of primary importance to understanding algal nutrition. From a thermodynamic standpoint, the preferred forms of nitrogen and phosphorus for algal use generally are considered to be ammonium and orthophosphate; however, algae also assimilate nitrate and various polyphosphates (Wetzel, 1983).

In the present study, the nutrients measured in water-quality samples were primarily limited to nitrogen and phosphorus species in filtered and unfiltered water samples (table 4). Nitrogen species include: filtered or dissolved ammonia, filtered or dissolved nitrite plus nitrate ($NO_2^- + NO_3^-$), and filtered or dissolved nitrite (NO_2^-). The sum of ammonia and NO_3^- concentrations is referred to as DIN. Phosphorus species include SRP (which incorporates both dissolved orthophosphate and other polyphosphates); unfiltered, digested phosphorus, or TP; and filtered, digested phosphorus, or total dissolved phosphorus (TDP).

Nutrient uptake by periphytic algae is a function of many different chemical and physical factors, including stream velocity, substrate (attachment points for algal cells), light availability, and temperature (Graham and others, 1982; Horner and others, 1983). In contrast to lakes and other lentic (nonflowing) environments where water velocity is essentially zero, the velocity of a stream can decrease the diffusion gradient of nutrients to periphyton from the overlying water and thereby increase the amount of nutrients to which the algae are exposed.

Table 4. Nutrient analyses in the South Umpqua River Basin, Oregon, 1990–92
[S, synoptic; F, fixed station; D, diel inflow/outflow; mg/L, milligrams per liter; LC, laboratory code; WWTP, wastewater-treatment-plant effluent; N, nitrogen; P, phosphorus; C, carbon]

Parameter name	Method code	Minimum detection limit	Sampling type
Nitrogen, ammonia, dissolved (mg/L as N) filtered, undigested	LC0830 LC0301	0.002 .01	S, F, D WWTP
Nitrogen, ammonia plus organic, total (mg/L as N) unfiltered, digested	LC084	.2	All
Nitrogen, nitrite, dissolved (mg/L as N) filtered, undigested	LC0827 LC0160	.001 .01	S, F, D WWTP
Nitrogen, nitrite plus nitrate, dissolved (mg/L as N) filtered, undigested	LC0826 LC0228	.005 .1	S, F, D WWTP
Phosphorus, total (mg/L as P) unfiltered, digested	LC0837 LC0129	.001 .01	S, F, D WWTP
Phosphorus, dissolved (mg/L as P) filtered, undigested	LC0829 LC0128	.001 .01	S, F, D WWTP
Phosphorus, soluble reactive, dissolved (mg/L as P) filtered, undigested	LC0828 LC0162	.001 .01	S, F, D WWTP
Carbon, organic, dissolved (mg/L as C) filtered	LC0113	.1	S
Carbon, organic total (mg/L as C) unfiltered	LC0114	.1	S

Consequently, the load (the product of discharge and concentration, in mass per unit time) of the nutrient in the stream is an essential component when defining relations of periphyton and nutrients. For this reason, and to identify sources and sinks in the river, water and nutrient loading budgets were developed for the South Umpqua River.

Point Sources

Five WWTPs greatly affect the water quality of the South Umpqua River. These five WWTPs are located, in downstream order, at the towns of Canyonville, Riddle (on Cow Creek), Myrtle Creek, Winston-Green, and Roseburg. From May 4 to September 29, 1992, 24-hour composite samples were collected twice a week from the effluent streams of the five WWTPs by using automatic samplers; the quantity of effluent for each sampling period was recorded. The median flow rate of the effluent ranged from 113,000 gal/d (gallons per day) at the Riddle WWTP to 3,523,000 gal/d at the Roseburg WWTP (table 5).

The median TP loading ranged from 1.4 kg/d (kilograms per day) at the Riddle WWTP to 48 kg/d at the Roseburg WWTP. The median SRP loading was approximately 80 percent of the TP loading and ranged from 1.1 kg/d at the Riddle WWTP to 40 kg/d at the Roseburg WWTP. At the Winston-Green WWTP, SRP in the effluent was highly variable, and the median SRP was much smaller than the median for TP. The operators of the Winston-Green WWTP frequently used alum (aluminum sulfate) as a coagulant to decrease the BOD of the effluent. On occasions when alum treatment was used, the SRP concentration in the effluent was low. When the alum treatment was not used, however, the SRP concentration was similar to that in effluent from the Myrtle Creek WWTP, which discharges a similar effluent volume.

DIN was calculated as the sum of dissolved NO_2^- plus NO_3^- and ammonia. The median DIN loading ranged from 3.2 kg/d at the Canyonville WWTP to 170 kg/d at the Roseburg WWTP.

In addition to the 24-hour composite samples of the WWTP effluent, grab samples of effluent were taken at 4-hour intervals for 24 hours at the Myrtle Creek and Winston-Green WWTPs by using automated samplers. Sampling dates were June 24 and 25, 1992; August 5 and 6, 1992; and September 15 and 16, 1992. The samples were collected to describe the daily variation of WWTP-effluent-nutrient loads during the diel inflow/outflow studies in 1992. These WWTPs were sampled because each discharges effluent into a reach that was studied.

Table 5. Loading characteristics of the five major wastewater-treatment plants in the South Umpqua River Basin, Oregon, May 4 to September 29, 1992

[WWTP, wastewater-treatment plant; RM, river mile; dissolved inorganic nitrogen, (dissolved nitrite+nitrate) + (dissolved ammonia)]

	Effluent flow (thousand gallons per day)				Total phosphorus (kilograms per day)				Dissolved orthophosphorus (kilograms per day)				Dissolved inorganic nitrogen (kilograms per day)			
WWTP name	**Number of samples**	**Maximum**	**Median**	**Minimum**	**Number of samples**	**Maximum**	**Median**	**Minimum**	**Number of samples**	**Maximum**	**Median**	**Minimum**	**Number of samples**	**Maximum**	**Median**	**Minimum**
Canyonville (RM 163.0)	43	178	135	124	43	2.1	1.6	0.85	43	2.0	1.4	0.55	43	9.7	3.2	1.5
Riddle (RM 158.9)	43	227	113	91	42	1.9	1.4	.79	42	1.6	1.1	.48	43	9.4	7.0	4.2
Myrtle Creek (RM 150.7)	40	1,370	690	580	38	14	9.5	6.4	38	12	8.2	5.3	39	56	33	7.0
Winston-Green (RM 132.6)	41	1,500	829	721	40	14	5.1	3.1	41	11	2.1	.74	41	60	49	33
Roseburg (RM 119.5)	42	7,730	3,520	2,910	41	58	48	38	40	47	40	35	42	230	170	55

Samples were analyzed for TKN and TP. (Dissolved nutrients were not analyzed, because it was not possible to immediately filter and preserve the samples). Data were available from strip chart recorders for effluent flow rates at the Myrtle Creek WWTP, making calculation of effluent loads possible. Effluent flow rates at the Winston-Green WWTP were not available for periods of less than 24 hours.

The changes in effluent loads for the Myrtle Creek WWTP on September 15 and 16, 1992 (fig. 14) were typical of those observed on all of the sampling dates. Loads of TKN and TP were smallest from 0300 to 0700 hours and largest at about 1500 hours. These trends were the result of daily changes in input loads to the WWTPs. Sampling of the South Umpqua River below the WWTPs was designed to anticipate these diel changes in effluent nutrient loads.

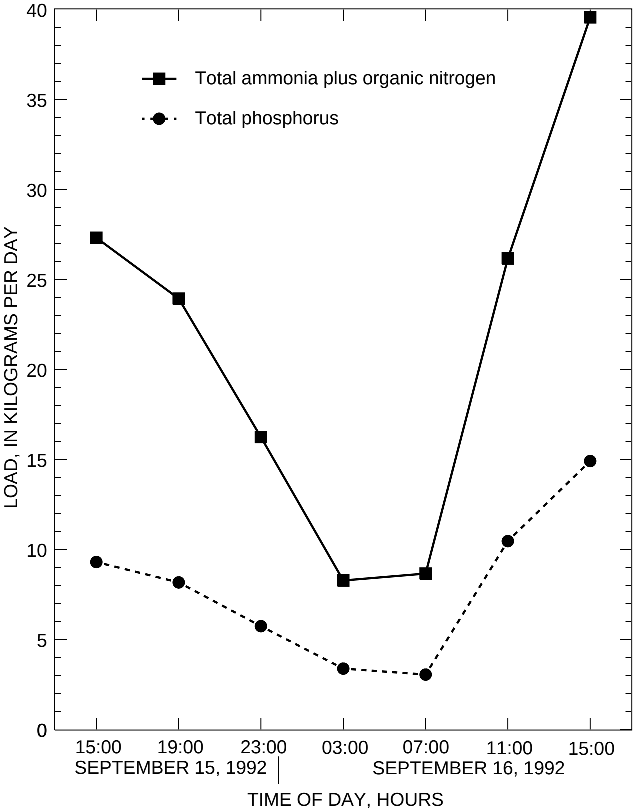

Figure 14. Nitrogen and phosphorus loads in the effluent of the Myrtle Creek, Oregon, wastewater-treatment plant over a 24-hour period from September 15 to September 16, 1992.

Nonpoint Sources

For the purposes of this report, nutrients from nonpoint sources were assumed to enter the South Umpqua River from its tributaries, except where otherwise stated. This assumption is reasonable, because most of the sampling was done during dry, relatively steady-state periods. Although irrigation of grazing lands or croplands is common along the banks of the river, little return flow was noted during reconnaissance surveys or other sampling trips—a result of the hot, dry weather. The tributaries, therefore, act as integrators of basin inputs to the South Umpqua River. Ground-water discharge to the river was assumed to be minimal.

For load estimation, the upstream boundaries during synoptic surveys (South Umpqua River above Jackson Creek, RM 192.8 or South Umpqua River at Tiller, RM 187.3) and diel surveys (South Umpqua River at Days Creek, RM 170.0) were treated as tributary inputs, thereby incorporating any loading that occurs upstream. Although these sites may not accurately represent “background” conditions, there are no known upstream point sources. Cow Creek near Riddle was used as an upstream or background site for Cow Creek.

Temporal Variability

In addition to the five WWTPs sampled twice weekly, five fixed sites on the South Umpqua River were visited weekly to biweekly during the summer of 1992. Data from these sites helped to provide an estimate of the temporal variability of nutrient inputs to the South Umpqua River Basin. The sites were South Umpqua River at Days Creek (RM 170.0), Cow Creek near Riddle (RM 6.7 of Cow Creek), South Umpqua River at Myrtle Creek (RM 151.3), South Umpqua River near Brockway (RM 132.8), and South Umpqua River near Roseburg (RM 118.0). Selection of these sites was based on several factors, including (1) the requirement for upstream (South Umpqua River at Days Creek) and downstream (South Umpqua River near Roseburg) monitoring stations to provide boundaries for conditions in the river during the summer low-flow period, (2) the need to account for major input sources to the river (Cow Creek near Riddle, and the five WWTPs) over a season, and (3) the need to observe nutrient trends at locations less affected by major point sources (South Umpqua River at Days Creek, at Myrtle Creek, and near Brockway).

Concentrations of SRP, TP, and DIN during 1992 at the five fixed sites are illustrated in figure 15.

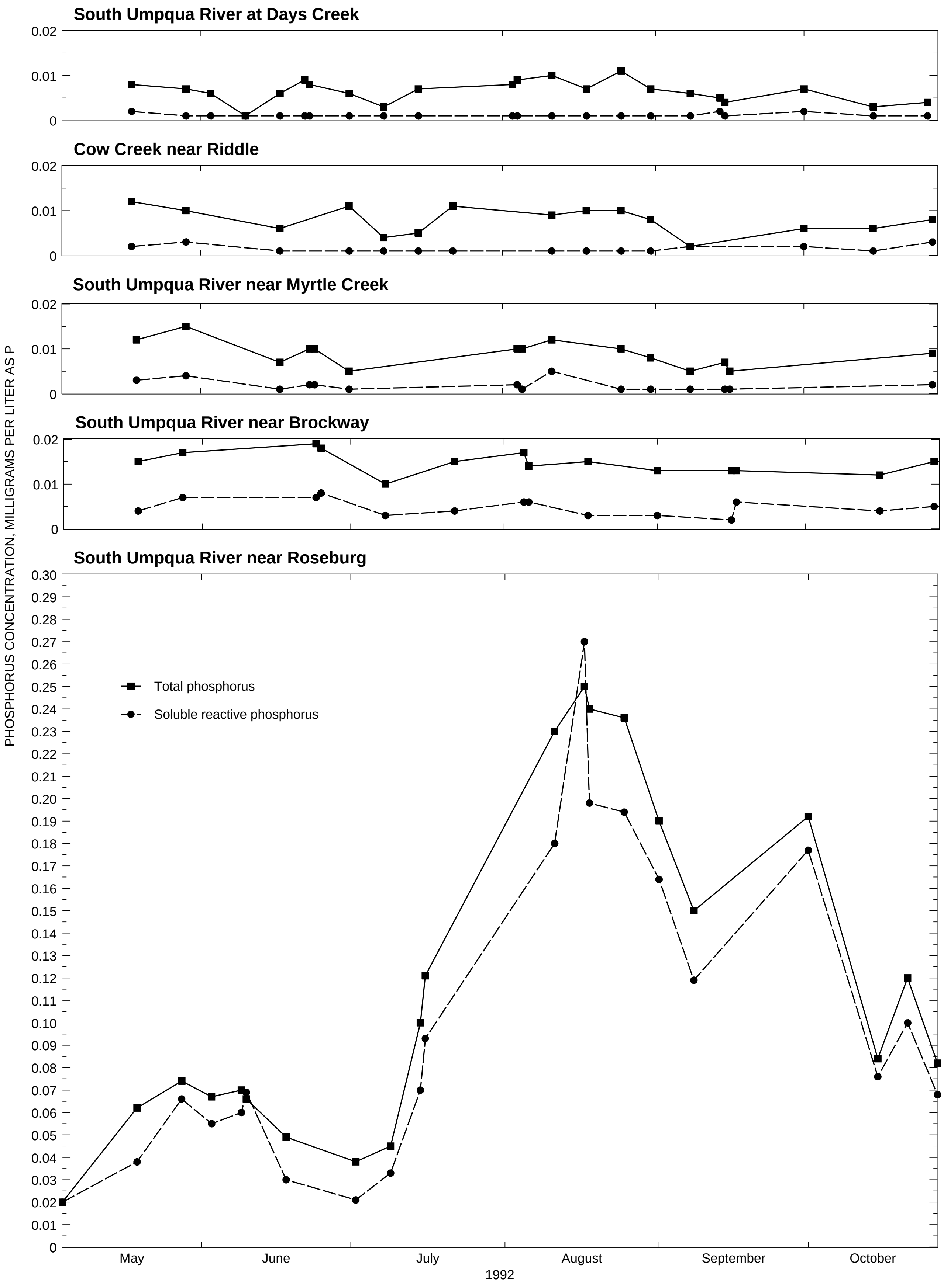

Figure 15. Nutrient concentrations at fixed stations in the South Umpqua River Basin, Oregon, 1992.

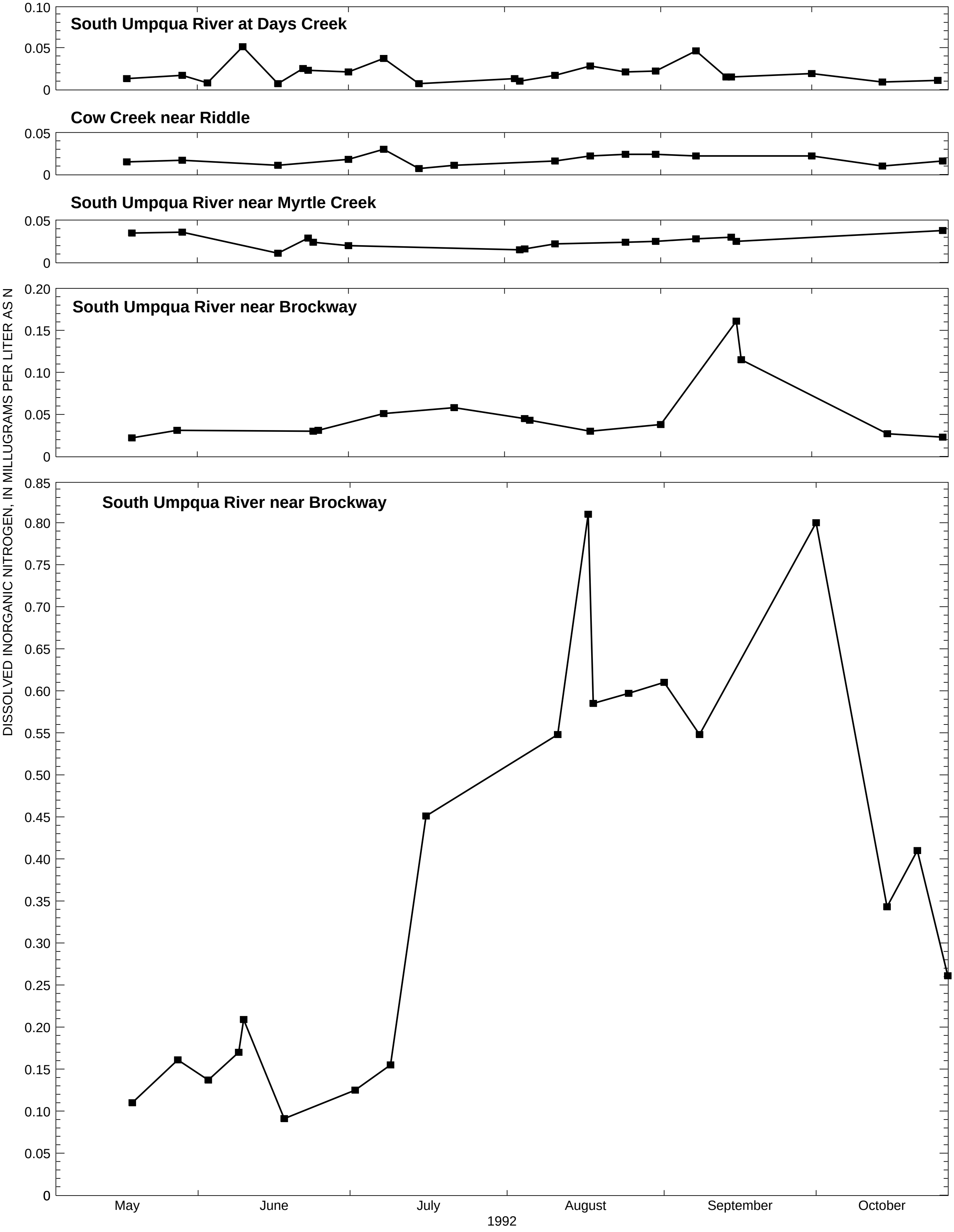

Figure 15. Nutrient concentrations at fixed stations in the South Umpqua River Basin, Oregon, 1992—Continued.

Although there was a large degree of variability in concentrations, some patterns were evident. Concentrations of SRP were near or below the detection limit of 0.001 mg/L much of the summer at the South Umpqua River at Days Creek and at Myrtle Creek sites and at Cow Creek near Riddle (means were 0.001, 0.002, and 0.001 mg/L, respectively). However, mean SRP concentrations were slightly higher at the South Umpqua River near Brockway site (0.006 mg/L) and were significantly higher near the Roseburg site (0.100 mg/L). SRP concentrations at the three fixed sites farthest upstream varied little—the standard deviations for SRP concentrations at South Umpqua River at Days Creek, Cow Creek near Riddle, and South Umpqua River near Myrtle Creek were 0.0003, 0.0007, and 0.001 mg/L, respectively. The standard deviation of SRP concentrations at Brockway also was small (0.002 mg/L), but near Roseburg was larger (0.069 mg/L).

Few major trends in the temporal variation of SRP concentrations at the fixed sites were observed during the summer of 1992 (fig. 15). A slight, temporary decrease in SRP concentrations early in July resulted when stream discharge increased because of a rainstorm, after which SRP concentrations remained relatively constant. In mid-July, after discharge at a station near Roseburg decreased to less than 90 ft^3/s, there was a distinct increase in SRP concentrations. SRP concentrations near Roseburg remained elevated until October, when flows increased slightly.

TP concentrations were somewhat more variable than SRP concentrations at the upstream stations, although the mean concentration remained at less than 0.010 mg/L (fig. 15). Mean TP concentration was 0.015 mg/L at the South Umpqua River at Brockway site and 0.12 mg/L at the South Umpqua River near Roseburg site. Similar to SRP, TP concentrations were related to flow, particularly at Roseburg, where TP concentrations increased in mid-July after discharge decreased. Phosphorus concentrations were higher than 0.10 mg/L for most of the summer and were more than an order of magnitude greater than concentrations upstream from the Roseburg WWTP.

Few well-defined trends for DIN were evident except at the South Umpqua River near Roseburg, although DIN concentrations were more variable at South Umpqua River at Days Creek site than at most fixed stations downstream (fig. 15). Some high concentrations of DIN occurred in September 1992 near Brockway, a site that is well downstream from any known point sources. These high concentrations of DIN may have been caused by an unknown point source upstream from the site, ground-water input, or a decrease in algal uptake because of reduced algal metabolism upstream. Large mats of periphytic algae were not observed earlier in the season but had developed by mid-September 1992 at Brockway, where the streambed is unstable and normally would be considered unfavorable for periphyton growth.

Budget

In order to account for sources and sinks of nutrients (develop a nutrient budget), it was necessary first to develop a water budget for the South Umpqua River. A mass balance of known inflows and outflows to the South Umpqua River was calculated by using data from the synoptic surveys. Nonpoint sources (such as ground water, agricultural return flow, and subsurface flow) were not measured directly but were assumed to enter the system, during the normally dry months of summer, primarily through tributaries. The tributaries that were measured are shown in figure 3. The streamflows were simulated by using a simple mass-balance additive model and compared with measured (and gaged) streamflows recorded during the synoptic surveys. Upstream boundaries of the simulated streamflow system were the South Umpqua River at Tiller site (RM 187.3) during 1990 and 1991 and the South Umpqua River above Jackson Creek site (RM 192.8) in 1992; the downstream boundaries were either the South Umpqua River at Roseburg site (RM 118.0) or the South Umpqua River at Melrose Road site (RM 116.6), depending on streamflow conditions. The synoptic surveys of June and September 1991 are representative of early and late conditions, respectively (fig. 16).

Attempts were made to conduct synoptic surveys during steady-state conditions to minimize the effects of nonpoint runoff and unsteady flow. In locations where more than one measured streamflow value was available, the values are daily averages of the gaged streamflow over the duration of the synoptic survey. The differing daily averages illustrate variations in streamflow during the synoptic surveys and identify possible sources of error or inconsistency between the measured and simulated values.

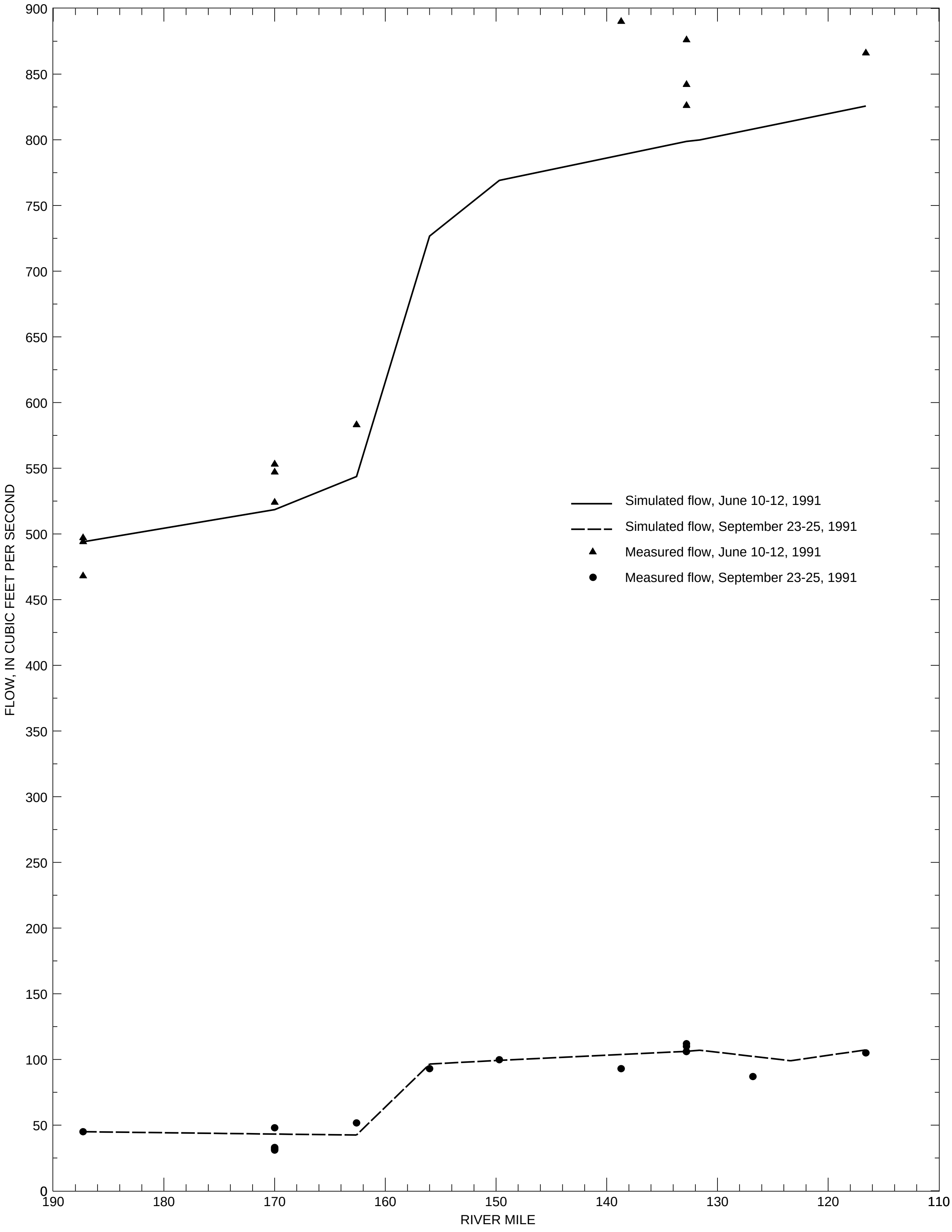

Figure 16. Measured and simulated flows in the South Umpqua River, Oregon, during synoptic surveys in June and September 1991.

Effluent samples from WWTPs were collected as grab samples in 1991 and as time-weighted composites in 1992 (Anderson and others, 1994). Effluent-discharge information was collected for the composite periods in 1992 and was reported by Anderson and others (1994); however, instantaneous discharge rates for the 1991 grab samples were unavailable. Calculations of effluent flows and nutrient loads for 1991, therefore, are based on daily total flow data reported to the State by each WWTP operator (table 1). During summer low-flow conditions, WWTPs contributed less than 15 percent of the streamflow to the South Umpqua River.

Data on permitted water withdrawals, derived from permit information provided by the Douglas County Watermaster, allowed estimation of maximum potential diversions. Water diversions were accumulated by reach into a withdrawal term. During spring, summer, and late fall, diversion amounts usually were set to zero. The withdrawal term in the mass balance was used as a model-calibration variable and, therefore, incorporated other uncertainties such as losses to evaporation and ground water or errors in flow measurements.

Ground-water data were not incorporated into the flow mass balance, because ground water has been previously reported to be a relatively small component of flow in the South Umpqua River (Rinella, 1986). In cases where the withdrawal term in the mass balance equals zero, the difference between the simulated and observed streamflow may be considered to represent a combination of ground water and other nonpoint-source inputs to the river. Dry conditions prevailed during the summers of 1991 and 1992, and few seeps or other small sources of flow were observed during reconnaissance studies (Anderson and others, 1994). Many of the tributaries, such as Elk Creek and Days Creek, were completely dry by late summer; the flows in other tributaries, such as Hamlin Creek, Myrtle Creek, and Deer Creek, were small enough to be almost negligible. Therefore, other nonpoint sources can be considered to be negligible in most cases, and ground-water input to the stream probably can be assumed to be the difference between simulated and observed values.

The synoptic surveys were conducted during reasonably dry periods, with the exception of one storm in May 1992. There were several storms prior to the June 1991 synoptic survey, but streamflow at gaged sites decreased during the survey. Except in May 1992, most of the simulated streamflows were within 10 to 12 percent, and many within 5 percent, of the measured or gaged flows. The relatively small error of the simulated values indicates that the major sources of water for the river were adequately accounted for, as were the major point sources of nutrients.

The pattern of streamflow in the South Umpqua River generally is consistent, regardless of conditions (fig. 16). The salient features are low flows upstream from Cow Creek (RM 160.0) and slight increases downstream from Cow Creek. The flow of Cow Creek is regulated by Galesville Reservoir, which provides a large part of the summer flow and maintains water quality. Flows in 1992 were the lowest during the 3-year study, reaching a daily mean of 32 ft^3/s at South Umpqua River near Tiller, 43 ft^3/s at Cow Creek near Riddle, and 64 ft^3/s at South Umpqua River near Brockway. Historically, base-flow discharge decreases between Tiller and Days Creek.

The nutrient budget was balanced by using the water-budget data. Because of the constant supply of nutrients flowing over the algae, measurement of periphyton response to nutrients necessarily requires nutrient loads and nutrient concentrations. In lentic (nonflowing) environments, the ambient concentration can be an indicator of algal response; in lotic (flowing) environments, the load also must be considered. Measured nutrient load, in kilograms per day, was the product of the observed flow and concentration at each site. Calculated nutrient loads for main-stem sites were the sum of influent load from upstream and incoming tributary and point-source loads. Loading from the Riddle WWTP was not added directly to the main-stem loading of the South Umpqua River, because the Riddle WWTP discharges into Cow Creek. In addition, the mouth of Cow Creek, downstream from the Riddle WWTP discharge location, was sampled during each trip. Nutrient loading at Cow Creek near the mouth represents the loading from the Riddle WWTP, combined with the load upstream from Riddle, minus the loads lost to periphyton in Cow Creek.

The error associated with calculated nutrient loads is dependent on the accuracy of the streamflow measurements and nutrient determinations (load = flow × nutrient concentration). In addition to this inherent error, observed streamflow measurements commonly were slightly greater than calculate streamflow; the disparity may have resulted from ungaged surface- and ground-water flows.

Nutrients associated with these ungaged flows will cause the observed nutrient loads to exceed the calculated loads. Differences between observed and calculated loads may decrease (and may be masked), however, if nutrients are being taken up by the biota or sorbed to the bed sediment.

Budget terms were calculated for TP, SRP, and DIN. DIN was used as the nitrogen term because algae can use nitrogen in either the oxidized (NO_3^-) or reduced (ammonia) form, and microbial and algal processes can rapidly change the form of DIN in the water through uptake, decay, and excretion. Calculated and observed nutrient loads for TP, SRP, and DIN for the synoptic surveys in June and September 1991 are shown in figure 17.

In the South Umpqua River, nutrient loads downstream from point sources were dependent on streamflow conditions. Nutrient loading data from the synoptic surveys (in June, July, August, and September 1991 and in September 1992) are summarized in table 6. Nutrient loading information for June and September 1991 is illustrated in figure 17. During June 1991, the period of highest flow studied during this project, WWTPs contributed 65, 73, and 70 percent of the TP, SRP, and DIN loading, respectively. Flow decreased during the summers in the drought years of 1991 and 1992, and the percentage of loadings from the WWTPs increased. During synoptic surveys in August and September 1991 and in September 1992, WWTPs contributed more than 90 percent of the TP, SRP, and DIN that entered the South Umpqua River. The relative contributions of nutrients from WWTPs probably are less during the winter months, when flow is greater and nutrient and periphyton problems are of less concern.

Nutrient loads from WWTPs (table 6) were calculated by using the instantaneous loads that were determined during individual synoptic surveys, rather than the median loads (table 5), to facilitate detection of load changes downstream from the WWTPs. Variability due to nitrification as an operating process at the Canyonville WWTP, alum addition at Winston-Green WWTP, or effluent flow changes at any of the WWTPs may have contributed to the small inconsistencies among the median nutrient loads in table 5 and the instantaneous nutrient loads in table 6.

During periods of high flow, such as June 1991, water originating from the Umpqua National Forest upstream from Tiller carried the largest nutrient load of the nonpoint or background sources (about 20 percent of the phosphorus and 13 percent of the nitrogen loads); Cow Creek carried the next largest load (table 6, fig. 17). As flows decreased during the summer and releases of water from Galesville Reservoir became the main source of water for the South Umpqua River, Cow Creek supplied a greater proportion of the nutrient load from nonpoint or background sources to the South Umpqua River. Several tributaries, such as Elk Creek and Days Creek, were dry or nearly dry by the end of each summer.

Calculated nutrient loads increased sharply at the point sources and slightly at tributaries (fig. 17). The measured loads increased at the WWTPs and decreased farther downstream, until additional sources produced load increases. This pattern was repeated both spatially and temporally. Unexpected sources or sinks of nutrients are indicated where the observed and calculated loads are not parallel (fig. 17). Because streamflow patterns (fig. 16) did not indicate major water losses, nutrient sinks probably represent uptake by the benthic community, especially periphyton. Unexpected nutrient sources may have been due to unsampled point sources, nonpoint sources, groundwater input, algal senescence, or analytical error. Analytical error can be ruled out in most cases except as it affects the magnitude of the sinks, because most of the loading changes appear consistently among constituents, between synoptic surveys, and along the length of the river.

Unexpected load increases (sources) were less predictable than load decreases (fig. 17). Several consistent increases, however, indicate possible load inputs unaccounted for in the synoptic surveys. One such increase occurred in the reach below Myrtle Creek, between the South Umpqua River at Mary Moore Bridge site (RM 143.3) and the South Umpqua River near Brockway site (RM 132.8). This load increase occurred in June 1991 for each constituent in table 6, as well as in August and September 1991 for DIN, in July and September 1991 and September 1992 for SRP, and in July 1991 for TP. However, the June 1991 increase occurred farther upstream—between Mary Moore Bridge (RM 143.3) and South Umpqua River at Dillard (RM 138.7)—than during other months, when the increase occurred between Dillard and Brockway. There seems to be an unidentified nutrient source between Mary Moore Bridge and Brockway.

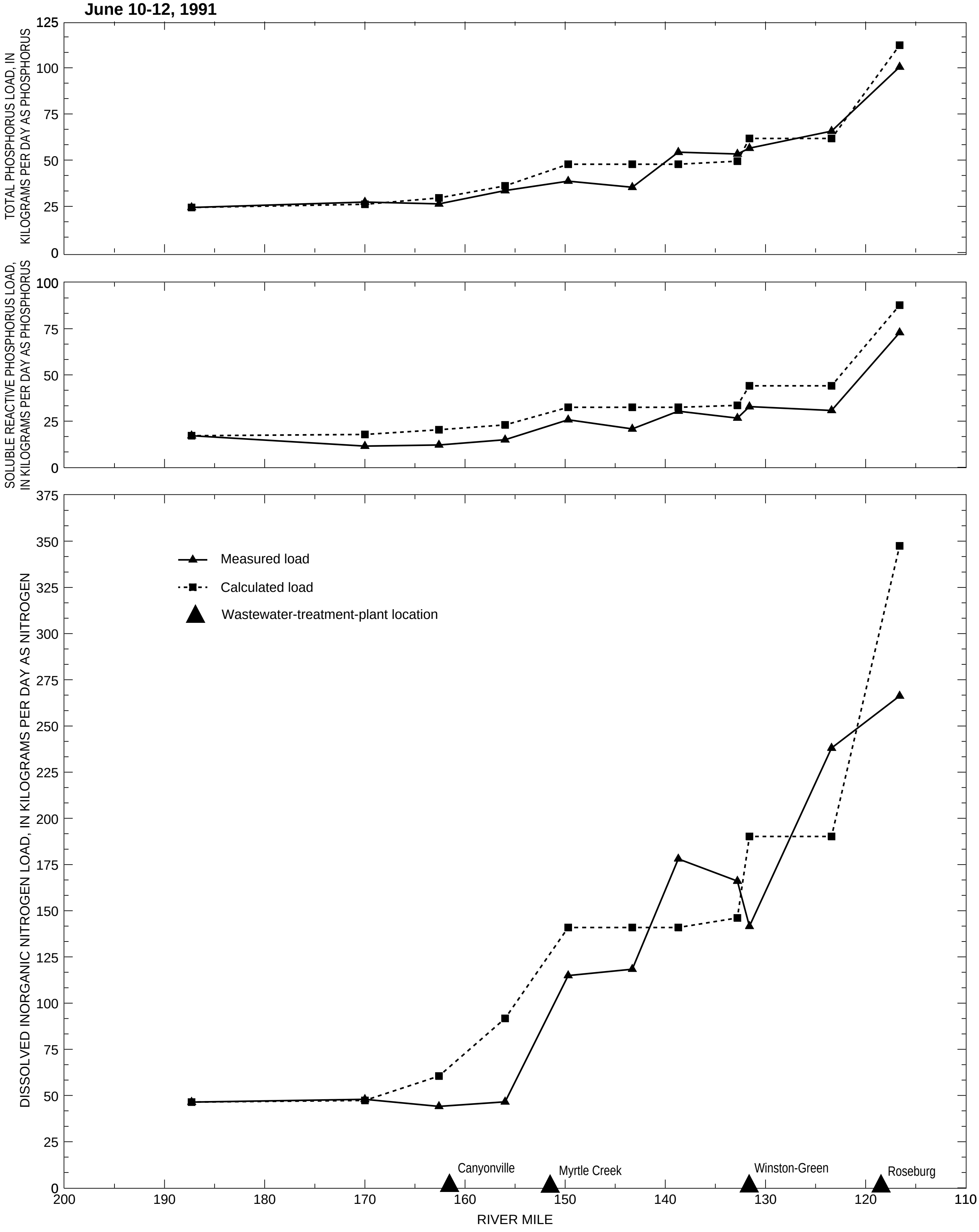

Figure 17. Measured and calculated nutrient loads in the South Umpqua River, Oregon, June and September 1991.

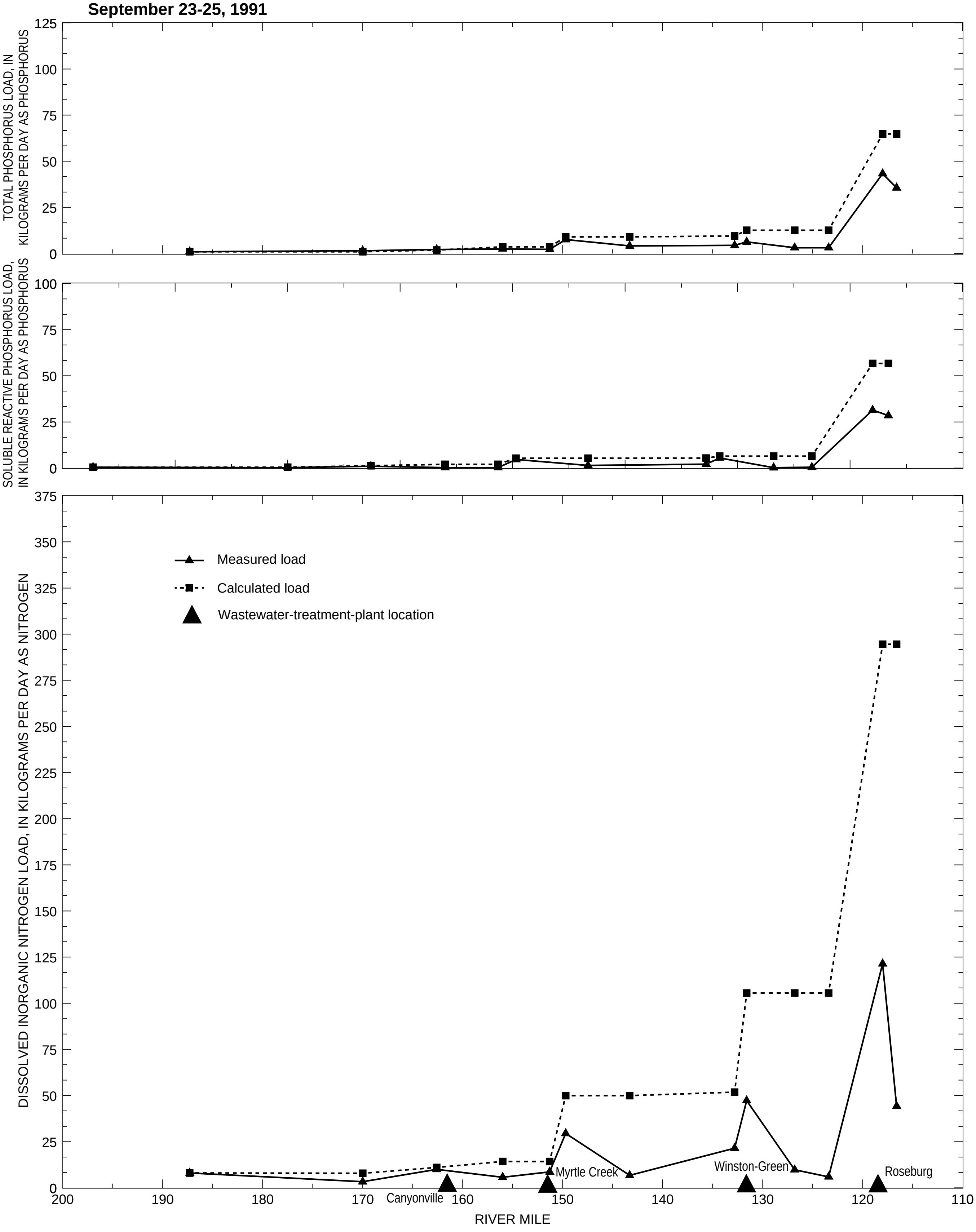

Figure 17. Measured and calculated nutrient loads in the South Umpqua River, Oregon, June and September 1991—Continued.

Table 6. Contributions of nutrient load to the South Umpqua River, Oregon, from various sources during synoptic surveys in 1991 and 1992

[Nutrient loading units are in kilograms per day. Discharges are averages from South Umpqua River near Brockway for the 3-day periods of the synoptic surveys. Q, discharge, in cubic feet per second (ft^3/s); WWTP, wastewater-treatment plant; TP, total phosphorus; SRP, soluble reactive phosphorus; DIN, dissolved inorganic nitrogen]

Source	Source type	June 10–12, 1991 Q = 840 ft^3/s			July 22–24, 1991 Q = 285 ft^3/s			August 26–28, 1991 Q = 137 ft^3/s			September 23–25, 1991 Q = 106 ft^3/s			August 31–September 2, 1992 Q = 75 ft^3/s		
		TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN
Canyonville	WWTP/ Point	2.1	2.0	9.2	0.4	0.3	8.5	3.3	3.0	9.0	2.2	1.8	7.1	1.3	1.2	2.0
Myrtle Creek	WWTP/ Point	10.2	9.0	40.9	7.2	7.0	45.3	5.3	4.5	33.4	10.9	6.8	69.5	9.0	8.2	34.4
Winston-Green	WWTP/ Point	12.3	10.6	44.2	2.0	.5	37.6	2.1	.7	46.3	2.2	.7	37.4	3.9	1.9	43.2
Roseburg	WWTP/ Point	48.1	42.8	150	50.3	44.3	155.7	52.0	48.0	160	56.6	53.8	204.1	53.4	41.4	187.2
South Umpqua River at Tiller	Tributary/ Nonpoint	24.4	17.1	46.4	4.1	1.4	5.5	1.5	.3	1.4	1.0	.4	8.0	.8	.2	1.8
Elk Creek	Tributary/ Nonpoint	1.7	.7	.9	.3	.2	.2	< .1	< .1	< .1	< .1	< .1	< .1	0	0	0
Days Creek	Tributary/ Nonpoint	.5	.2	< .1	.1	< .1	.1	< .1	< .1	< .1	0	0	0	0	0	0
Canyon Creek	Tributary/ Nonpoint	.9	.3	4.0	.1	< .1	.4	.1	< .1	.1	< .1	< .1	.1	< .1	< .1	< .1
Cow Creek	Tributary/ Nonpoint	6.6	2.6	31.2	4.9	2.0	6.3	2.5	.8	7.0	2.0	.7	3.8	1.2	.3	2.2
Myrtle Creek	Tributary/ Nonpoint	1.5	.5	8.3	.2	.1	1.1	.1	< .1	.6	.1	< .1	1.2	.1	< .1	.3
Lookingglass Creek	Tributary/ Nonpoint	1.6	1.0	5.1	.1	< .1	.1	.3	< .1	.4	.7	.1	2.3	.8	.1	1.8
Deer Creek	Tributary/ Nonpoint	2.4	.8	7.7	.4	.2	.4	.5	.1	1.6	.1	< .1	.1	< .1	< .1	< .1
Total		112.3	87.6	348	70.1	56.3	261.2	67.9	57.9	260	76	64.7	333.7	70.7	53.6	271.3

Data on ground-water quality along the South Umpqua River were sparse; however, data collected by Robison and Collins (1978) from several wells in the Winston area indicated that ground water may contribute to nutrient loads in the reach between Mary Moore Bridge and Brockway. Two shallow wells adjacent to the river (with depths of water-bearing zone of 34 to 57 feet and 22 to 28 feet, respectively) had relatively high NO_3^- concentrations (higher than 1.0 mg/L as nitrogen) and moderately high phosphate concentrations (from 0.03 to 0.12 mg/L as phosphorus). These wells were located within the reach from the South Umpqua River at Mary Moore Bridge site to the South Umpqua River near Brockway site. Streamflows in the reach frequently were slightly underestimated; therefore, ground-water input could explain the observed nutrient load increases between Mary Moore Bridge and Brockway.

Alternatively, the increased loading upstream from the South Umpqua River near Brockway site could have originated in one of three unsampled creeks (Willis Creek, Rice Creek, or Kent Creek) that enter the river along this reach; however, these creeks were not observed to contribute significant amounts of water during the 3-year study. Two gravel quarries, located along the river in this reach, may contribute nutrients associated with particulates from gravel mining operations at the edge of the river. In June 1991, loading increases for TP, SRP, and DIN were 18, 5.9, and 48 kg/d, respectively. The ratio of increase in DIN or SRP to TP at that site was lower in June 1991 than most DIN:TP or SRP:TP ratios for the river (table 7), indicating that the loading increase may have included a large amount of particulate or sediment from the gravel mining operations.

The other unexpected source of nutrients was in the Roseburg area, between Winston (RM 131.6) and sites upstream from the Roseburg WWTP (fig. 17). There were no known point sources in this long reach (up to 12 miles), which is located in the most urbanized part of the South Umpqua River Basin. The load increases were small in most cases and were downstream from load sinks located immediately downstream from the Winston-Green WWTP. These load increases may have been the result of analytical uncertainty, algal senescence, unmonitored point-source discharges, failing septic systems, urban runoff, or other nonpoint discharge.

More consistent than the unexplained nutrient sources in the South Umpqua River were the nutrient sinks located immediately downstream from each WWTP. In general, the water balance (fig. 16) indicated a negative bias regarding expected flow in the river; therefore, the magnitude of most nutrient sinks has been underestimated in this report. This loss of nutrients can best be explained by benthic (particularly algal) uptake of nutrients during the summer. There are no significant water diversions that could account for these nutrient losses. The loss of DIN was particularly pronounced. If nitrification were responsible for the loss of ammonia, an increase in NO_3^- load would be expected; however, such an increase was observed only occasionally below the Roseburg WWTP (Anderson and others, 1994). The difference between the simulated and observed increase in nutrient load was used to estimate the magnitude of uptake between selected sites (fig. 18; table 7).

Nutrient uptake was also observed in the Days Creek, Myrtle Creek, and Winston reaches during diel surveys in 1992. With the exception of the WWTP discharges and Myrtle Creek itself, the study reaches had no tributary inputs. Flow information and water samples were not collected for Myrtle Creek during these surveys; however, mass balances for the Myrtle Creek reach of the South Umpqua River could be reasonably calculated by assuming average loads from the creek on the basis of synoptic survey data. Owing to drought conditions in 1992, most tributaries, including Myrtle Creek, had little flow during the diel surveys in 1992, and ungaged input of water or nutrients was not considered to be significant.

Uptake of nutrients during diel surveys was similar in August and September 1992 for most nutrients and in most river reaches (table 7). Uptake of nutrients during June 1992 was less pronounced than in August and September, indicating either that algal growth had not yet reached its maximum or that periphyton was already undergoing a midseason decline. This phenomenon has been reported previously for *Cladophora* (Whitton, 1970; Lorenz and Herdendorf, 1982; Mantai and others, 1982). Because the spring of 1992 was dry and algal growth was established by May, it is probable that by June there had been an early peak in the biomass of *Cladophora*.

Table 7. Sources and sinks of total phosphorus, soluble reactive phosphorus, and dissolved inorganic nitrogen, South Umpqua River, Oregon, 1991 and 1992

[Includes results from synoptic surveys and diel studies. Nutrient loading values are expressed in kilograms per day. Discharges are averages from South Umpqua River near Brockway for the periods of the surveys. Negative values indicate unaccounted for sinks, positive values indicate unaccounted for sources. Q, flow; ft^3/s, cubic feet per second; TP, total phosphorus; SRP, soluble reactive phosphorus; DIN, dissolved inorganic nitrogen; ‘--’, reach not studied]

Reach and river miles	Synoptic surveys															Diel studies								
	June 10–12, 1991 Q = 840 ft^3/s			July 22–24, 1991 Q = 285 ft^3/s			Aug. 26–28, 1991 Q = 137 ft^3/s			Sept. 23–25, 1991 Q = 106 ft^3/s			Aug. 31– Sept. 2, 1992 Q = 75 ft^3/s			June 22–26, 1992 Q = 152 ft^3/s			Aug. 3–7, 1992 Q = 82 ft^3/s			Sept. 14–18, 1992 Q = 78 ft^3/s		
	TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN	TP	SRP	DIN
Jackson Creek to Canyonville																								
192.8–187.3	--	--	--	--	--	--	--	--	--	--	--	--	-0.5	-0.1	-0.1	--	--	--	--	--	--	--	--	--
187.3–170.0	0.2	-0.6	0.6	0.9	-0.4	0.0	-0.1	0.2	-0.3	0.6	-0.2	-4.6	-.2	-.1	-.1	--	--	--	--	--	--	--	--	--
170.0–166.8	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-0.2	0.0	4.6	0.1	0.1	7.7	0.2	0.0	11
166.8–165.3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	.2	.0	-2.5	-.1	-.1	-3.9	.0	-.1	-2.3
170.0–162.6	-3.4	-1.9	-17	-1.5	-.3	5.1	2.1	-.5	4.0	-.3	-.1	3.5	2.1	.1	.4	--	--	--	--	--	--	--	--	--
Canyonville to Myrtle Creek																								
162.6–156.0	.6	.2	-22	-1.5	-1.6	-12	-3.7	-.4	-8.1	-1.3	-1.4	-7.5	-1.3	-1.1	-1.1	--	--	--	--	--	--	--	--	--
162.6–151.3	--	--	--	--	--	--	-4.0	-1.7	-7.7	-1.6	-1.4	-4.6	-1.6	-1.1	-1.6	--	--	--	--	--	--	--	--	--
156.0–149.7	-6.7	1.4	-7.9	2.4	2.3	1.2	.8	-1.9	-34	-.3	-2.2	-12	-3.3	-4.3	-27	--	--	--	--	--	--	--	--	--
151.3–149.7	--	--	--	--h	--	--	-1.2	-.6	-34	-.1	1.0	-15	-3.0	-4.2	-27	2.0	-1.5	-2.2	-3.5	-2.8	-20	-3.5	-3.9	-18
149.7–146.6	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-3.0	-2.1	-13	-3.4	-3.6	-12	-.3	-1.5	-9.0
Myrtle Creek to Winston																								
146.6–145.2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-1.1	-2.1	-10	-.6	-.8	1.9	-1.0	-.8	10
149.7–143.3	-3.3	-5.0	3.5	-4.0	-6.0	-42	-5.8	-3.2	-16	-3.4	-3.2	-23	-.5	-3.2	-9.5	--	--	--	--	--	--	--	--	--
143.3–132.8	18	5.9	48	.5	2.3	-2.1	.05	-1.6	6.7	-.3	.6	15	-1.0	-.5	2.7	--	--	--	--	--	--	--	--	--
132.8–131.6	-9.2	-4.4	-69	-.5	2.3	-3.2	-0.6	-.3	-22	-1.3	2.4	-28	-1.8	-.8	-33	--	--	--	--	--	--	--	--	--
132.8–132.3	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-.2	-4.0	6.2	-8.9	-4.4	-54	-7.3	-2.5	-75
Winston to Roseburg																								
132.3–130.0	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	.3	-1.3	-31	-1.1	-2.6	-22	-2.6	-2.1	-28
130.0–126.6	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	-1.7	-1.0	-17	-1.5	-.4	-7.5	-1.0	-.4	-9.0
131.6–126.6	--	--	--	-3.5	-4.2	-37	-1.2	-7.2	-26	--	--	--	1.0	-.5	-14	--	--	--	--	--	--	--	--	--
131.6–123.4	9.2	-2.1	97	-1.3	3.5	-40	1.4	.7	-25	-3.1	-5.1	-41	7.5	-.9	-12	--	--	--	--	--	--	--	--	--
123.4–118.0	-13	-1.4	-130	--	--	--	--	--	--	-13	-20	-75	--	--	--	--	--	--	--	--	--	--	--	--
Roseburg to North Umpqua River																								
126.8–119.6	--	--	--	--	--	--	--	--	--	--	--	--	7.5	-.3	1.2	--	--	--	--	--	--	--	--	--
123.4–116.6	--	--	--	-5.4	-8.2	-122	-21	-32	-125	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
119.6–118.0	--	--	--	--	--	--	--	--	--	--	--	--	-31	-13	-83	--	--	--	--	--	--	--	--	--
118.0–116.6	--	--	--	--	--	--	--	--	--	-7.2	-3.0	-75	--	--	--	--	--	--	--	--	--	--	--	--
118.0–112.2	--	--	--	--	--	--	--	--	--	--	--	--	-.9	-2.2	--	--	--	--	--	--	--	--	--	--

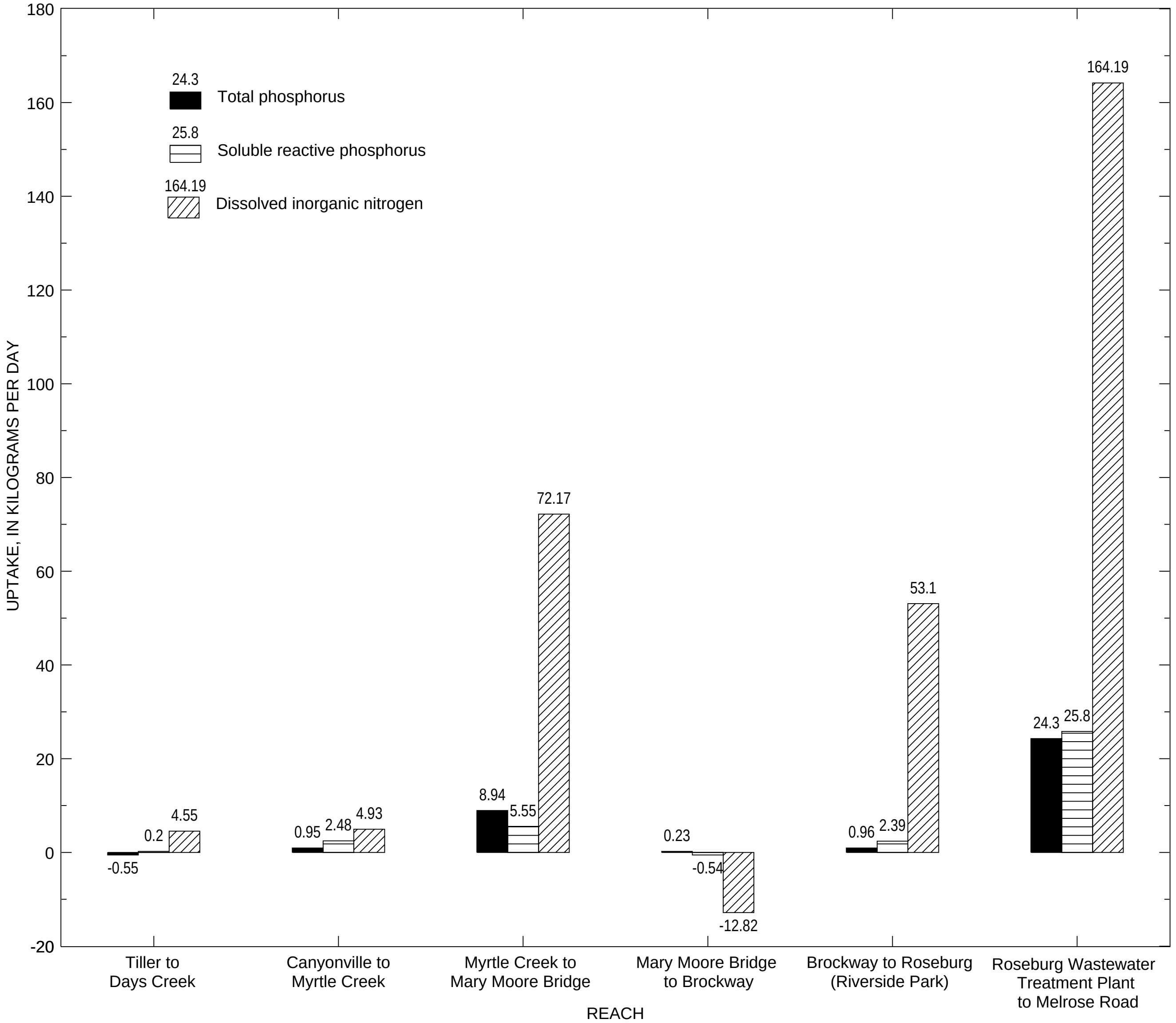

Figure 18. Uptake of nutrient load in selected reaches of the South Umpqua River, Oregon, September 23–25, 1991. (Positive differences in load indicate potential nutrient uptake; negative differences indicate potential nutrient sources.)

The removal of DIN by algae, particularly downstream from WWTPs, reduced DIN loads to low levels. During August and September 1992, the DIN load at Ruckles (RM 146.6) and at Oaks (RM 126.6) was lower than the DIN load above Morgan Creek (RM 165.3). DIN was apparently removed preferentially from the river compared with TP or SRP, indicating possible nitrogen limitation.

The nitrogen:phosphorus ratio is often used as an indicator of nutrient limitation; a value of approximately 7 indicates a proper balance in terms of algal physiological requirements for the two nutrients (Reynolds, 1984, p. 160–180; Welch, 1992, p. 131–141). However, this value has been shown to be variable; Shanz and Juon (1983) published a nitrogen:phosphorus ratio of 10 to 20, and DeVries and Hotting (1985) published a ratio of 7 to 10.

The concept of nitrogen or phosphorus limitation of algal growth must be qualified for the South Umpqua River. Given the large concentrations of nitrogen and phosphorus in some reaches, algal growth may not be limited by either nutrient. In those reaches, space, light, or water temperature may limit growth. Therefore, the concentration of a nutrient, as well as the nitrogen:phosphorus ratio, should be considered. Nevertheless, DIN:SRP ratios can be indicators of the potential for growth and the metabolic state of algae in the South Umpqua River.

Evidence of nitrogen limitation downstream from WWTPs can be found by examining the DIN:SRP ratios in these reaches (fig. 19). The DIN:SRP ratios in the Days Creek reach (RM 170–165.3) were high and increased in a downstream direction, indicating possible phosphorus limitation in this reach, particularly in September 1992. The sites upstream from the Myrtle Creek and Winston-Green WWTPs (RM 150.7 and 132.6, respectively), which are well downstream from any other known nutrient sources, appear to have phosphorus-limiting conditions as well. However, as more phosphorus is discharged from the WWTPs and nitrogen is used by periphyton communities, an apparent shift towards nitrogen limitation occurs in the reaches located immediately downstream from the WWTPs.

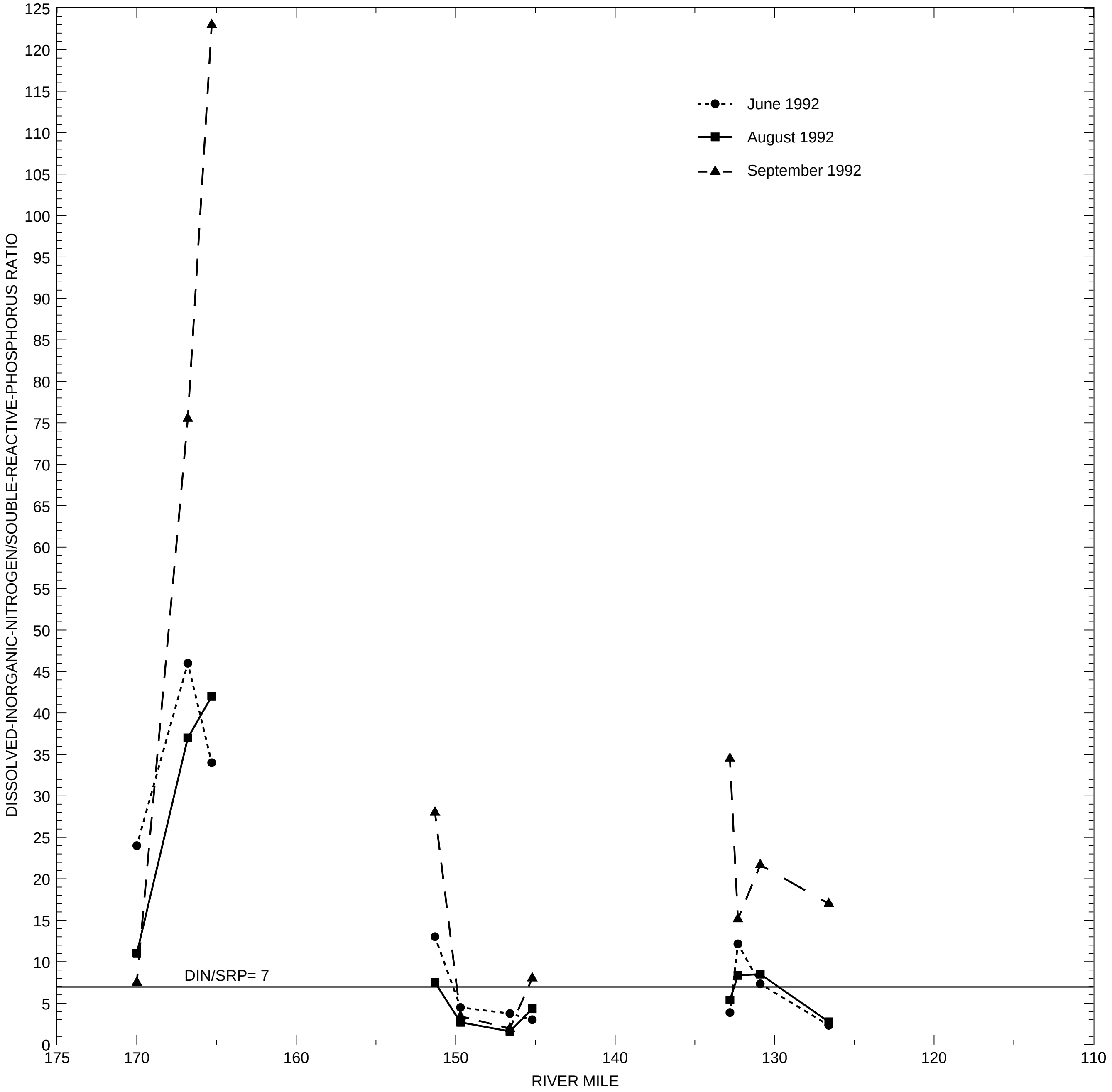

Figure 19. The ratio of dissolved inorganic nitrogen concentration (DIN) to soluble reactive phosphorus concentration (SRP), South Umpqua River, Oregon, 1992. (The horizontal line represents a ratio of 7. Points above this line indicate possible phosphorus limitation, whereas points below this line indicate possible nitrogen limitation.)

The shift from phosphorus limited to nitrogen limited, according to the DIN:SRP ratios, was less marked immediately downstream from the Winston-Green WWTP (RM 131.6) than immediately downstream from the Myrtle Creek WWTP (RM 150.7). The difference was probably due to the use of alum (aluminum sulfate) at the Winston-Green WWTP. Alum is a flocculant that precipitates solids, thereby reducing BOD and removing nutrients. Phosphorus removal from the Winston-Green-WWTP effluent (table 5) would move the system towards phosphorus limitation. Downstream from the Winston-Green WWTP, the DIN:SRP ratio continues to decrease until nitrogen apparently becomes limiting again (fig. 19). Two possible explanations for the decreasing ratio are (1) there is a source of phosphorus in the reach between Winston (RM 131.6) and Oaks (RM 126.6), or (2) algae use nitrogen from the river faster than algae use phosphorus, until the amount of nitrogen is reduced to a limiting level. Although some increases in phosphorus occurred in this reach during synoptic surveys (figs. 17 and 18), the increases were not consistent; at times, load decreases also were noted. Furthermore, TP and SRP loads decreased during the diel surveys in this reach. The decrease in DIN:SRP ratio below Winston, therefore, was due to rapid uptake of nitrogen by algae. The DIN:SRP ratio in the Winston reach in September 1992 was greater than 10 at all sites, indicating the potential for phosphorus limitation throughout the reach. Alum was not added on a regular basis at the Winston-Green WWTP, however, and the DIN:SRP ratio for this reach was probably more variable over time than for upstream reaches.

ALGAL BIOMASS AND PRODUCTIVITY

Algal biomass is a measure of the accumulation of carbon that is fixed by an algal community. Algal productivity is the net result of photosynthesis and respiration and apparently controls DO and pH fluctuations in most of the South Umpqua River. Photosynthesis during the day raises DO and pH; overnight respiration has the opposite effect (eqs. 4 and 5). Algal productivity is central to water-quality problems of the South Umpqua River but varies greatly seasonally and spatially. Two approaches were used to quantify algal productivity: measured biomass and calculated net aquatic-community productivity (of which algal productivity is a part).

The species of algae present and the composition of the associated macroinvertebrate communities are important to an overall understanding of algal ecology and water quality in the South Umpqua River. The dominant algal genera in the lower reaches of the river (below the city of Myrtle Creek at RM 150.0) included the filamentous green algae *Cladophora, Spirogyra,* and *Ulothrix* and the diatoms *Fragilaria, Cocconeis,* and *Epithemia* (Anderson and others, 1994).

All macroinvertebrate sampling was done downstream from Myrtle Creek. The most prevalent macroinvertebrate group was the midges (Insecta, Chironomidae). Also common were flatworms (Turbellaria, Planariidae), segmented worms (Oligochaeta), and snails (Gastropoda) (Anderson and others, 1994). Most of the macroinvertebrates observed are classified as collectors and gatherers. Therefore, with the possible exception of colonization of *Cladophora* tufts by chironomid midges (Power, 1991), a phenomenon that may occur in the South Umpqua River, the extent of macroinvertebrate grazing on the periphyton community may have been negligible. However, epiphytic diatoms (growing on or attached to filamentous algae) may have been effectively grazed by some of these invertebrates (Dodd, 1991).

Biomass

Although algal biomass is not a direct measure of productivity, it is the result of the net accumulation of carbon fixed by an aquatic community. Biomass can be defined as the quantity of living matter present at any given time, expressed as the mass of organic matter or chlorophyll per unit area or volume of habitat (Britton and Greeson, 1987, p. 307). Periphytic biomass in streams is extremely variable because algal growth is controlled by physical factors (light, substrate, and velocity), chemical factors (nutrient loading) and biological factors (grazing). In addition, because biomass tends to increase during the growth season, a single measurement does not indicate the rate of algal growth or accumulation. Algae were sampled using either Surber or Hess samplers, which were placed on the riverbed at representative locations (Anderson and others, 1994, p. 10). Biomass as ash-free dry weight ranged from 4 to 340 grams per square meter and increased in a downstream direction (fig. 20), indicating that algal biomass is positively correlated with nutrient loading. Biomass generally was larger in September than in June or August of 1991 and 1992, indicating that periphytic algal growth is cumulative and that larger biomass measurements would be expected towards the end of the growing season (in September).

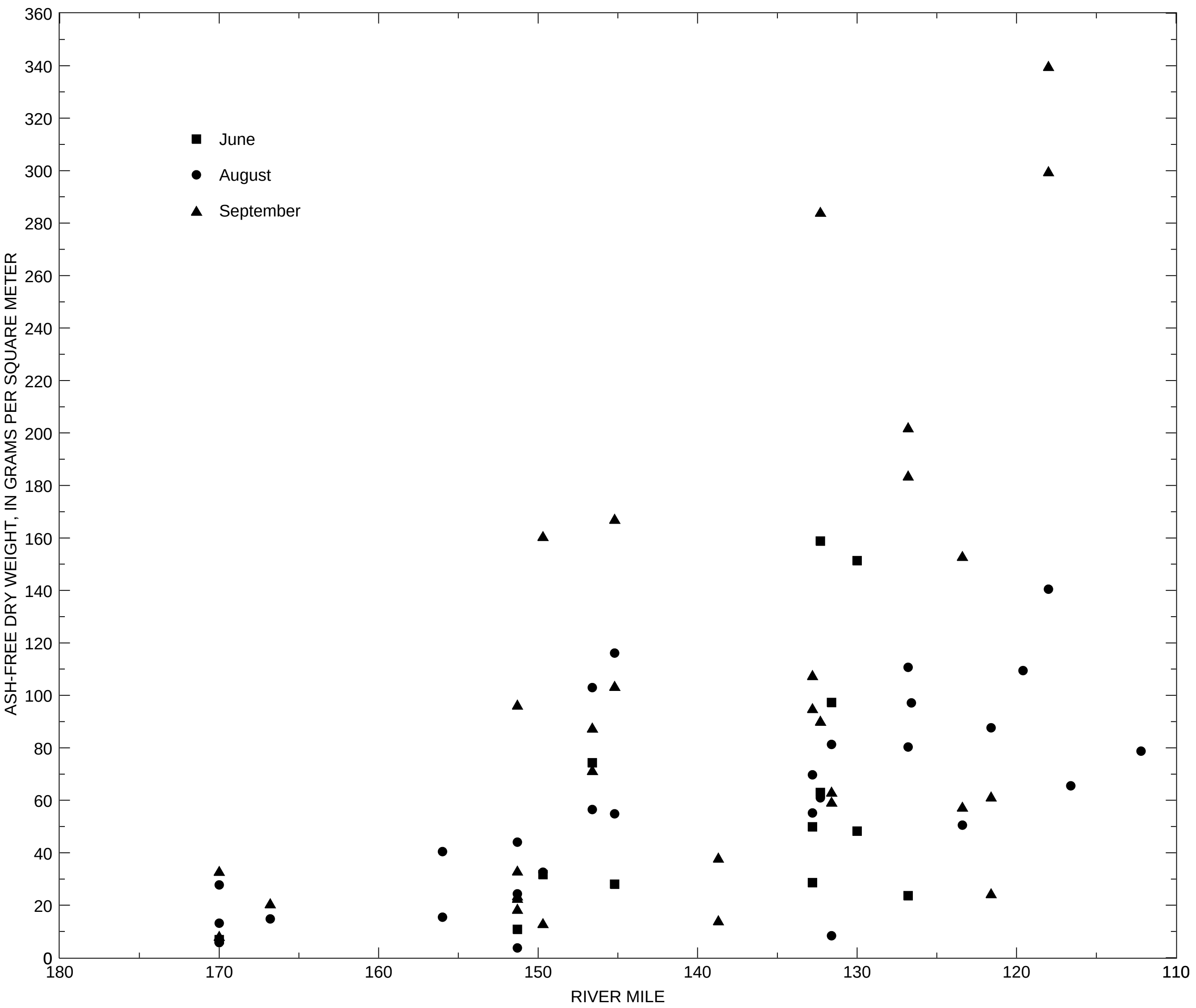

Figure 20. Biomass (as ash-free dry weight) in the South Umpqua River, Oregon, June, August, and September 1991 and June, August, and September 1992. (Sample size is 72.)

Exceptions to this seasonal pattern could be caused by (1) temporary scour events from rainstorms, (2) early growing seasons, as in 1992, that might result in an earlier achievement of a “steady state” biomass, or (3) the bimodal growth pattern of *Cladophora*, wherein an initial biomass peak in early summer may be followed by a partial decline in biomass during midsummer and a subsequent late season biomass maximum (Bellis and McLarty, 1967; Whitton, 1970).

Productivity

Net productivity is the difference between total photosynthesis and respiration. Net productivity was calculated by using a two-station analysis of diel oxygen curves, as described by Odum (1956) and Vollenweider (1974). Reaeration coefficients were calculated from the O’Connor and Dobbins (1958) formula for reaeration and based on time-of-travel and reaeration studies done in the South Umpqua River Basin in 1991 (Laenen and Woo, 1994). Reaeration was calculated rather than measured because flow conditions were different at the time of the diel surveys than flow conditions during the reaeration studies. Physical characteristics for each reach (depth, width, and velocity) were assigned on the basis of reconnaissance surveys of the reaches (Anderson and others, 1994) and adjusted for flow differences. These characteristics and the calculated reaeration coefficient are shown in table 8.

Table 8. Physical characteristics of the South Umpqua River, Oregon, June 22–26, August 3–7, and September 14–18, 1992

[Average width for each segment was computed from relations of stream discharge and cross-sectional width. Average depth for each segment was determined as the quotient of stream discharge and computed stream width. Average velocity for each segment was computed from relations of stream discharge and velocity and corrected according to travel times determined by dye studies (Laenen and Woo, 1994). Reaeration coefficients were determined through the use of the formula by O'Connor and Dobbins (1958), which was previously shown to be applicable to the South Umpqua River (Laenen and Woo, 1994). ft^3/s, cubic feet per second]

	Discharge (ft^3/s)			Average width (feet)			Average depth (feet)			Average velocity (feet/second)			Reaeration coefficient, k_2 (per day)		
Reach segment and river mile	June 22–26	August 3–7	September 14–18	June 22–26	August 3–7	September 14–18	June 22–26	August 3–7	September 14–18	June 22–26	August 3–7	September 14–18	June 22–26	August 3–7	September 14–18
Days Creek Reach															
170.0–166.8	85	50	33	115	110	105	1.7	1.5	1.4	.44	.30	.22	4.14	4.12	3.91
166.8–165.3	85	50	33	85	81	78	2.3	2.8	2.2	.44	.22	.19	2.63	1.38	1.85
Myrtle Creek Reach															
151.3–149.7	131	77	66	126	117	115	4.9	4.7	4.4	.21	.14	.13	.58	.51	.54
149.7–146.6	131	77	66	130	125	122	4.0	4.1	4.2	.25	.15	.13	.86	.65	.58
146.6–145.2	131	77	66	210	192	188	3.0	2.7	2.5	.21	.15	.14	1.22	1.21	1.31
Winston-Green Reach															
132.8–132.3	135	76	76	190	170	170	2.4	2.1	2.1	.30	.21	.21	2.04	2.08	2.08
132.3–130.0	135	76	76	195	175	175	3.6	4.0	4.0	.19	.11	.11	.88	.57	.57
130.0–126.6	135	76	76	220	195	195	2.6	2.6	2.6	.24	.15	.15	1.61	1.28	1.28

Results from net aquatic-productivity calculations are given in table 9. Each value represents productivity in the stream segment immediately upstream from that site; a reach with four data-collection sites, therefore, will have three values available for productivity calculations. The results of the productivity calculations are in general agreement with the patterns of other water-quality parameters measured in the South Umpqua River during the diel surveys. That is, there is a trend toward increasing productivity downstream, and the greatest productivity is immediately downstream from point sources of nutrients. The magnitudes of these net productivity values also were similar to those found for periphyton in the Willamette River (Gregory, 1993), but maximum productivities in the South Umpqua River (2–4 grams of oxygen per square meter per day) were slightly larger than the maximum productivities in the Willamette River (1.5–2.5 grams of oxygen per square meter per day).

Table 9. Net aquatic-community productivity, South Umpqua River, Oregon, June 22–26, August 3–7, and September 14–18, 1992

[Productivity was determined by using 24-hour measurements of oxygen and a two-station analysis as outlined by Odum (1956); g $O_2/m^2/d$, grams of oxygen per square meter per day; '--', missing data]

Reach	Stream segment (river mile)	Net aquatic-community productivity (g $O_2/m^2/d$)		
		June 22–26	August 3–7	September 14–18
Days Creek	170.0–166.8	-0.82	--	-0.44
	166.8–165.3	-.83	--	.32
Myrtle Creek	151.3–149.7	-.18	1.31	.87
	149.7–146.6	.02	-.68	.65
	146.6–145.2	1.42	.21	.29
Winston	132.8– 132.3	.38	--	3.42
	132.3–130.0	2.10	3.77	1.95
	130.0–126.6	.61	.88	.72

Few seasonal trends in productivity were observed in 1992, possibly because of drought (fig. 21). Lower than normal streamflows could have caused the maximum productivities to be reached earlier in the summer in many parts of the stream, with the remainder of the summer consisting of various cycles of decay and regrowth (maintenance of biomass). A negative net productivity indicates that a reach had greater respiration than productivity, suggesting that respiration by aquatic animals or bacteria, rather than by algae, was predominant. Negative net productivity occurred most frequently in the upstream reaches (particularly near Days Creek), which is consistent with the conceptual model of a less eutrophic environment upstream of nutrient inputs from the first significant WWTP in Canyonville. Uptake of DIN was well correlated with net productivity during September 1992.

RELATIONS AMONG WATER QUALITY, NUTRIENTS, AND PRODUCTIVITY

During the study period exceedances of the State standards for DO and pH generally increased in frequency and magnitude in a downstream direction in the South Umpqua River (figs. 9 and 11) and in summer (figs. 10 and 12). Nutrient dynamics have been detailed, and increasing downstream concentrations, loads, and uptake were noted for phosphorus and nitrogen (figs. 15, 17, and 18). Finally, net aquatic-community productivities calculated for three reaches were found to increase in a downstream direction (fig. 21).

A problem encountered when investigating nutrient, DO, and pH relations in a system such as the South Umpqua River, where large loads of nutrients are lost to uptake and storage within algal mats, is that the measurement of a nutrient concentration (or load) at a site is, in most cases, an underestimate of the actual amount of nutrient that is either available, stored, or transported in that reach. As a result of the potential for rapid recycling of low concentrations of nutrients in streams that support large growths of periphytic algae (Mulholland and others, 1991; Mulholland and Rosemond, 1992), as well as of the unmeasured load exported in unsampled, drifting mats of algae, much of the nutrient-processing capacity cannot be assessed when stream water is sampled at a point. For that reason, nutrient properties other than ambient water-column concentrations or loads were used to determine relations among DO, pH, and productivity. These properties include nutrient uptake and upstream nutrient concentrations. Uptake provides a measure of the metabolic activity that has occurred between two sites, whereas the concentration at an upstream site represents the amount of nutrients available for uptake within the reach between the two sites.

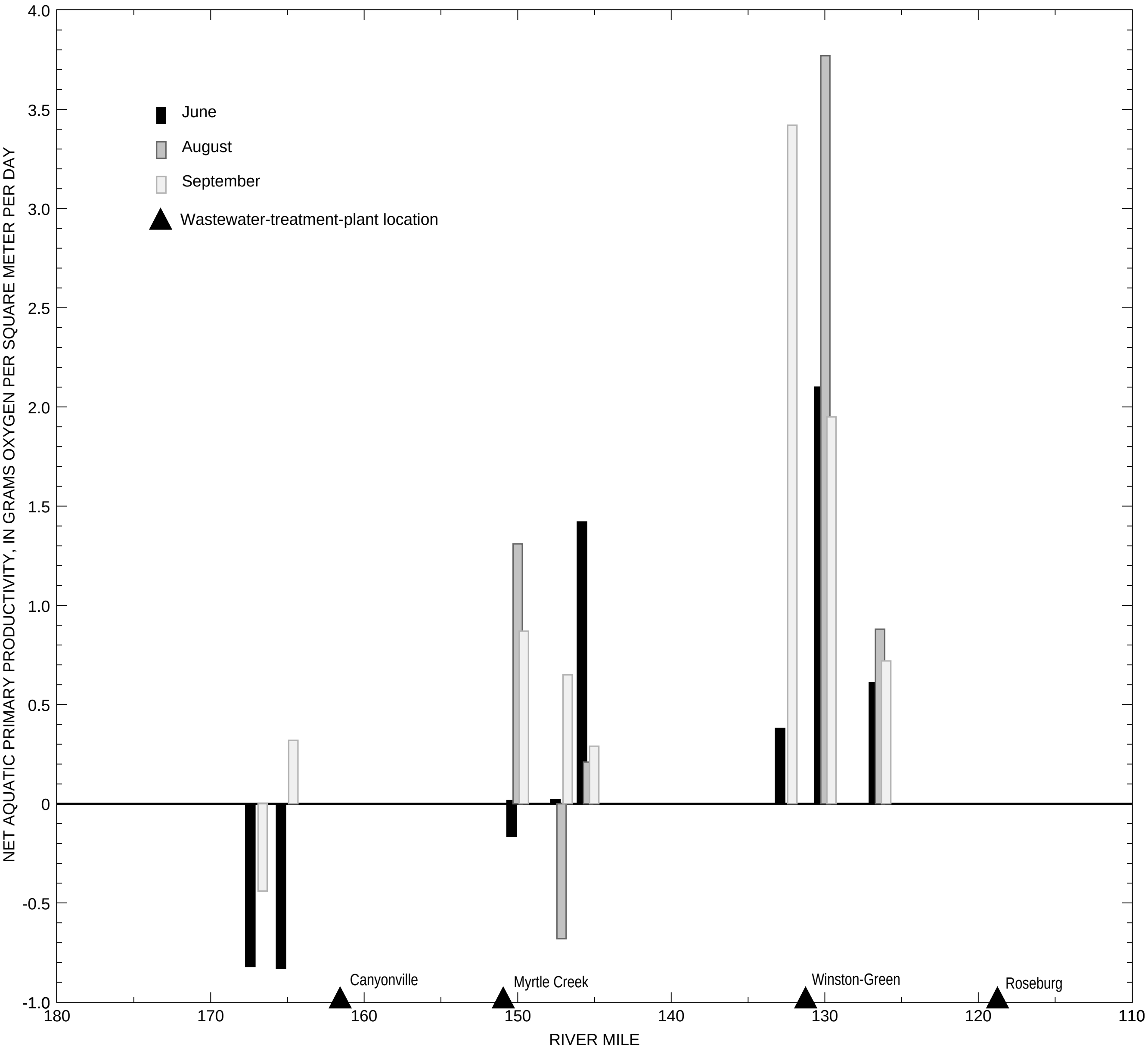

Figure 21. Net aquatic productivity during diel surveys, South Umpqua River, Oregon, 1992, as calculated from two-station analysis of 24-hour oxygen curves.

Although nutrient uptake and upstream nutrient concentrations represent parts of the nutrient budget that are not included in measurements of nutrient concentrations in the water column, they still may not fully quantify the availability of nutrients to algae because of unmeasured recycling processes.

The 1991 and 1992 distributions of daily minimum DO values and their associated nutrient concentrations indicate several relationships (fig. 22). For median SRP, TP, and DIN concentrations higher than 0.04, 0.06, and 0.18 mg/L, respectively, all sites exceeded the State standard for minimum DO. These SRP, TP, and DIN concentrations might be considered extremely low in some river systems; however, in the South Umpqua River, these concentrations were within the 85th to 95th percentile range of the concentration distributions and occurred almost exclusively at the fixed station in Roseburg (RM 118.0). At lower concentrations of SRP, TP, and DIN, the frequency of DO standard violations decreased slightly, but for almost any given concentration, more than 50 percent of the samples had DO concentrations that were in violation of the State standard. This pattern was similar for exceedances of the State standard for pH as well.

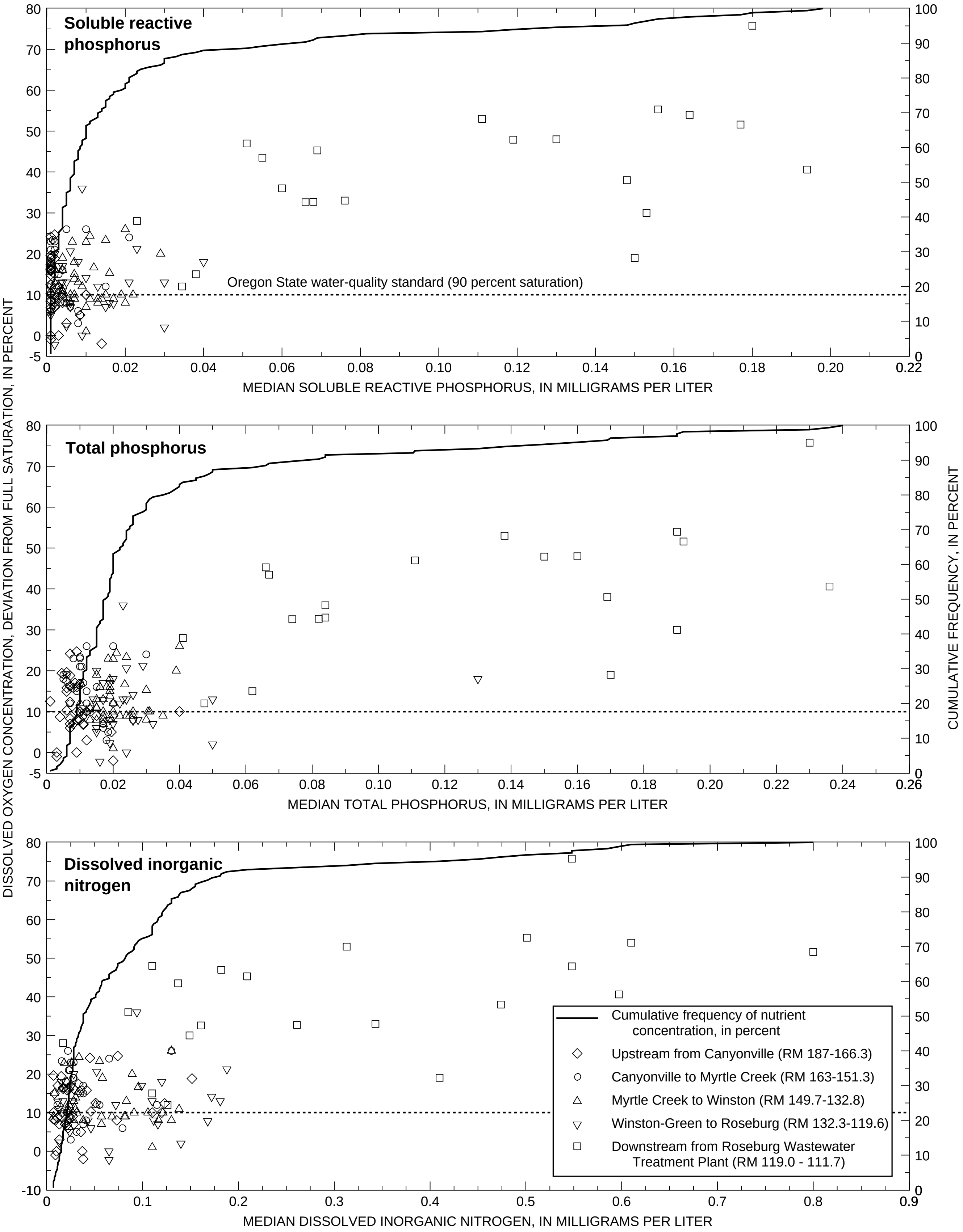

Figure 22. Deviation from saturation of daily minimum dissolved oxygen concentration and associated median concentration of soluble reactive phosphorus, total phosphorus, and dissolved inorganic nitrogen in the South Umpqua River, Oregon, 1991 and 1992.

The reason that 100-percent violations of the DO standard at high nutrient concentrations occurred mostly at the Roseburg site was that such high nutrient concentrations were not observed in any other reach of the river. When upstream nutrient concentrations are considered, however, a larger number of sites fall into the 100-percent violation category, including reaches below both Myrtle Creek and Winston (fig. 23). This is because the upstream nutrient concentration takes into account the concentration immediately below point sources. When upstream nutrient concentration data are used, 100-percent violations of the DO standard occurred at SRP, TP, and DIN concentrations greater than 0.03, 0.05, and 0.2 mg/L, respectively. Again, however, concentrations of those magnitudes are common in the South Umpqua River, falling within the 80th–90th percentile range of upstream concentrations calculated in the South Umpqua River for 1990–92.

Figure 24 shows the percentage of DO and pH measurements exceeding State standards for ranges of calculated upstream SRP, TP, and DIN concentrations; each range of concentration is based on at least 10 measurements made during synoptic surveys (figs. 9 and 12). DO and pH standards generally were exceeded in more than 50 percent of the measurements, even at low nutrient concentrations. The frequency of violations increased with increasing nutrient concentrations.

Linear regression analyses of daily minimum DO and daily maximum pH were evaluated for relations with nutrient concentrations, both at a site and at the next site upstream, for all samplings on the main stem of the South Umpqua River. None of these regressions produced correlations that would indicate that more than about 50 percent of the variability could be explained by individual nutrient concentrations. Segregation of the data by low or high N:P ratio (nitrogen or phosphorus limited) produced small but insignificant increases in correlation. The low correlations could have been caused by the preponderance of observed nutrient concentrations that were either very low or very high (75th percentile concentrations of upstream SRP, TP, and DIN were 0.025, 0.035, and 0.11 mg/L, respectively). Samples with intermediate nutrient concentrations, necessary for statistically meaningful correlations, were sparse.

Regressions of net productivity relative to DIN, TP, and SRP uptake loads measured in June, August, and September 1992 and in September 1992 alone were done to determine possible correlations (table 10). DIN uptake was correlated most closely with algal productivity during the low-flow period of September 1992. Uptake of TP was highly correlated with productivity ($r^2 = 0.83$) when all data points for September were considered; however, the correlation was due primarily to the value from the reach immediately below the Winston-Green WWTP. Removal of this data point resulted in a correlation that was significantly reduced ($r^2 = 0.43$). In contrast, the close correlation of DIN uptake with productivity ($r^2 = 0.86$) was not greatly affected by removal of the outlying data point ($r^2 = 0.74$), indicating that the overall relation of productivity to uptake of DIN was stronger than for TP. Results of a regression analysis of productivity and SRP uptake indicated a poor correlation between the two variables; the correlation was changed little by omitting the outlying data point from the Winston reach. The cause of the poor correlation may have been that concentrations of SRP in many stream samples were at or below the minimum reporting levels for the analysis; uptake determinations, therefore, may have been erroneous. Rapid recycling of low concentrations of phosphorus from nonpoint sources in phosphorus-limited reaches may mask the true nutrient inputs, thus contributing to errors in SRP uptake estimates.

Data from September 1992 provided the best overall fit between nutrients and productivity. Pooled linear regressions of all productivity calculations relative to DIN uptake from all surveys yielded a regression coefficient of 0.56; whereas, regressions with phosphorus for uptake, concentration, concentration at upstream sites (assuming instantaneous mixing at WWTP-outfall locations), instream loads, and reach-area-adjusted loads failed to produce coefficients larger than 0.50.

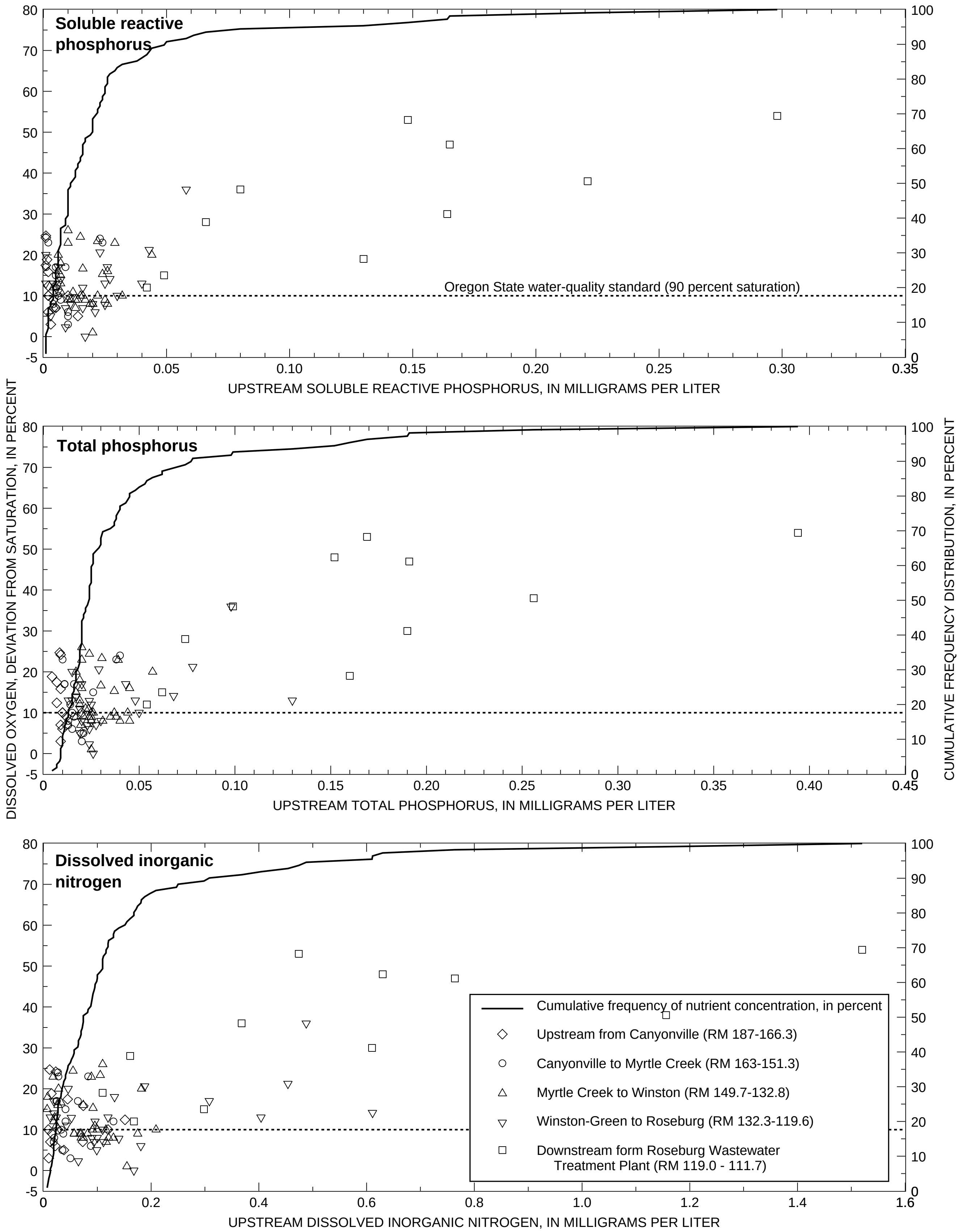

Figure 23. Deviation from saturation of daily minimum dissolved oxygen concentration and associated median upstream concentration of soluble reactive phosphorus, total phosphorus, and dissolved inorganic nitrogen in the South Umpqua River, Oregon, 1991 and 1992.

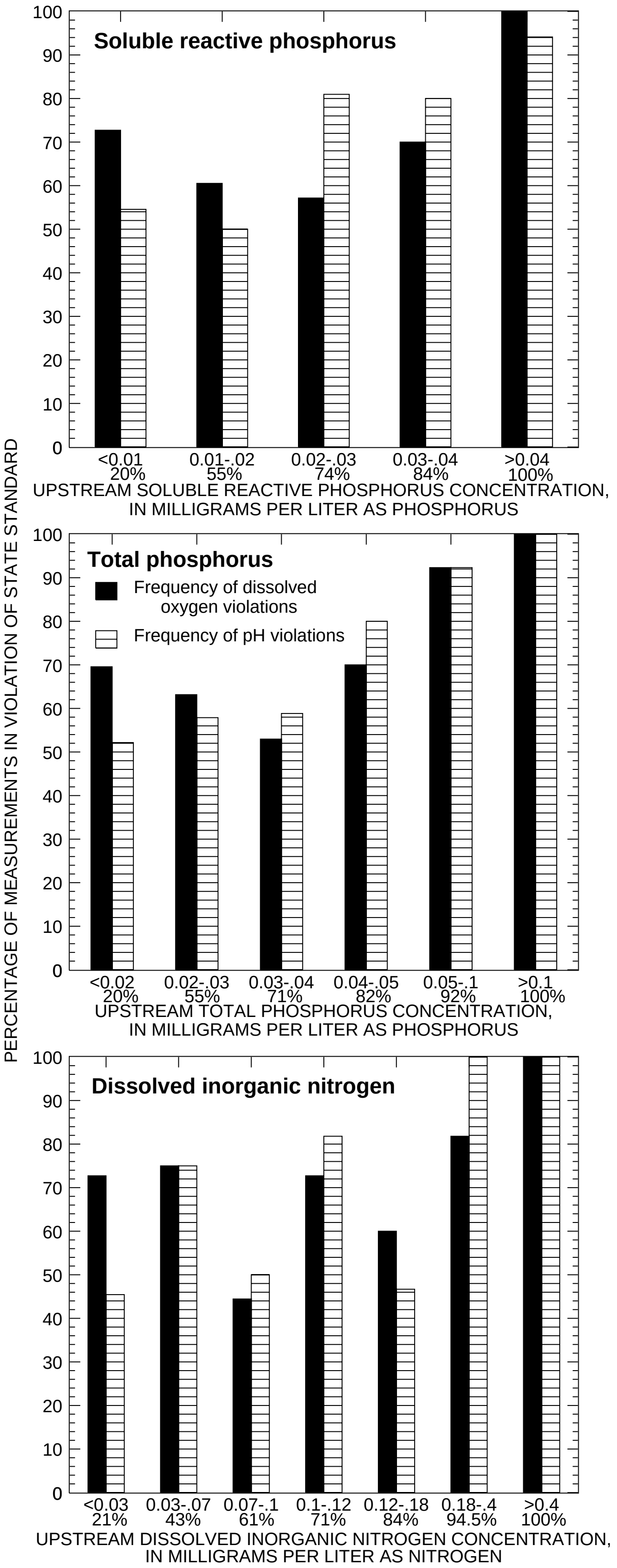

Figure 24. Percentage of dissolved oxygen and pH values in violation of Oregon State standards for ranges of upstream concentrations of soluble reactive phosphorus, total phosphorus, and dissolved inorganic nitrogen in the South Umpqua River, Oregon, 1990–92. (Percentage shown beneath concentration is cumulative frequency of nutrient concentrations.)

Table 10. Correlation coefficients from linear regressions of net productivity and nutrient uptake, South Umpqua River, Oregon, 1992

[DIN, dissolved inorganic nitrogen; TP, total phosphorus; SRP, soluble reactive phosphorus; n, number of samples; RM, river mile. One TP value from September 1992 at RM 132.3 was considered an outlier]

Diel survey data set	DIN uptake	DIN and TP uptake	TP uptake	SRP uptake
September 1992 (n = 8)	0.86	0.91	0.83	0.26
September 1992, without RM 132.8-132.3 (n = 7)	.74	.73	.43	.25
June, August, and September 1992 (n = 20)	.56	.56	.18	.09

MANAGEMENT ALTERNATIVES

Nutrient loading to the South Umpqua River has caused the river to become eutrophic and has limited the beneficial uses of the river. Preceding discussions have demonstrated that the proliferation of periphytic algae in the South Umpqua River is the result of nutrient loadings to the river (fig. 7). Nuisance growths of algae degrade the quality of the river water by causing low concentrations of DO in the morning and high values of pH in the afternoon.

Possible management alternatives for the South Umpqua River that would reduce point-source nutrient inputs include flow augmentation, land application and storage of WWTP effluent, and reduction of nitrogen and (or) phosphorus loading from WWTP effluent (tertiary treatment). Tertiary treatment commonly is used to reduce nutrient loading to receiving water. Tertiary treatment may include biological oxidation of ammonia to nitrate (nitrification) and subsequent biological reduction of nitrate to nitrogen gas (denitrification); phosphorus can be removed by biological and chemical methods.

The most significant water-quality problems in the South Umpqua River occur during the algal growing season (generally from May through October). A reasonable time period for management of water quality in the South Umpqua River, therefore, is May 1 to October 1 (summer). Median monthly streamflow at the South Umpqua River near Brockway is 1,610 ft^3/s in May and reaches a low of 114 ft^3/s in September (Moffatt and others, 1990).

This discussion of management alternatives assumes that nutrient loadings remain similar to levels observed in 1990–92. For example, the DIN concentration in the effluent of the Canyonville WWTP (RM 163.0) was consistently low (median concentration of 3.2 mg/L) during the summers of 1991 and 1992 (table 5). If these conditions were to change significantly, such that DIN in the WWTP effluent increased to levels similar to the other major WWTPs in the South Umpqua River Basin, the nitrogen loading to the South Umpqua River below Canyonville would change and could have effects downstream in terms of DO and pH exceedances. DO and pH exceedances may also occur if phosphorus removal using alum, a process currently employed for BOD removal at the Winston-Green WWTP, is discontinued.

Flow Augmentation

Flow augmentation is frequently used as a partial solution to water-quality problems. In the South Umpqua River, a relation exists between stream discharge and the magnitude of problems associated with algae, such that higher flows during late spring and early summer have resulted in higher minimum DO and lower maximum pH. However, the effectiveness of flow augmentation may vary considerably from year to year because of variation in light, temperature, and length of the growing season.

The May 1 to October 1 periods of 1990–93 represent a typical range of summer flow conditions in the South Umpqua River Basin. Mean daily discharges at the South Umpqua River near Brockway (RM 132.8) during these summers were 464, 848, 229, and 1,247 ft^3/s, respectively (U.S. Geological Survey, 1991–94), indicating that flows in 1993 were substantially greater than those in the previous three summers and that flows during 1992 were substantially less than in 1990, 1991, and 1993. Data from 1993 were used even though data collection specifically for this study ended in fall 1992, because 1993 was the first relatively wet summer after 1986, when modification were made to the Roseburg WWTP. During the intervening years, persistent drought conditions caused low flows in the South Umpqua River.

Water-quality data recorded at South Umpqua River near Roseburg during the summers of 1990–93 indicate the effects of summertime flow on water quality (fig. 25). During 1993, the median of the daily mean water temperatures at the Roseburg station was approximately 2°C cooler than in 1992 and slightly cooler than in 1991 and 1990. Also, the extremely warm temperatures (greater than 25°C) recorded during 1990–92 occurred less frequently and cooler temperatures (less than 17°C) occurred more frequently than in the previous three summers. In contrast, daily mean water temperatures in 1992 were higher and the distribution was narrower than in previous years, suggesting that 1992 represented the most stable (and degraded) conditions during the 1990–93 time period.

In 1993, the high summer flows and low stream temperatures in the South Umpqua River Basin resulted in increased DO concentrations; the daily DO minimum was greater than 80 percent of saturation on more than one-half of the days, and no measurements of less than 60 percent saturation were recorded (fig. 25). However, although conditions improved in 1993, only about 15 percent of the DO minima did not fall below the State standard of 90 percent saturation. Almost all nonexceedance days were in May 1993, and August–October daily minimum DO concentrations always violated the 90-percent standard. Of the 4 years studied (1990 to 1993), flows were lowest in 1990 and 1992. DO concentrations were lowest during the summers of 1990 and 1992, and extremely low concentrations of DO (less than 50-percent saturation) occurred more frequently during 1990 and 1992 than during 1991 and 1993.

Daily maximum pH also improved (decreased) when flows increased in 1993. Exceedances of the State standard for pH (8.5 units) were recorded on only one-half of the days at the Roseburg site, and the maximum recorded pH was 9.0. During 1992, nearly as many measurements of daily maximum pH exceeded 9.0 as met the State standard. The year 1991 was an intermediate flow year and had exceedance patterns that were also intermediate to the extremes of pH in 1992 and 1993.

Although it appears that the high flows in 1993 were at least in part responsible for improvements in water quality at the Roseburg site, it is unclear to what extent this improvement may have been due to decreased light availability. High flows that result from summer rainstorms might be associated with reduced light due to an increase in cloud cover.

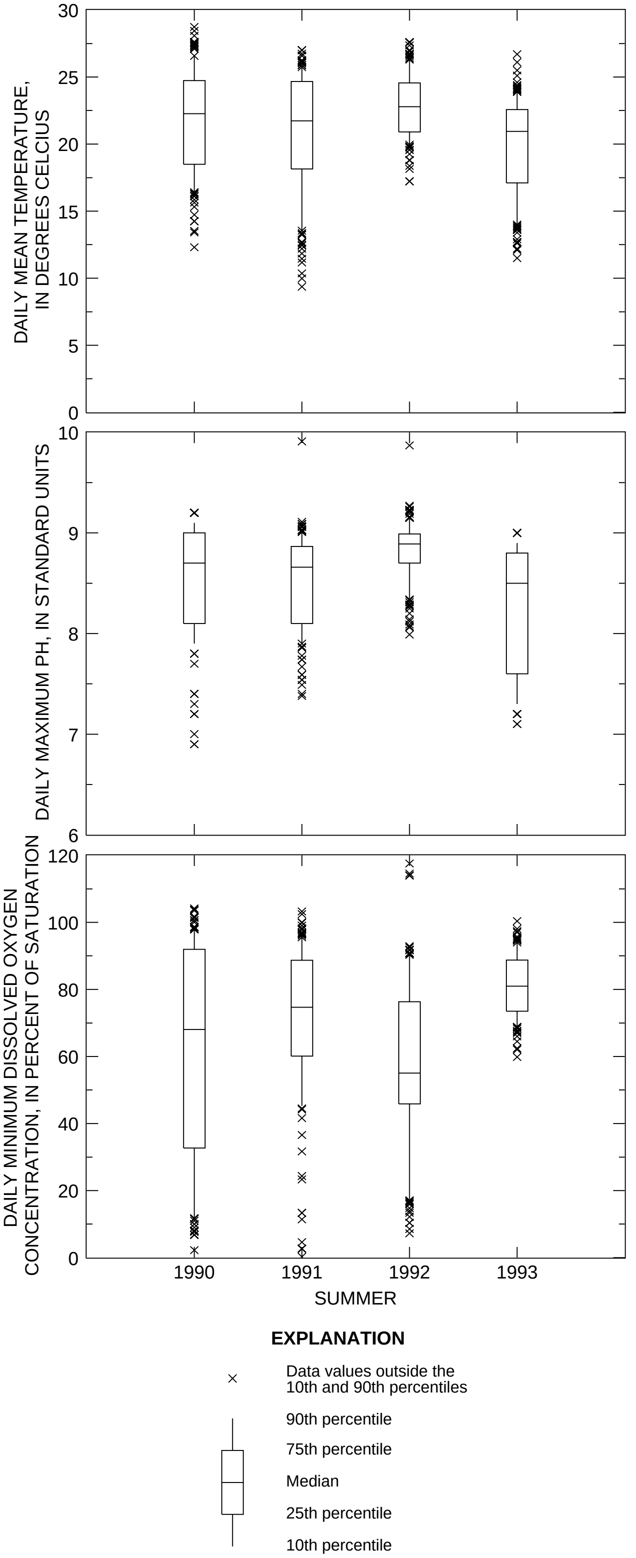

Figure 25. Daily mean water temperature, daily minimum dissolved oxygen concentration, and daily maximum pH near Roseburg, Oregon, from May 1 to October 1, 1990, 1991, 1992, 1993. (Mean daily discharge at the Brockway gaging station was 464, 848, 229, and 1,247 cubic feet per second in 1990, 1991, 1992, and 1993, respectively.)

Algal productivity can be correlated with light availability (Gerloff and Fitzgerald, 1976; Graham and others, 1982; Wootton and Power, 1993); thus, decreased light availability could partially account for the apparent decrease in algal activity at the Roseburg site. This correlation is important when considering flow augmentation, because increased flows during an otherwise hot, dry, sunny summer may not assure the same degree of water-quality improvements that were noted during 1993. The degree to which decreased light may have contributed to the water-quality improvements in 1993 is speculative, however, because the light meter used in previous summers was removed from the Winston-Green WWTP in October 1992.

Assuming that flow augmentation could enhance water quality, it is not clear from the 1993 data what increase in flows would be necessary to control algal growth in the South Umpqua River. The answer is partially dependent on whether there is a need to meet State of Oregon standards for DO and pH at all times and all places. For instance, even in summer 1993, the pH and DO standards were exceeded at the Roseburg site on 90 and 100 percent of the days, respectively, during August and September. However, it is likely that upstream sites were more frequently in compliance with State standards. An indication of the effects of high flow on the upper part of the basin was found during the synoptic surveys of June 1991 and May 1992, when flows were 855 and 455 ft^3/s, respectively, and most of the basin was in compliance with State DO and pH standards (figs. 9 and 11). However, many sites, including those upstream from Canyonville, came close to exceeding the standards on sampling dates and probably did exceed these standards at other times. Even if flow conditions had remained stable at those levels in 1991 and 1992, violations of DO and pH standards would have become increasingly frequent as the summer growing seasons progressed.

If exceedances of the State standards for DO and pH are to be minimized, summertime discharges at the gaging station near Brockway would probably have to be maintained at levels in excess of the 1993 mean summertime flow of 1,247 ft^3/s, and even those flows were not sufficient to eliminate violations at the Roseburg site. In 1993, the August–September mean flow was 321 ft^3/s; moderation of the high flow in May and June, coupled with release of more flow during late summer, might have improved water-quality conditions.

However, such a levelling of flow might allow increased growth of algae in May and June, as was noted in 1991 and 1992. The 1993 total summer flow (May to October) was 378,000 acre-feet of water, which was less than the storage obtainable with one of the design alternatives for the proposed Days Creek Lake project (U.S. Army Corps of Engineers, 1971). Water storage under this alternative would be 480,000 acre-feet, and releases would maintain water temperatures at less than 13°C and flow at 750–900 ft^3/s throughout the summer.

Violations of the State standard for percent of DO saturation at the Roseburg site also occurred from November to April during 1991–93. Mean flows during those time periods were 3,056, 1,831, and 4,787 ft^3/s, respectively, and violations of the DO standard occurred on 50 percent, more than 25 percent, and more than 50 percent of the days (U.S. Geological Survey, 1991–93). Thus, even with limited light and cold temperatures, the higher flows of winter were not enough to maintain DO and pH within State standards below the Roseburg WWTP. However, factors controlling DO and pH during winter may be different from factors controlling these parameters during summer.

Several other aspects of water quality in the river could be affected by flow augmentation, which in turn could affect algal growth and ultimately DO and pH concentrations. Scouring of algal mats due to increased water velocity might help prevent the accumulation of periphytic biomass, as would increased inhibition of light caused by increased turbidity and added depth. Factors tending to increase DO and lower pH include increased physical reaeration; decreased temperature, which increases DO solubility; and decreased nutrient concentrations resulting from dilution (thereby decreasing algal growth). However, in places, especially near an impoundment outflow, nutrient concentrations could increase (depending on nutrient dynamics in the impoundment) and increased suspension of sediment or other particulates could occur. Because of resuspension, lack of uptake (if algal productivity were significantly curtailed), and additional loads from an impoundment, dilution of nutrient concentrations would not be proportional to increases in flow.

One mode of flow augmentation that might prove useful in helping to control algal biomass would be periodic releases from reservoirs to produce flow peaks downstream. These high flows would probably scour unhealthy algae from attachment points or from floating mats and thereby reduce algal biomass for a time. However, as during the fall storms in 1991 and 1992, it is possible that such high flows could produce undesirable, temporary decreases in the daily minimum DO because of BOD created by dying algae. Also, such flows could actually cause increases in primary production, because the removal of dying algae would enhance the productivity of healthy algae that resisted scouring (Power, 1992). Nevertheless, the use of periodic disturbances to control algae might warrant additional study and testing.

Land Application and Storage of Effluent

A combination of land application and storage of WWTP effluent during the summer months could effectively prevent the effluent from reaching the South Umpqua River. (Storage of all summertime effluent may be an option for the smaller WWTPs). If land application and storage were practiced for each WWTP in the South Umpqua River Basin, most of the nutrient load would be eliminated from the system. Algal growth would be reduced, and if nutrient inputs from nonpoint sources remained at 1990–92 levels, DO and pH values would be expected to approximate present conditions in the upper reaches of the South Umpqua River.

Because the Roseburg WWTP is the largest in the South Umpqua River Basin, calculations for that facility illustrate the largest degree of land application and storage necessary for any facility in the basin. For May 1 to October 1 (summer), 1992, the Roseburg WWTP discharged a median of 3.5 Mgal/d of effluent (table 5), which could have been used to irrigate crops. The quality of WWTP effluent has not been shown to be suitable for direct contact with crops for human consumption, so other crops are considered. Alfalfa hay in the Umpqua region requires an average of 19.14 inches of net irrigation water from May 1 to October 1 (Cuenca and others, 1992). (Net irrigation requirement was calculated by subtracting the effective precipitation from the crop water requirement; consequently, the net irrigation also includes the effects of evapotranspiration.)
At this rate of irrigation, 1,040 acres of alfalfa hay would be needed to use the median effluent flow from the Roseburg WWTP from May 1 to October 1.

Similar calculations show that 784 acres of apples or 1,170 acres of silage corn could be irrigated using the effluent of the Roseburg WWTP. Fiber-producing trees such as poplar also could be irrigated to provide an economic benefit. Landscaped acreage, such as golf courses, could also be irrigated with WWTP effluent. Ideally, the irrigated land would be in close proximity to the WWTP in order to decrease pumping costs.

An economic analysis of such alternatives would include crop value, operational costs (including storage and pumping), nutrient content of the effluent, nutrient requirements of the crop, and land value. It might also be necessary to assess potential retention and accumulation of effluent trace elements in soil. Any runoff or return flow would have to be managed; if the quality were satisfactory, the return flow could be discharged to the South Umpqua River.

Storage of WWTP effluent would be a necessary component of land-application scenarios. Temporary storage would be necessary early in the growing season (May), when precipitation would meet much of a crop's water requirements. Late in the growing season (September), crop water requirements are again comparatively small, so effluent would be stored until discharge to the South Umpqua River was resumed.

If land application and storage are chosen as effluent-management solutions, they may be needed at each major WWTP that is discharging to the South Umpqua River. Calculation of the area needed for land application would be proportional to the median effluent flow for each facility (table 5). For example, at the Riddle WWTP, the median effluent flow of 0.113 Mgal/d would irrigate 33 acres of alfalfa hay.

Reduction of Nitrogen Loading

Nitrification of WWTP effluent alone probably would not be effective for controlling algal growth in the South Umpqua River because of the observed rapid NO_3^- downstream from point sources. Ammonia that is oxidized to NO_3^- would still be available for algal consumption once it entered the stream. Both nitrification and denitrification as tertiary-treatment strategies, therefore, will be assumed in the discussion of nitrogen removal as a management alternative.

There are several indications that algal biomass, as well as DO and pH exceedances, could be reduced in the South Umpqua River if nitrogen loading were reduced. These indications include (1) the rapid uptake of DIN as ammonia and as NO_3^-, (2) nitrogen-to-phosphorus ratios that are between 1 and 6 immediately downstream from most WWTPs, (3) positive correlations of DIN uptake with net community productivity, (4) the possibility that nitrogen-fixing algae associated with periphytic communities are present in the South Umpqua River, and (5) the potential for natural phosphorus sources in the Umpqua National Forest or inputs of phosphorus from ground water (J.C. Greene, Oregon State University, unpub. data, 1992). Thus, tertiary treatment to enhance nitrogen removal from WWTP effluent could produce a more immediate reduction in algal biomass or productivity in certain places than would removal of phosphorus.

The best indication of the potential effects of nitrogen removal as a WWTP-treatment method may have been provided by current processes at the Canyonville and Riddle WWTPs. These two WWTPs are similar in size (table 1), and flows in Cow Creek (which receives effluent from the Riddle WWTP) are similar to those in the South Umpqua River near Canyonville for at least a part of the summer (figs. 2 and 10). Phosphorus loads in the effluent of the two WWTPs are comparable (table 5). Finally, nutrient concentrations upstream from the WWTPs (South Umpqua River at Days Creek and Cow Creek near Riddle) also are similar (fig. 16). Although oxidation of ammonia to NO_3^- (nitrification) apparently occurs in the WWTP at Riddle, there is no removal of NO_3^- prior to discharge into Cow Creek, so that median DIN loads in the effluent at Riddle are more than twice those at Canyonville (table 5).

Median minimum DO, maximum pH, and SRP, TP, and DIN concentrations from synoptic surveys at monitoring sites immediately downstream from the Canyonville and Riddle WWTPs are shown in table 11. Although the South Umpqua River at Canyonville site is closer to the Canyonville WWTP than the mouth of Cow Creek is to the Riddle WWTP, minimum DO saturation was lower and maximum pH values were higher at the Cow Creek site than at the Canyonville site, indicating increased algal productivity. Conversely, nutrient concentrations were lower at the mouth of Cow Creek than downstream from Canyonville, indicating the probability of greater algal uptake between the Riddle WWTP and the mouth than exists immediately downstream from Canyonville.

Table 11. Comparison of median water-quality parameters downstream from the Canyonville and Riddle, Oregon, wastewater-treatment plants, 1990–1992

[Water-quality values are medians of values from synoptic surveys. WWTP, wastewater-treatment plant; DO, dissolved oxygen; SRP, soluble reactive phosphorus; TP, total phosphorus; DIN, dissolved inorganic nitrogen; mg/L, milligrams per liter]

Site	Distance from WWTP (miles)	Minimum DO (percent saturation)	Maximum pH	SRP (mg/L)	TP (mg/L)	DIN (mg/L)
South Umpqua River at Canyonville	0.4	88	8.7	0.008	0.019	0.056
Cow Creek near mouth	2.0	78	8.8	.004	.013	.024

Reconnaissance surveys confirmed that algal growth was prolific in the last 2 miles of Cow Creek, whereas no major mats of algae were noted in the South Umpqua River immediately downstream from Canyonville (Anderson and others, 1994).

Concentrations of SRP and TP at points of discharge from the Canyonville and Riddle WWTPs, assuming instantaneous mixing and a discharge of 60 ft^3/s in each stream, are approximately 0.01 and 0.018 mg/L, respectively. The contributions of DIN from these two WWTPs would result in concentrations of 0.06 and 0.04 mg/L, respectively. Because the volume of effluent was small when compared to streamflow for these WWTPs, the concentrations of nutrients in the effluent need not be reduced to the same concentrations as the upstream river water to produce a significant dilution in effluent load below the discharge point. Even with nitrogen removal at the Canyonville WWTP, exceedances of the DO and pH State standards occur frequently downstream from this outfall (table 11 and fig. 9).

Another caveat when considering nitrogen removal as a management alternative is that the resulting nitrogen limitation might contribute to a shift of the algal community, from filamentous green algae and diatoms to nitrogen-fixing algae such as *Epithemia* diatom species (Power, 1991), *Nostoc, Anabaena,* or *Oscillatoria*. Such algae could prove difficult to manage and could increase nitrogen loads in the stream after senescence.

Reduction of Phosphorus Loading

One management alternative is to create phosphorus limitation in the South Umpqua River and Cow Creek by reducing phosphorus loading from WWTP effluent. This practice can be attractive to water-management agencies, because controlling phosphorus sources is easier than controlling nitrogen sources. The Winston-Green WWTP, which currently uses alum (aluminum sulfate) to reduce effluent BOD concentrations, achieved median effluent SRP concentrations of 0.45 mg/L. That concentration represents an approximate 85-percent reduction from the median SRP concentration at that WWTP when alum was not being applied, a reduction consistent with typical alum phosphorus removal efficiencies (Viessman and Hammer, 1985).

Because of the addition of alum at the Winston-Green WWTP, the phosphorus concentration of the effluent was almost an order of magnitude less than for the other WWTPs. Assuming that the other WWTPs used similar single-stage alum addition and assuming that future median discharges from these WWTPs are the same as during 1991–92 (table 5), the combined SRP load to the river from the five major WWTPs would be approximately 9.0 kg/d. However, with additional treatment, removal efficiencies could approach 95 percent (Viessman and Hammer, 1985), thereby reducing the daily combined SRP load to the South Umpqua River from WWTP effluent to approximately 3 kg/d.

Unless it is nearly complete, however, phosphorus removal alone probably will not alleviate DO and pH problems in the South Umpqua River. For example, even downstream from the Winston-Green WWTP, where some phosphorus removal occurs, there are DO and pH problems. Nitrogen-to-phosphorus ratios in the South Umpqua River downstream from the Myrtle Creek WWTP to the mouth indicate possible nitrogen limitation (fig. 19). These considerations make it difficult to predict the result of phosphorus reduction in the absence of nitrogen limitation.

Also, although phosphorus removal might help control algal growth in the South Umpqua River, it could create other problems, including increased nitrification and ammonia toxicity. If phosphorus limitation were achieved, reductions in algal biomass, net community productivity, and nutrient uptake could result.

When a diminished uptake of ammonia is accompanied by unchanged nitrogen concentrations in WWTP effluent, nitrification and ammonia toxicity could create even greater problems.

Nitrification as an Effect of Phosphorus Load Reduction

The potential effects of nitrification on DO were found to be minimal, except in the reach downstream from the Roseburg WWTP. Using conservative figures to determine the worst-case effect of nitrification associated with phosphorus removal at WWTPs, a mass balance of ammonia concentrations was calculated, and the potential for nitrification was assessed based on the resulting ammonia concentrations. This calculation assumes that (1) the concentration of SRP in the WWTP effluent is 0.07 mg/L (that value is conservative, because such a concentration creates severely phosphorus-limited conditions in the river and effectively reduces the ammonia uptake to a minimum), (2) concentrations of phosphorus and nitrogen species in tributaries were the median values observed in 1991–92, (3) ammonia is the preferred form of nitrogen for uptake by periphyton, (4) the concentration of DIN (in particular, ammonia) in the WWTP effluent remains unchanged from 1992 levels, (5) the ratio of uptake of nitrogen to uptake of phosphorus by algae in the river is 13:1 (13:1 is the mean of the uptake ratios in table 7, in which uptake is indicated for DIN and SRP), (6) algal uptake reduces SRP to 0.001 mg/L after inputs from each point source, (7) flows are 35 ft^3/s at South Umpqua River at Tiller and 65 ft^3/s at Cow Creek near Riddle, and the discharges from the WWTPs are equal to the median of their 1992 discharges (table 5), (8) no significant nonpoint or ground-water inputs to the river are present, and (9) nitrification consumes 4.33 grams of oxygen for every gram of nitrogen oxidized (Velz, 1970).

In performing the calculations for this mass balance, determination of the uptake of phosphorus loads resulting from the inflow of a tributary or point source were based on a comparison with nutrient uptakes observed during 1990–92 (table 7) at a particular site. The resulting SRP uptake was multiplied by 13 to determine the ammonia uptake in the same stream segment, and that amount was subtracted from the total ammonia load to indicate the amount available for nitrification.

The results of the mass balance indicated that the incoming phosphorus was used so quickly that SRP concentrations had returned to 0.001 mg/L at the next site downstream from each source. Because of small amounts of nitrogen uptake relative to the size of the incoming loads, ammonia concentrations increased significantly below each source. To determine the effect of nitrification on DO, the river was divided into three reaches corresponding to the sources of nutrients and resulting ammonia concentrations: Days Creek to Myrtle Creek (RM 170.0–150.7), Myrtle Creek to Roseburg (RM 150.7–119.5), and Roseburg to the mouth (RM 119.5–111.7). These reaches were labelled low, medium, and high nutrient reaches, respectively.

The consumption of ammonia from nitrification was determined by using the rate equation:

$$L_T = L_O 10^{-kt} \qquad (6)$$

where

L_T = the ammonia load remaining at time t, in kilograms per day,
L_O = the original ammonia load,
k = the nitrification rate per day, and
t = the time in days.

The time used in the nitrification calculations was the travel time in the river between nutrient sources. The nitrification rate (k) was selected on the basis of ammonia concentrations in each river reach and the likelihood that healthy populations of nitrifying bacteria could become established and thrive over the course of the summer. In reaches with low concentrations of ammonia, k was lower than in reaches with high ammonia concentrations. Values chosen for k may be higher than actual values because (1) late growing season flow conditions were simulated, (2) water temperatures in the South Umpqua River can be quite warm (as high as 30°C in the lower reaches of the river), (3) the river's cobble-to-bedrock substrate could be highly conducive to nitrification, and (4) the calculation was intended to provide an estimate of maximum oxygen consumption by nitrification. The k values were 0.05, 0.2, and 0.4 per day in the reaches with low, medium, and high nutrient concentration, respectively. These k values may be underestimated; however, measured nitrification rates were approximately 0.7 per day in the Willamette River in the 1970's (Hines and others, 1977), and in the Tualatin River, where ammonia concentrations are larger, rates were approximately 0.06 per day (V.J. Kelly, U.S. Geological Survey, oral commun., 1993).

The resulting profile of ammonia concentration from the mass balance, before calculation of the nitrification consumption, was 0.02, 0.3, and 0.4 mg/L in the low, medium, and high concentration ranges, respectively. The calculated medium and high concentrations are considerably higher than river concentrations of ammonia observed during 1990–92 (Anderson and others, 1994, table 9). Except for the reach with the highest concentration (downstream from the Roseburg WWTP), however, the effect on DO from nitrification was minimal. When equation 6 was applied, the ammonia loads were consumed almost entirely, in each case resulting in ammonia concentrations below 0.02 mg/L that were accompanied by decreases in DO of 0.02, 0.35, and 1.66 mg/L in the reaches with low, medium, and high ammonia concentration, respectively.

In the reach below Roseburg, nitrification could consume up to 1.6 mg/L of DO if phosphorus removal resulted in increased ammonia concentrations. This amount of DO consumption is significant, considering that water temperatures in this reach regularly exceed 25°C and have been as high as 30°C; in this temperature range, the saturation concentration of DO is between 7.5 and 8.2 mg/L. The consumption of 1.6 mg/L of DO would result in DO saturation between 75 and 80 percent, assuming that algal production or benthic respiration were not significant. However, algal production, in the form of uptake of SRP and some ammonia is assumed to occur as part of this scenario, albeit at a lower rate. There would be, therefore, a small contribution to the daily DO cycle from periphyton, and the minimum DO saturation could be even less than the 75 to 80 percent previously mentioned, because of algal respiration.

Ammonia Toxicity as an Effect of Phosphorus Load Reduction

Ammonia toxicity, resulting from phosphorus load reduction, probably would be of concern only downstream from the Roseburg WWTP. With decreased phosphorus loading, and in the absence of significant uptake of nitrogen as ammonia, ammonia toxicity could increase in importance when compared to current water-quality conditions. Ammonia toxicity would occur if reductions in algal biomass and net productivity were smaller than expected, such that the daily maximum pH did not decrease greatly. Some researchers have found that decreased productivity or biomass did not occur when nutrient loads were reduced. The reasons for this may include increased nutrient recycling (Mulholland and others, 1991), increased efficiency of productivity due to grazing effects (Mulholland and Rosemond, 1992; Gregory, 1993), or increased reliance of periphyton on internal nutrient contents in cell tissues (Auer and Canale, 1982). Also, nonpoint or ground-water inputs may have a significant effect on South Umpqua River nutrient dynamics, thus invalidating one of the assumptions made previously when the effects of increased ammonia on nitrification were calculated. Finally, the large mats of periphyton observed within the Umpqua National Forest and the relatively high values of pH and low concentrations of DO measured near Days Creek indicate that periphyton are able to thrive with low concentrations of nutrients, including phosphorus at or near the analytical limit of detection. This ability may allow the maintenance of high biomass or productivity even with decreased nutrient loading.

To evaluate ammonia toxicity in a worst-case scenario, the mass balance of ammonia, as used for analysis of nitrification, was employed. In this case, the nine assumptions that were used to calculate mass balance were used again, and the following three assumptions were added:

(1) A small reduction in net periphyton productivity occurs as the system shifts towards phosphorus limitation, resulting in a slight decrease in the frequency and magnitude of the extreme pH measurements observed in 1990–92,

(2) nitrification in this case is negligible, such that ammonia concentrations in the river are largely unaffected, and

(3) water temperatures were the same as during the August 1991 synoptic survey (Anderson and others, 1994), when flow levels were similar.

For a worst-case scenario, daily maximum pH values in the upper South Umpqua River (upstream from Winston at RM 132.8) were assumed to be 8.5 throughout; however, no extremely high values (close to 9.0) occurred. Daily maximum pH values in the reach from Winston to Roseburg (RM 132.6–119.6) were assumed to be as high as 8.7, indicating increased algal activity. Daily maximum pH below Roseburg (RM 119.5–111.7) was assumed to reach as high as 9.0, indicating that nuisance growth may still occur.

By using the concentrations of ammonia determined previously and the assumed maximum pH value, ammonia toxicity was evaluated. The results indicate that only below Roseburg WWTP (RM 119.5) could ammonia toxicity pose a significant threat, even if ammonia concentrations in the water column are not reduced by periphytic uptake or nitrification. Below Roseburg WWTP, the ratio of un-ionized ammonia to the toxicity standard was 4.2 (a ratio higher than 1.0 indicates an exceedance of the State standard).

As in the case of nitrification and its effects on DO, these calculations indicate that the ammonia toxicity resulting from unconsumed ammonia is likely to be of concern only below the Roseburg WWTP at RM 119.5. It is emphasized that this is a worst-case scenario—mitigating effects could include greater uptake of ammonia due to nitrification or greater than expected algal growth. Further, because nitrification frees hydrogen ions (H^+) and thus reduces the pH of a system, the probability of ammonia toxicity is even less, because toxicity is less at low pH levels.

SUMMARY

The water-quality constituents of major interest in this study were primarily dissolved oxygen and pH; of secondary interest were bacteria and ammonia. The nighttime respiration of biota, including periphytic algae, caused exceedances of the State standard for dissolved oxygen at several sites on the South Umpqua River. Biochemical oxygen demand, nitrification, and periphyton sloughing in the fall made minor contributions to low concentrations of dissolved oxygen. Conditions of low dissolved oxygen concentrations were most severe in the lower reaches of the South Umpqua River (where the largest point sources are located) and during periods of low flow and high water temperature in late summer. Daytime photosynthesis caused many exceedances of the State pH standard. The diel patterns and spatial distributions of dissolved oxygen and pH values indicate that photosynthesis and respiration by periphyton is responsible for water-quality problems in the South Umpqua River during the summer.

The three exceedances of the Oregon criterion for fecal-coliform bacteria (200 colonies per 100 milliliters) were associated with high streamflows. Fecal-streptococcus counts as large as 4,400 colonies per 100 milliliters were associated with low streamflows. Fecal-streptococcus counts were much larger than historical values and require confirmation.

Five wastewater-treatment plants contributed less than 15 percent of the flow but more than 90 percent of the nitrogen and phosphorus present in the South Umpqua River during the low streamflows of summer. These nutrient inputs were associated with, and were largely responsible for, dense growths of periphytic algae that produced biomass of as much as 340 grams of ash-free dry weight per square meter. Ammonia from wastewater-treatment-plant effluent combined with high values of pH and water temperature to create the potential for chronic-ammonia toxicity in lower reaches of the South Umpqua River, but actual exceedances of standards were not observed.

Net productivity, calculated from hourly measurements of dissolved oxygen concentrations, was as large as 3.8 grams of oxygen per square meter per day. Productivity was directly related to the concentration and load of dissolved inorganic nitrogen. Aquatic-community metabolism was responsible for a large amount of nutrient uptake from the river, resulting in lowered nutrient concentrations downstream from nutrient from point sources.

Management alternatives for the South Umpqua River Basin include several methods to reduce nutrient concentrations and loads:

(1) Flow augmentation would decrease water-quality problems in the South Umpqua River, but it is difficult to predict the magnitude of the effects of increased velocity and decreased temperature on algal growth.

(2) Land application and storage of wastewater-treatment-plant effluent during the summer months would reduce the effects of nutrient point sources.

(3) Reduction of dissolved inorganic nitrogen and soluble reactive phosphorus loads from wastewater-treatment-plant effluent (tertiary treatment) would lessen the frequency of violations of dissolved oxygen and pH standards. A combination of flow augmentation, effluent storage, land application, and tertiary treatment also could be considered as a management alternative.

REFERENCES CITED

Anderson, C.W., Tanner, D.Q., and Lee, D.B., 1994, Water-quality and related data from the South Umpqua River Basin, 1990–1992: U.S. Geological Survey Open-File Report 94–40, 165 p.

Auer, M.T., and Canale, R.P., 1982, Ecological studies and mathematical modelling of *Cladophora* in Lake Huron 3—The dependence of growth rates on internal phosphorus pool size: Journal of Great Lakes Research, v. 8, no. 1, p. 93–99.

Bellis, V.J., and McLarty, D.A., 1967, Ecology of *Cladophora glomerata* (L.) Kuetzing in southern Ontario: Journal of Phycology, v. 3, p. 57–63.

Britton, L.J., and Greeson, P.E., 1987, Methods for collection and analysis of aquatic biological and microbiological samples: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A4, 363 p.

Buchanan, T.J., and Somers, W.P., 1984, Discharge measurements at gaging stations: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A8, 65 p.

Center for Population Research and Census, 1992, Population estimates for Oregon, 1980–1991: Portland, Oregon, Portland State University, School of Urban and Public Affairs, 22 p.

Columbia Basin Inter-Agency Committee, 1966, River mile index, Umpqua River and tributaries, Umpqua River Basin, Oregon: Hydrology Subcommittee, 25 p.

Cuenca, R.H., Nuss, J.L., Martinez-Cob, Antonio, Katul, G.G., and Gonzales, J.M., 1992, Oregon crop water use and irrigation requirements: Oregon State University Extension Service, Extension Miscellaneous 8530, 184 p.

DeVries, P.J.R., and Hotting, E.J., 1985, Bioassays with *Stigeoclonium tenue* Kutz. on waters receiving sewage effluent: Water Resources, v. 19, no. 11, p. 1405–1410.

Dodd, W.K., 1991, Community interactions between the filamentous alga *Cladophora glomerata* (L.) Kuetzing, its epiphytes, and epiphyte grazers: Oecologia, v. 85, p. 572–580.

Duke, J.H., Jr., and Masch, F.D., 1973, Computer program documentation for the stream quality model DOSAG3, Volume I, *in* U.S. Environmental Protection Agency, 1985, Rates, constants, and kinetic formulations in surface water quality modeling (2d ed.): U.S. Environmental Protection Agency, EPA/600/3–85/040, 455 p.

Edwards, T.K., and Glysson, D.G., 1988, Field methods for measurement of fluvial sediment: U.S. Geological Survey Open-File Report 86–531, 118 p.

European Inland Fisheries Advisory Commission, 1970, Water-quality criteria for European freshwater fish—Report on ammonia and inland fisheries: EIFAC Technical Paper no. 11, 12 p.

Fishman, M.J., and Friedman, L.C., 1989, Methods for the determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. A1, 546 p.

Gerloff, G.C., and Fitzgerald, G.P., 1976, The nutrition of Great Lakes *Cladophora*: U.S. Environmental Protection Agency, EPA/600/3–76–044, 111 p.

Grady, C.P., and Lim, H.C., 1980, Biological wastewater treatment—Theory and applications: New York, Marcel Dekker, Inc., 963 p.

Graham, J.M., Auer, M.T., Canale, R.P., and Hoffman, J.P., 1982, Ecological studies and mathematical modeling of *Cladophora* in Lake Huron 4—Photosynthesis and respiration as functions of light and temperature: Journal of Great Lakes Research, v. 8, no. 1, p. 100–111.

Gregory, S.V., 1993, Willamette River Basin study—Periphyton algal dynamics [Final Report to Oregon Department of Environmental Quality]: Corvallis, Oregon State University, 112 p.

Hines, W.G., McKenzie, S.W., Rickert, D.A., and Rinella, F.A., 1977, Dissolved oxygen regimen of the Willamette River, Oregon, under conditions of basinwide secondary treatment: U.S. Geological Survey Circular 715–I, 52 p.

Horner, R.R., Welch, E.B., and Veenstra, R.B., 1983, Development of nuisance periphytic algae in laboratory streams in relation to enrichment and velocity, *in* Wetzel, R.G., ed., Periphyton of freshwater ecosystems: The Hague, Netherlands, Dr. W. Junk Publishers, p. 121–134.

Kennedy, E.J., 1983, Computation of continuous records of streamflow: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. A13, 53 p.

Kilpatrick, F.A., Rathbun, R.E., Yotsukura, N., Parker, G.W., and DeLong, L.L., 1989, Determination of stream reaeration coefficients by use of tracers: U.S. Geological Survey, Techniques of Water-Resources Investigations, book 3, chap. A18, 52 p.

Laenen, Antonius, and Woo, W.H., 1994, Stream velocity and reaeration coefficients for the South Umpqua River between Tiller and Roseburg, Oregon, 1991: U.S. Geological Survey Water-Resources Investigations Report 92–4191, 26 p.

Lorenz, R.C., and Herdendorf, C.E., 1982, Growth dynamics of *Cladophora glomerata* in western Lake Erie in relation to some environmental factors: Journal of Great Lakes Research, v. 8, no. 1, p. 42–53.

Mantai, K.E., Garwood, P.E., and Peglowski, L.E., 1982, Environmental factors controlling physiological changes in *Cladophora* in Lake Erie: Journal of Great Lakes Research, v. 8, no. 1, p. 61–65.

Moffatt, R.L., Wellman, R.E., and Gordon, J.M., 1990, Statistical summaries of streamflow data in Oregon—Volume 1, Monthly and annual streamflow, and flow-duration values: U.S. Geological Survey Open-File Report 90–118, 413 p.

Mulholland, P.J., and Rosemond, A.D., 1992, Periphyton response to longitudinal nutrient depletion in a woodland stream—Evidence of upstream-downstream linkage: Journal of the North American Benthological Society, v. 11, no. 4, p. 405–419.

Mulholland, P.J., Steinman, A.D., Palumbo, A.V., Elwood, J.W., and Kirschtel, D.B., 1991, Role of nutrient cycling and herbivory in regulating periphyton communities in laboratory streams: Ecology, v. 72, no. 3, p. 966–982.

National Oceanic and Atmospheric Administration, 1991, Climatological data—Annual summary, Oregon, 1990: Asheville, North Carolina, U.S. Department of Commerce, v. 96, no. 13, 33 p.

———1992, Climatological data—Annual summary, Oregon, 1991: Asheville, North Carolina, U.S. Department of Commerce, v. 97, no.13, 33 p.

———1993, Climatological data—Annual summary, Oregon, 1992: Asheville, North Carolina, U.S. Department of Commerce, v. 98, no.13, 33 p.

O'Connor, D.J., and Dobbins, W.E., 1958, Mechanism of reaeration in natural streams: Transactions, American Society of Civil Engineers, v. 123, no. 2934, p. 641–684.

Odum, H.T., 1956, Primary production in flowing waters: Limnology and Oceanography, v. 1, no. 2, p. 102–117.

Oregon Water Resources Department, 1978, Map—Umpqua drainage basin, Oregon, Land Use: Salem, Oregon, scale 1:260,000.

Oster, E.A., 1972, Flood profiles in the Umpqua River Basin—Part 1: U.S. Geological Survey Open-File Report, 119 p.

Power, M.E., 1991, Shifts in the effects of tuft-weaving midges on filamentous algae: The American Midland Naturalist, v. 125, p. 275–285.

———1992, Hydrologic and trophic controls of seasonal algal blooms in northern California rivers: Archives für Hydrobiologia, v. 125, no. 4, p. 385–410.

Ramp, L., 1972, Geology and mineral resources of Douglas County, Oregon: Oregon Department of Geology and Mineral Industries, Bulletin 7.

Reynolds, C.S., 1984, The ecology of freshwater phytoplankton: Cambridge University Press, 384 p.

Rinella, J.F., 1986, Analysis of fixed-station water-quality data in the Umpqua River Basin, Oregon: U.S. Geological Survey Water-Resources Investigations Report 85–4253, 96 p.

Robison, J.H., and Collins, C.A., 1978, Availability and quality of ground water in the Winston area, Douglas County, Oregon: U.S. Geological Survey Water-Resources Investigations Report 77–28, 2 sheets, scale 1:62,500.

Shanz, F., and Juon, H., 1983, Two different methods of evaluating nutrient limitations of periphyton bioassays, using water from the River Rhine and eight of its tributaries: Hydrobiologia 102, 187–195.

State of Oregon, 1992, Regulations relating to water quality control: Salem, Oregon Department of Environmental Quality Administrative Rules, chap. 340.

Tsivoglou, E.C., 1967, Tracer measurement of stream reaeration: Washington, D.C., U.S. Department of the Interior, Federal Water Pollution Control Administration, 86 p.

Umpqua Regional Council of Governments, 1985, South Umpqua River Basin water-quality management plan: Roseburg, Oregon, 42 p.

U.S. Army Corps of Engineers, 1971, Review report on Umpqua River and tributaries, Oregon—Interim report, South Umpqua River, Volume III, Appendix B, Hydrology, Meteorology, and Reservoir Regulation: Portland, Oregon, [variously paged].

U.S. Environmental Protection Agency, 1986, Quality criteria for water 1986: The Gold Book, EPA 440/5–86–001.

U.S. Geological Survey, 1991, Water resources data, Oregon, water year 1990: U.S. Geological Survey Water-Data Report OR–90–2, 334 p.

———1992, Water resources data, Oregon, water year 1991: U.S. Geological Survey Water-Data Report OR–91–1, 475 p.

———1993, Water resources data, Oregon, water year 1992: U.S. Geological Survey Water-Data Report OR–92–1, 474 p.

———1994, Water resources data, Oregon, water year 1993: U.S. Geological Survey Water-Data Report OR–93–1, 498 p.

Viessman, W.J., and Hammer, M.J., 1985, Water supply and pollution control—4th ed: New York, Harper and Row, Pub., p. 684.

Velz, C.J., 1970, Applied stream sanitation: New York, Wiley and Sons, 619 p.

Vollenweider, R.A., 1974, A manual on methods for measuring primary production in flowing waters: Blackwell Scientific, Oxford, International Biological Programme Handbook no. 12, 225 p.

Walker, G.W., and MacLeod, N.S., 1991, Geologic map of Oregon: U.S. Geological Survey, 2 sheets, scale 1:500,000.

Welch, E.B., 1992, Ecological effects of wastewater—applied limnology and pollutant effects, 2d ed.: London, Chapman and Hall, 425 p.

Wetzel, R.G., 1983, Limnology, 2d ed.: Philadelphia, Saunders College Publishing, 858 p.

Whitton, B.A., 1970, Biology of *Cladophora* in freshwaters: Water Research, v. 4, p. 457–476.

Wootton, T.J., and Power, M.E., 1993, Productivity, consumers, and the structure of a river food chain: Proceedings of the National Academy of Sciences, v. 90, p. 1384–1387.

Page Intentionally Blank