# Sources and Transport of Phosphorus and Nitrogen During Low-Flow Conditions in the Tualatin River, Oregon, 1991–93

U.S. Geological Survey
Open-File Report 99–232

Prepared in cooperation with the
UNIFIED SEWERAGE AGENCY OF
WASHINGTON COUNTY, OREGON

USGS
science for a changing world

# Sources and Transport of Phosphorus and Nitrogen During Low-Flow Conditions in the Tualatin River, Oregon, 1991–93

By Valerie J. Kelly, Dennis D. Lynch, and Stewart A. Rounds

U.S. Geological Survey
Open-File Report 99–232

Prepared in cooperation with the
UNIFIED SEWERAGE AGENCY OF
WASHINGTON COUNTY, OREGON

1999

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

U.S. GEOLOGICAL SURVEY
Charles G. Groat, Director



For additional information write to:

District Chief
U.S. Geological Survey, WRD
10615 S.E. Cherry Blossom Drive
Portland, OR 97216-3159
E-mail: info-or@usgs.gov

Copies of this report can be purchased from:

U.S. Geological Survey
Branch of Information Services
Box 25286
Denver, CO 80225-0286
E-mail: infoservices@usgs.gov

# CONTENTS

## FIGURES

## TABLES

# CONVERSION FACTORS

[SI, International System of units, a modernized metric system of measurement]

| Multiply | By | To obtain |
|---|---|---|
| *A. Factors for converting SI metric units to inch/pound units* | | |
| | Length | |
| centimeter (cm) | 0.3937 | inch (in) |
| millimeter (mm) | 0.03937 | inch |
| meter (m | 3.281 | foot (ft) |
| | 1.094 | yard (yd) |
| | Volume | |
| milliliter (mL) | 0.001057 | quart (qt) |
| liter (L) | 1.057 | quart |
| liter | 0.2642 | gallon (gal) |
| | Mass | |
| gram (g) | 0.03527 | ounce (oz avoirdupois) |
| kilogram (kg) | 2.205 | pound (lb avoirdupois) |
| | Temperature | |
| degree Celsius (°C) | Temp degree F = 1.8 (Temp degree C) + 32 | degree Fahrenheit (°F) |
| *B. Factor for converting inch/pound units to SI metric units.* | | |
| | Volume per unit time (flow) | |
| cubic foot per second ($ft^3/s$) | 0.02832 | meter per second ($m^3/s$) |
| acre | 4,047 | cubic meter ($m^3$) |
| *C. Factors for converting SI metric units to other miscellaneous units* | | |
| | Concentration, in water | |
| milligrams per liter (mg/L) | 1 | parts per million (ppm) |
| nanograms per liter (ng/L) | 1 | parts per trillion (ppt) |
| nanograms per liter | 0.000001 | parts per million |
| | Concentration, in bed sediment | |
| micrograms per kilogram (μg/kg) | 1 | parts per billion (ppb) |
| micrograms per kilogram (μg/kg) | 0.001 | parts per million |
| | Concentration, in tissue | |
| micrograms per gram (μg/g) | 1 | parts per million |

Electrical conductivity is measured as specific electrical conductance, in units of microsiemens per centimeter (μS/cm) at 25 degrees Celsius.

# Sources and Transport of Phosphorus and Nitrogen During Low-Flow Conditions in the Tualatin River, Oregon, 1991–93

*By* Valerie J. Kelly, Dennis D. Lynch, *and* Stewart A. Rounds


## Abstract

In the 1980s significant nutrient-related water-quality problems that impacted beneficial uses were identified in the Tualatin River during the low-flow summer months, defined as May 1 to October 31. Unsightly algal blooms resulted in fluctuations in oxygen concentrations and pH conditions; reduction of phosphorus concentrations was determined to the most effective control mechanism for these conditions. Elevated ammonia concentrations also contributed to low oxygen concentrations. Because standards for beneficial uses were not being met, the Oregon Department of Environmental Quality established Total Maximum Daily Loads (TMDLs) for phosphorus and ammonia in the Tualatin Basin, as required by the Clean Water Act. To provide necessary context for the TMDL process, data were collected during the period 1991–93 to characterize the sources and transport of water, phosphorus, and major forms of nitrogen in the main-stem Tualatin River during the summer. A significant source of water to the river was not accounted for by surface-water inputs, and was consistent with direct discharge of ground water to the main-stem river channel. Ground water is also the primary source of water for the tributaries during the summer low-flow season. Because large natural supplies of highly mobile phosphorus exist in the upper 500 feet of valley-fill sediments throughout the Tualatin Basin, ground water in the basin is naturally enriched with phosphorus. While improvement in wastewater treatment efficiencies and land management practices have resulted in significant reductions in nutrient concentrations in the Tualatin River, phosphorus concentrations continue to exceed TMDL criterion concentrations. The presence of significant geologic sources of phosphorus in the basin will confound the achievement of current TMDL criteria for phosphorus in the Tualatin River and its tributaries. In contrast, natural sources of all forms of nitrogen to the Tualatin River are insignificant relative to the effluent from the wastewater treatment plants in the basin. Efficient wastewater treatment is, therefore, an effective means for controlling ammonia concentrations in the main-stem river.


## INTRODUCTION

The Tualatin River is located in northwestern Oregon and is one of the major tributaries to the Willamette River. Land use in the Tualatin Basin is generally characterized by forestland along the perimeter and agricultural and urban land in the central valley. When light and temperature conditions are favorable during the low-flow summer months, large algal blooms develop in the meandering and sluggish reaches of the lower river. The biomass of phytoplankton (free-floating algae), as measured by the concentration of chlorophyll-a, often exceeds 30 μg/L (micrograms per liter) in the lower river and periodically exceeds 100 μg/L, surpassing the State of Oregon action level of 15 μg/L. Excessive growth of phytoplankton in the Tualatin River is associated with elevated levels of nutrients, especially phosphorus.

Elevated nutrient concentrations not only help create aesthetic algal problems in the main-stem river, but also contribute to periodically low dissolved oxygen (DO) concentrations when the algal community dies and sinks to the bottom. Organic matter formed during algal blooms can rapidly decay, consuming DO in the water column and periodically dropping DO concentrations below the minimum Oregon State standard of 6 mg/L (milligrams per liter). Large algal blooms in the lower river also result in periodic supersaturation of DO, occasionally exceeding 200 percent of saturation. High pH values frequently coincide with algal blooms as well. Values exceeding 8.5 (Oregon State standard for maximum pH) can occur during the summer when algal uptake of carbon dioxide from the water column exceeds the rate of replenishment. In addition, the high pH conditions associated with algal blooms can increase the toxicity of instream ammonia to aquatic organisms. Before the wastewater treatment plants (WWTPs) initiated the advanced treatment procedures to remove ammonia, concentrations of total ammonia (un-ionized plus ionized ammonia) exceeded 3 mg/L on occasion during low-flow periods. Elevated concentrations of ammonia also contribute to oxygen depletion under certain conditions that favor instream nitrification (oxidation of ammonia to nitrate).

Because most of these water-quality problems are related to elevated nutrient concentration, efforts to improve conditions in the river have focused on reducing the loading of nutrients to the river from all identifiable sources. Nutrient sources to the river include its tributaries, WWTPs, ground water discharge, tile drains, urban runoff, release from bottom sediments, and riparian vegetation (primarily leaf litter). Invoking the Total Maximum Daily Load (TMDL) provision of the Clean Water Act of 1972, the Oregon Department of Environmental Quality (ODEQ) has established criterion concentrations of total phosphorus and ammonia in the main-stem river and various tributaries, and waste-load allocations for the WWTP effluents. These regulations are intended to bring the Tualatin River into compliance with Oregon State water-quality standards and to ensure protection of the river's designated beneficial uses. In 1990, the U.S. Geological Survey (USGS) entered into a cooperative agreement with the Unified Sewerage Agency (USA) of Washington County, Oregon, to conduct a water-quality study of the Tualatin River, with an emphasis on the sources of phosphorus and ammonia (and other primary forms of nitrogen) to the river.

## Purpose and Scope

The purpose of this report is to characterize the sources and transport of phosphorus and major forms of nitrogen in the main-stem Tualatin River during the low-flow periods of summer, where "summer" is defined as the period May 1 through October 31. Only the main-stem river between river mile (RM) 60 and the mouth is discussed in detail. This analysis of nutrients is based primarily on information collected from 1991 through 1993; data from other years are included at times to provide a more complete analysis. The report focuses on nutrients in the main-stem river; consequently, inputs from tributaries and tile drains, ground water, and WWTP effluent, and losses from withdrawals are discussed primarily as sources or sinks of nutrients to the main-stem river.

A close accounting of nutrients entering and leaving the Tualatin River is needed by planning and regulatory agencies to design a nutrient-reduction plan that is attainable and cost effective. Without such an accounting, nutrient-reduction plans might target relatively small nutrient sources while neglecting larger sources, which could delay the success of the plan and greatly increase its cost. Moreover, a thorough evaluation of nutrients entering the river provides perspective as to which sources might result from human activities and perhaps be amenable to remediation efforts, and which sources are probably natural and very difficult to change. This report provides the data and understanding of the sources of nutrients in the basin necessary to prepare a sound nutrient management plan, with the ultimate goal of improving the quality of the Tualatin River and its aquatic ecosystem.

Electronic records of the streamflow and water-quality data from this study have been published on CD-ROM (Doyle and Caldwell, 1996); data are also available through the U.S. Environmental Protection Agency's STORET database.

## Acknowledgments

The staff of Unified Sewerage Agency of Washington County, Oregon, are gratefully acknowledged for their technical assistance, laboratory analyses, and financial assistance. Particularly, Gary Krahmer, William Gaffi, John Jackson, Janice Miller, Tom VanderPlaat, Jan Wilson, and the staff of the Water Quality Laboratory deserve special recognition for their enthusiastic support, without which this co-operative study would not have been possible. Wesley Jarrell, Mary Abrams, and many other scientists at the Oregon Graduate Institute of Science & Technology are gratefully acknowledged for sharing their knowledge of nutrient processes in the Tualatin Basin. Jerry Rodgers (Oregon Water Resources Department) and Dan Wilson (Tualatin Valley Irrigation District) contributed hydrologic data and insights of the flow system which helped make this study quantitative. The Oregon Community Foundation, which administers the Tualatin Valley Water Quality Endowment Fund, is gratefully acknowledged for providing funding to expand the ground-water component of this study. Finally, we thank the Tualatin River Research Advisory Committee members for their valuable input and guidance during the study. In particular, Bob Baumgartner (Oregon Department of Environmental Quality) is gratefully acknowledged for his keen scientific insights over the course of the study.

# DESCRIPTION OF STUDY AREA

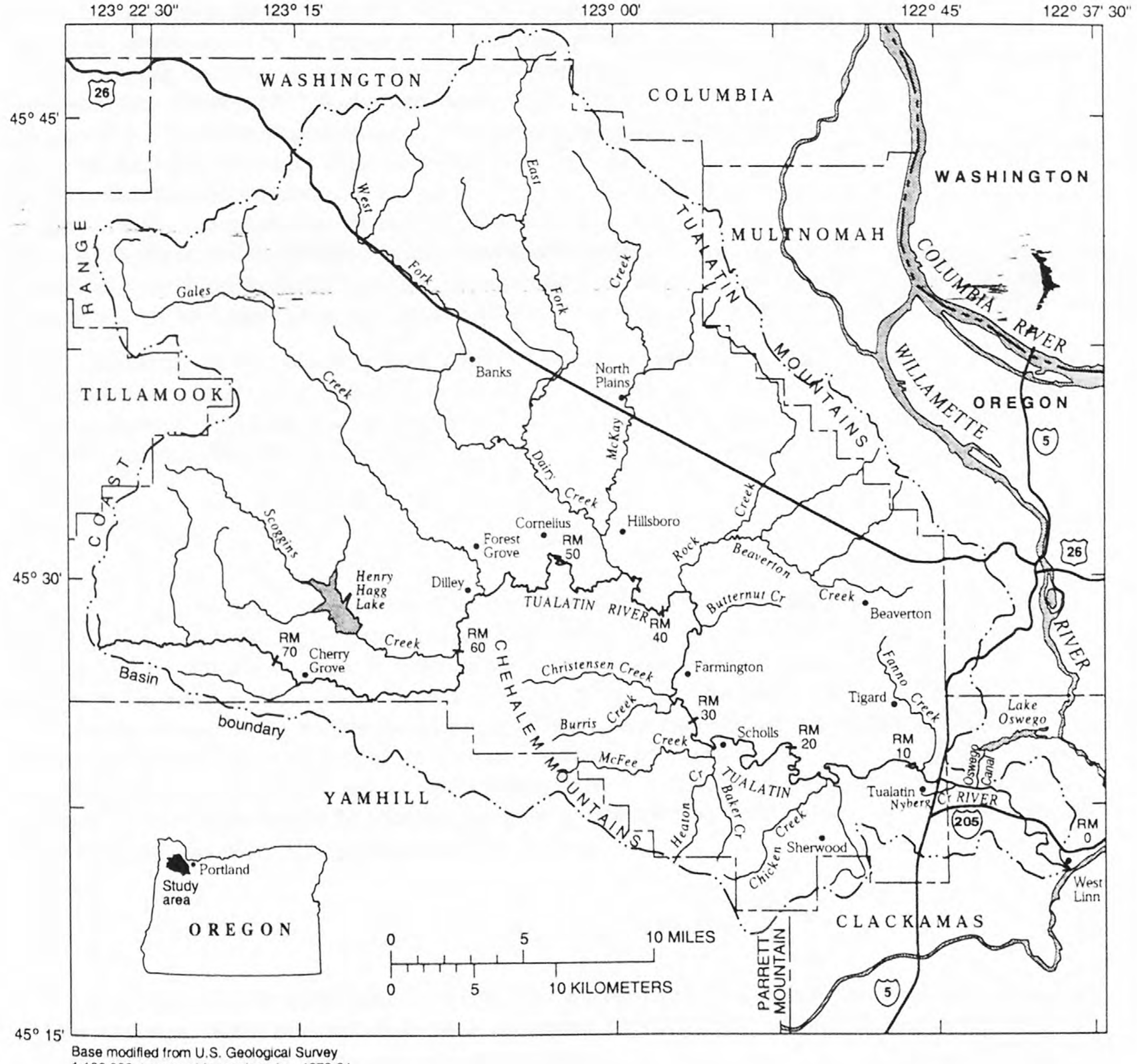
The Tualatin River is a major tributary to the Willamette River and drains an area of 712 $mi^2$ (square miles) in northwestern Oregon, on the western side of the city of Portland metropolitan area (fig. 1). The basin is bounded by the Tualatin Mountains on the east and northeast, the Coast Range on the west and northwest, and Parrett Mountain and the Chehalem Mountains on the south. The river originates in a steep forested eastern slope of the Coast Range; for most of its length, however, the river meanders through a flat valley plain before emptying into the Willamette River at West Linn, Oregon. This study focused on the reach from the confluence with Scoggins Creek at RM 60.0 to Weiss Bridge, near the river's mouth at RM 0.2.

## Physical Setting

The Tualatin Basin trends northwest to southeast in approximately an oval shape, about 40 miles long and 20 to 30 miles wide (fig. 1). The boundary of the basin is nearly contiguous with the Washington County boundary but includes small portions of Clackamas, Multnomah, Tillamook, Yamhill, and Columbia Counties as well. The elevation of the basin ranges from nearly 3,000 feet above sea level at the western border in the Coast Range to about 60 feet near the river mouth in the southeast (Hart and Newcomb, 1965). The dominant topographical feature is the broad and flat plain of the Tualatin Valley, bounded by the adjacent mountain slopes.

The major tributaries to the Tualatin River include Scoggins, Gales, Dairy, Rock, and Fanno Creeks. These creeks drain most of the basin north of the main-stem river. The Dairy Creek watershed is the largest, with a drainage area of 225 $mi^2$ or about 30 percent of the total area of the Tualatin Basin; the combined drainage areas for the other four tributaries account for another one-third of the basin area. The remainder of the basin is drained by numerous smaller tributaries, as well as tile drains that collect shallow ground water and funnel it directly into the river and its tributaries.

The main-stem river is about 80 miles long and undergoes significant changes in geomorphology as it flows from its headwaters toward the mouth (fig. 1). At the headwaters, the river channel is narrow, about 15 feet wide, and is heavily shaded by dense riparian vegetation. The channel alternates between steep riffles and quiet pools, with an average slope of 74 feet per mile until it flows out of the Coast Range near RM 55.3.




Base modified from U.S. Geological Survey
1:100,000, topographic quadrangles, 1978-84

**Figure 1.** Tualatin River Basin, Oregon. (RM, river mile).

After the river flows out of the mountains and enters the valley bottom, the channel widens to 40–50 feet and begins to deepen to about 6–10 feet. The slope decreases sharply in this reach (RM 55.3–33.3) to an average of 1.3 feet per mile; water velocity decreases similarly and the river begins a meandering course. The streambed is a mixture of clay, occasional outcrops of bedrock, and soft silts and organic materials that are subject to transport during high streamflow. The streambank is susceptible to erosion in many areas; extensive slumping of the streambank occurs in some reaches.

Streamflow in the lower river (RM 33.3–3.4) is sluggish due to a very flat gradient (about 0.08 feet per mile), compounded by the presence of a low-head diversion dam at RM 3.4. Water temperatures increase during the summer as the water moves downstream due to a reduction in shading and a longer residence time (Risley, 1997; Risley and Doyle, 1997). The river in this reach widens to 100–200 feet and is more like a reservoir, characterized by almost-slack water and an uneven streambed. Several bedrock sills separate occasional deep pools with depths of 20 to 30 feet. During the summer, some of these pools undergo thermal stratification that may persist for days or weeks at a time. Extensive amounts of silt and organic material accumulate in the streambed in many areas. In the warm summer months when streamflow is low, this material exerts a significant sediment oxygen demand. This sediment oxygen demand results in a significant reduction in DO concentrations in the water column as well as a potential influx of nutrients from the decay of organic material in the sediments (Rounds and Doyle, 1997).

Below the Oswego diversion dam at RM 3.4 to the river mouth, the channel is relatively constricted and the gradient increases considerably to an average of 13 feet per mile, resulting in greatly increased water velocities. This reach is characterized by small pools and riffles and a streambed composed of exposed bedrock, boulders, and cobbles.

## Climate

The Tualatin Basin is characterized by a modified maritime climate, with seasons clearly defined by patterns in precipitation. Winters are cloudy and wet, with most of the storms moving in from the west, where they accumulate moisture from the Pacific Ocean. Annual precipitation at Forest Grove, near the center of the basin, averages about 45 inches per year, with approximately 80 percent occurring as rain during the months November through April. Cloudy skies predominate during this season as a consequence of the rainy conditions. In contrast, conditions during the months May through October are generally dry, with less than 1 inch of rain typically falling during the midsummer months of July and August. Summer skies tend to be clear and sunny, with light intensity generally peaking from May through July and gradually decreasing as the season progresses.

## Land Use

Land use in the Tualatin Basin is mostly forest and agricultural, accounting for more than 80 percent of the total area. Nearly one-half of the basin is forested, predominantly in the mountainous western region; timber production from public and private industrial lands comprises about 20 percent of land use (Unified Sewerage Agency, 1990). The areas of the basin dominated by forested land are the upper Tualatin River subbasin, in the vicinity of the headwaters and downstream to about RM 65, and the Scoggins and Gales Creek watersheds.

Agriculture constitutes about one-third of land use in the basin, and is most prominent on the smaller hills and in the central valley. Major agricultural uses include specialty horticulture, fruit and nut orchards, berries, vegetable crops, small grains, grass seed, dairy products, and hay. Agriculture is concentrated in the Tualatin River valley in areas adjacent to the main-stem river and in the Dairy Creek watershed, as well as portions of the Rock Creek watershed.

Urban land use in the basin is concentrated in the eastern part of the valley, which includes parts of Portland and many of its suburbs. Urban land use in the western valley is relatively sparse, except in the cities of Hillsboro and Forest Grove (fig. 1). The areas most urbanized, therefore, include the region adjacent to the lower main-stem river below about RM 10, the Fanno Creek watershed, and portions of the Rock Creek watershed. These areas experienced very rapid growth during the 1980–95 period. The total population within the Tualatin Basin was approximately 312,000 in 1990, and is projected to be about 440,000 by 2010 (USA, Washington County, unpub. data, 1994). Although the regions of high population density comprise a relatively small percentage of the overall land use in the basin (less than 15 percent), the effect on water quality in the river can be significant because of the effect of municipal wastewater as well as urban runoff.

## Soils

Undisturbed soils in the Tualatin valley contain concentrations of phosphorus that are high relative to other soils in the United States. Total phosphorus concentrations greater than 1,000 mg/kg (milligrams per kilogram) have been measured in the Dairy Creek subbasin, compared to the national mean concentration of 600 mg/kg (Abrams and Jarrell, 1995). Additionally, relatively high concentrations of phosphorus were found to be labile or water-extractable, that is, weakly adsorbed onto the surface of soil particles rather than embedded in minerals or humic material. Concentrations of soil-solution phosphorus in equilibrium with sorbed phosphorus were found to range from 0.01 to 0.29 mg/L for soils from upland benches, and from 0.07 to 0.82 mg/L in soils from the central valley (Abrams and Jarrell, 1995).

Elevated concentrations of phosphorus in the lowland soils of the Tualatin Basin cause considerable concern about the effect of erosion. Soils in the valley plain, characterized by the highest extractable phosphorus concentrations and relatively low affinities for phosphorus, are generally poorly drained and frequently flooded in the winter (Washington County, 1982). These soils are highly susceptible to erosion, especially when subject to cultivation. Upland soils are probably less important as potential sources of phosphorus to streams in the Tualatin Basin because they are generally more permeable and undisturbed. Nonetheless, these soils may contribute phosphorus to surface waters in the basin if they are eroded from steep hillslopes after timber harvest.

If soil particles are retained within the system after they enter the streams, they can rapidly release dissolved phosphorus to the water column, or they can settle to the bottom of the channel and release phosphorus to the overlying water more slowly over a longer period of time. Much of the soil phosphorus that is available for release to water is associated with small-grained silt and clay particles because they have large surface areas and tend to be more readily eroded than larger silt and sand particles. Soil particles that are eroded to a stream, therefore, may be significantly enriched in phosphorus relative to the parent soil. As a consequence, these enriched stream bottom sediments may produce equilibrium phosphorus concentrations in the overlying water that are greater than expected based on the phosphorus content of the streambank or eroded field sediment.

## Geology

The general shape of the Tualatin River valley is similar to a bowl; the valley is surrounded by mountains and underlain entirely by Columbia River Basalt, dating from the middle Tertiary period. This basalt forms the uppermost consolidated rock or bedrock of the basin. The basalt layer is dense and resistant, and is composed of an aggregation of lava flows which vary in thickness from zero to more than 1,000 feet. The depth from the surface to the basalt layer ranges from zero to several feet along the basin boundaries, where outcrops occur occasionally, to nearly 1,500 feet in the center of the valley, near Hillsboro.

This "bowl" of basalt is partially filled with unconsolidated sedimentary material which has been described in several different ways. The valley fill deposits were grouped together by Hart and Newcomb (1965) as undifferentiated Tertiary and Quaternary valley fill. Trimble (1963) distinguished two basic layers: the lower or pre-Quaternary sediments, which he termed the "Troutdale Formation and Sandy River Mudstone equivalent," and the upper layer of lacustrine deposits dating from the Missoula Floods during the Pleistocene. In this report, the sediment layers are classified according to Madin (1990), who described the older, deeper deposits simply as the Sandy River Mudstone equivalent on the basis of similarity to the Sandy River Mudstone of Trimble. This material consists of quartzo-micaceous silts, clays, and fine grained sands with occasional interbeds of gravel, as well as considerable deposits of woody debris and peat. The uppermost Missoula Flood deposits are described as the catastrophic flood deposits, composed of coarse facies of gravel and fine facies of lacustrine sands, clays, and silts. These deposits range in thickness from zero feet around the valley perimeter to about 60 to 100 feet in the center of the basin (Madin, 1990). In many locations, this uppermost layer has been cut deeply by the major tributaries and the main stem of the Tualatin River. This layer corresponds to the terrace, sand and silt, and lacustrine deposits of Trimble (1963), and contains very little organic material. The interface between the two layers, in contrast, is characterized by extensive amounts of organic matter.

## Hydrology

Streamflow in the Tualatin River is responsive to precipitation in the basin, mainly in the form of winter rain, and exhibits a distinct pattern of high flow during the winter and low flow during the summer (fig. 2). Mean daily streamflows in the Tualatin River at RM 1.8 are characterized by a series of peaks ranging from 2,000 to 4,000 $ft^3/s$ (cubic feet per second) during the period November through April (water years 1976–93). With the end of the rainy season in the late spring, mean daily flows decrease significantly, and remain less than 500 $ft^3/s$ throughout the summer.

A major factor governing summer streamflow patterns in the Tualatin River is the release of water from Henry Hagg Lake, located in the Scoggins Creek subbasin. Henry Hagg Lake was created behind Scoggins Dam, constructed by the U.S. Bureau of Reclamation in the mid-1970s, to satisfy various water rights in the basin during the summer low-flow season. The operational plan for Scoggins Dam calls for full-pool conditions to exist in Henry Hagg Lake by the first of May of each year. This plan ensures that water in adequate quantities is available for irrigation, drinking, and flow augmentation during the summer season. The initiation of flow augmentation via Scoggins Creek from Henry Hagg Lake in 1976 significantly increased the streamflow in the river during the summer (fig. 3). During the late summer (July through September), mean monthly streamflow increased three- to fivefold. Since 1987, USA has ordered water releases from Henry Hagg Lake to maintain a minimum flow of 150 $ft^3/s$ at RM 33.3.

Ground water provides the major source of streamflow to the other tributaries during the summer; surface runoff is limited because of the scarcity of rainfall and dry soils. Local flow systems, percolating through the catastrophic flood deposits filling the valley, are probably the primary route for discharge of ground water to the tributaries (Hart and Newcomb, 1965). In general, local flow systems are characterized by short flow paths (with residence times on the order of days to years) (fig. 4), and tend to be relatively shallow and responsive to recharge events. Consequently, ground water in local flow systems is usually not highly mineralized, and conditions tend to be oxidizing rather than reducing, especially in systems characterized by little organic material, such as the catastrophic flood deposits in the Tualatin Basin.

In contrast, the main-stem river below about RM 55 is fed by a combination of shallow and regional ground water. The regional flow moves through the deeper strata (Sandy River Mudstone equivalent) and discharges more toward to the center of the basin. Flowpaths are relatively long in regional systems, are well insulated from events on the surface, and generally are characterized by slow velocities (fig. 4). Residence times tend to be long as a result, on the order of centuries. In deeper ground-water flow systems that contain large amounts of organic matter, like the Sandy River Mudstone equivalent, regional ground water tends to be more mineralized and more chemically reducing than shallow ground water.

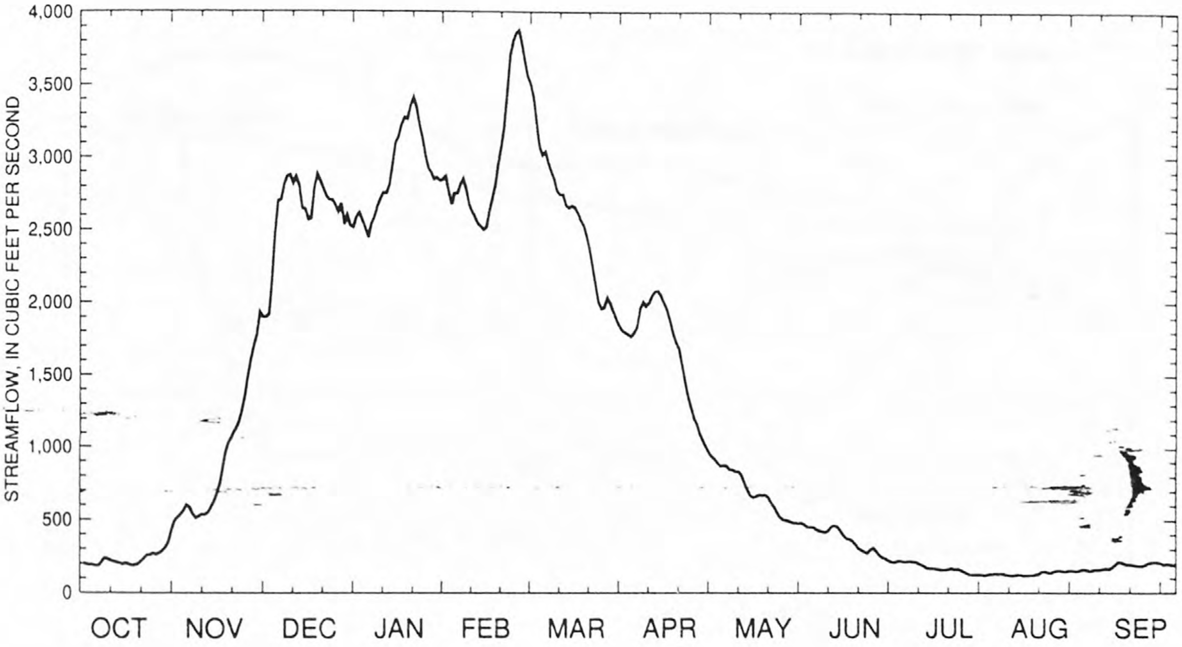



**Figure 2.** Mean daily streamflow in the Tualatin River, Oregon, at river mile 1.8 (West Linn) for water years 1976–93.

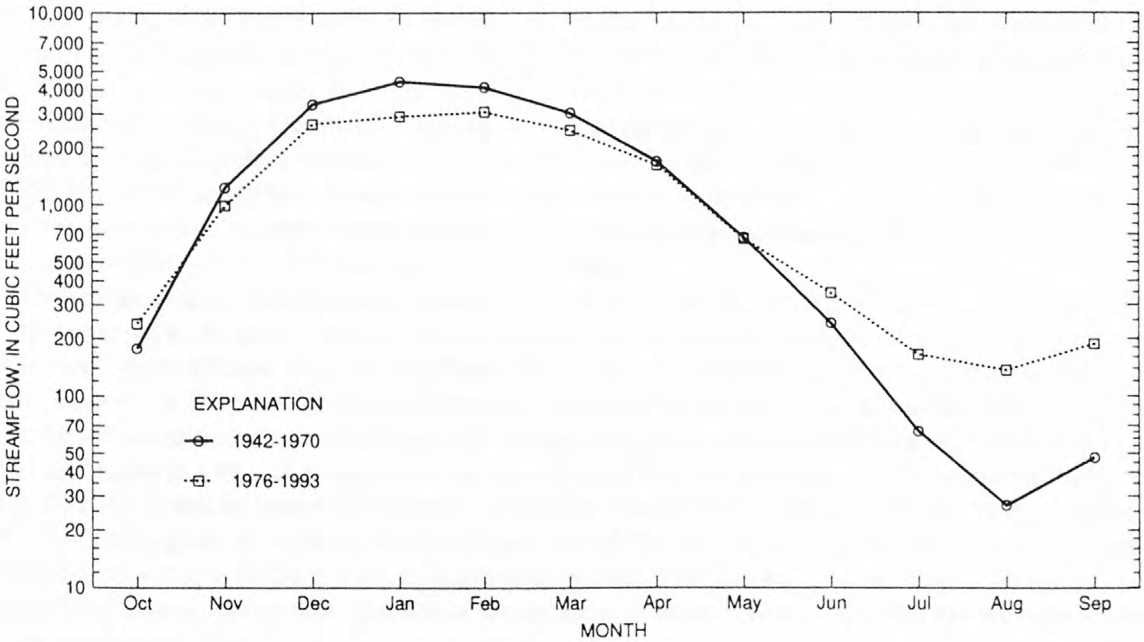



**Figure 3.** Mean monthly streamflow in the Tualatin River, Oregon, at river mile 1.8 (West Linn) for the period prior to flow augmentation from Henry Hagg Lake (water years 1942–70) and after flow augmentation began (water years 1976–93).

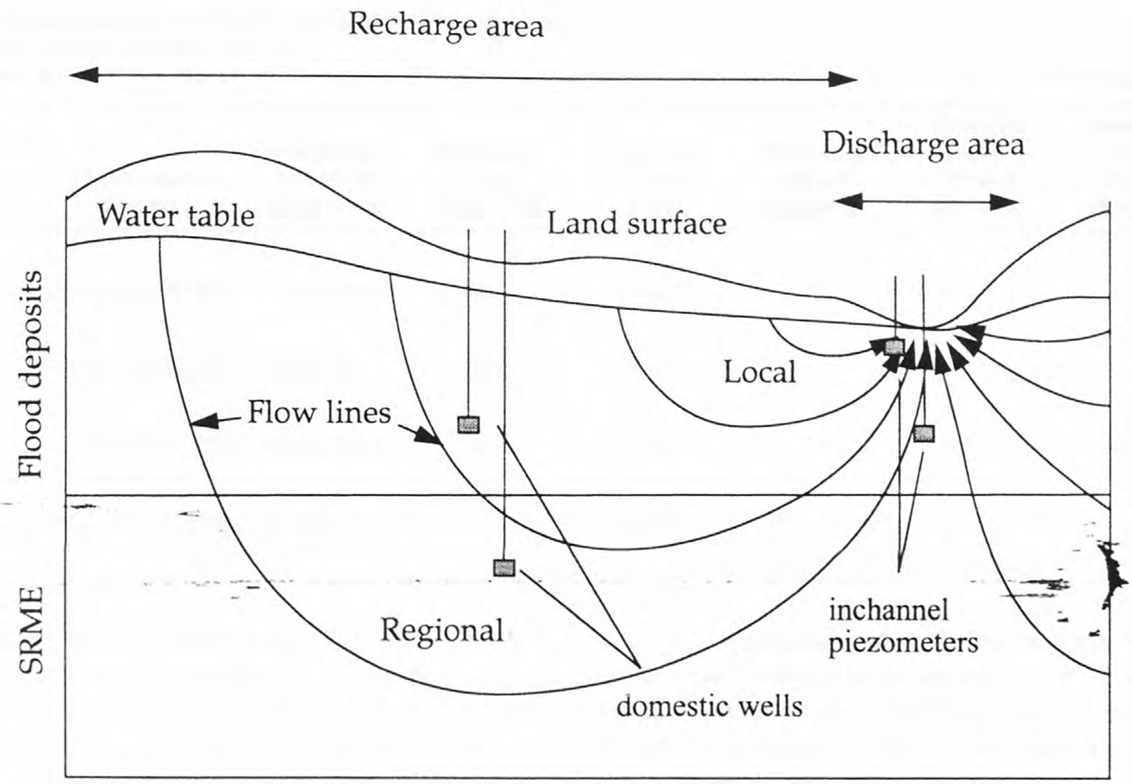



**Figure 4.** Conceptual diagram of ground-water flow lines in regional and local ground-water systems in the Tualatin River, Oregon (adapted from Heath, 1983; SRME, Sandy River Mudstone equivalent). Also shown are two hypothetical pairs of domestic wells and inchannel piezometers.

Four major WWTPs are operated by USA within the Tualatin Basin, and they vary considerably in size and impact on streamflow and water quality in the river (table 1). Two of these plants are small and are located in the western part of the valley at Forest Grove and Hillsboro. Treated effluent from these plants is diverted to irrigated land from May 1–October 31; during the rest of the year, the effluent is discharged directly to the river. Primary and secondary treatment is used in these smaller plants. The two larger plants, at Rock Creek (RM 38.1) and Durham (RM 9.3), are located in more densely populated areas, and discharge treated effluent to the river throughout the year. Primary and secondary treatment is maintained all year, with advanced tertiary treatment designed for nutrient removal during the summer.

One of the smaller surface-water sources to the Tualatin River is a large natural wetland (approximately 450 acres) known as Jackson Bottom, located near the low point of the basin south of Hillsboro. During the summer, treated effluent from the Hillsboro WWTP (RM 43.8) historically was diverted to wetlands at Jackson Bottom for the purpose of enhancement of wetland habitat as well as additional nutrient removal. To reduce the influence of Jackson Bottom on the Tualatin River, the acres available for irrigation were doubled in 1991 and again in 1993. Drainage from Jackson Bottom into the Tualatin River is primarily via Jackson Slough (RM 43.8) and an unnamed tributary informally named "Miller Swale" (RM 43.5). Additionally, in 1989, USA established the Jackson Bottom Experimental Wetland on about 15 acres in the eastern portion of the wetland, adjacent to Miller Swale, to explore the potential for the wetlands to remove phosphorus and nitrogen from treated wastewater. The use of the Jackson Bottom Experimental Wetland was discontinued after the summer of 1992.

The withdrawals from the Tualatin River for irrigation and municipal water supply divert a significant amount of water from the river. Irrigation withdrawals from the river occur at multiple points. Approximately 25,000 acres are irrigated by surface water in the basin, with about 10,500 of these serviced by the Tualatin Valley Irrigation District) directly from the main-stem river by a pipeline at the Springhill Pumping Plant at RM 56.6. In addition, approximately 10,000 acres are irrigated directly from the river by individual farmers,

**Table 1.** Characteristics of effluent discharge for the major wastewater treatment plants in the Tualatin River Basin, Oregon, during May through October 1991–93
[Map number, see fig. 10; discharge in cubic feet per second (million gallons per day); --, effluent discharge to land; data from Unified Sewerage Agency]

| Map number | USGS station number | Wastewater treatment plant name | Discharge point (river mile) | Population served (1990) | Mean daily effluent discharge | Minimum daily effluent discharge | Maximum daily effluent discharge |
|---|---|---|---|---|---|---|---|
| 33 | 453037123051700 | Forest Grove | 55.2 | 14,000 | -- | -- | -- |
| 34 | 453040123052000 | Hillsboro | 42.8 | 19,100 | -- | -- | -- |
| 35 | 452938122565500 | Rock Creek | 38.1 | 135,000 | 24.1 (15.6) | 19.0 (12.3) | 43.0 (27.8) |
| 36 | 452359122454500 | Durham | 9.3 | 142,000 | 23.8 (15.4) | 18.3 (11.8) | 39.4 (25.5) |

primarily between RM 55 and 16.2. Peak withdrawals for irrigation generally occur during July and August because the weather is hot and dry and most of the land has an actively growing crop. Drinking water for the cities of Hillsboro, Forest Grove, and Beaverton is also provided from the Springhill Pumping Plant by the Joint Water Commission. Withdrawals for municipal use are more constant than withdrawals for irrigation, although there may be wide diel and day-to-day variations.

Water is also diverted from the Tualatin River at RM 6.7 by the Lake Oswego Corporation into a canal that empties into Lake Oswego. The river is impounded by a low-head diversion dam located on a natural geologic sill at RM 3.4, which raises the surface elevation by several feet to allow adequate flow to enter the canal via gravity. During the summer, when the inriver streamflow is low, flashboards are installed on the dam to raise the water level slightly higher. The dam at RM 3.4 affects water surface elevation in the Tualatin River for nearly 25 miles upstream, and contributes to the distinct reservoir-like character of the lower river. The increased water elevation is most pronounced (about 4–6 feet) downstream of a natural sill at RM 10; upstream from this sill, the increase in water elevation is less (about 1–2 feet). Water velocities are low throughout the lower river, especially during summer low-flow periods. Additionally, the streambed is irregular and characterized by pools more than 12 feet deep that are interrupted by relatively shallow sills, especially downstream of RM 12. As a consequence, thermal stratification can occur in this region of the lower river during the summer months during periods of high solar insolation.

## WATER-QUALITY ISSUES

During the summer, when streamflow is low and light and nutrient conditions are favorable for algal growth, the relatively long residence time in the lower reservoir-like reach of the river supports the growth of large populations of phytoplankton. These populations begin to develop below RM 30, and increase by up to eightfold (as measured by concentrations of chlorophyll-a) over the course of the next 25 miles (fig. 5). Chlorophyll-a concentrations reach their maximum in the lower river, observed at RM 5.5, and exceed 30 μg/L for long periods during the summer in violation of the State action level of 15 μg/L (fig. 6). Peaks in chlorophyll-a concentrations often exceed 50 μg/L at this site, and occasionally exceed 100 μg/L. Generally, extended periods of streamflow less than 300 $ft^3/s$ are necessary for the growth of large algal blooms. When flow, light, and nutrient conditions are favorable, these blooms persist for long periods, sometimes several months.

Concentrations of DO exhibit a distinct diel cycle during the summer as a result of algal photosynthesis and respiration. A range of 3 to 5 mg/L between minimum and maximum values is commonly

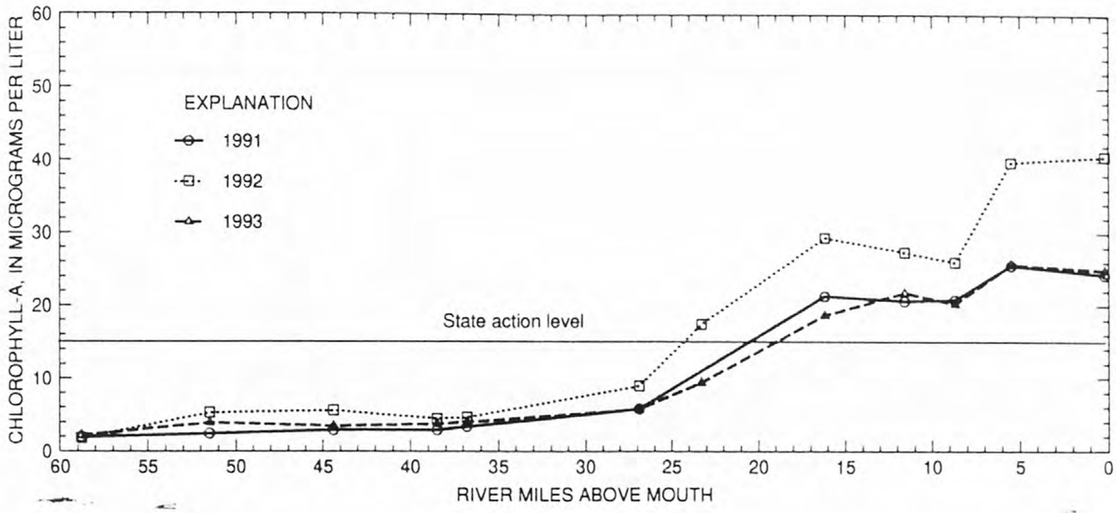



**Figure 5.** Mean concentrations of chlorophyll-a (averaged over the top 10 feet of the water column) at sample sites in the Tualatin River, Oregon, during May through October 1991–93.

observed in the lower river during the height of an algal bloom (fig. 7). Supersaturated concentrations of DO can result from the high rates of photosynthesis and the slow rate of reaeration; peaks as high as 200 percent of saturation have been observed on occasion. When skies are overcast, however, phytoplankton populations decline substantially, resulting in a precipitous drop in concentrations of both chlorophyll-a and DO. As a consequence, violations of the Oregon State minimum DO standard of 6 mg/L (the standard in effect during the 1991–93 period) periodically occur in the lower river (fig. 7). For example, in July 1991, chlorophyll-a concentrations dropped from greater than 120 to less than 10 µg/L in one week; these values were associated with a concomitant reduction in maximum DO concentrations from 21 to 5.6 mg/L during the same period. Inriver nitrification can also contribute to oxygen depletion when WWTP ammonia loads are large and water temperatures are warm enough to stimulate the growth of nitrifying bacteria.

The effect of algal decline and nitrification on DO is augmented by sediment oxygen demand resulting from bacterial decay of the organic-rich bottom sediments, a major sink for DO in the Tualatin River (Rounds and Doyle, 1997; Rounds and others, 1998). Several interacting factors are involved: First, the reduced rate of streamflow in the lower river during the summer increases the exposure of the overlying water column to the sediment, both in terms of exposure time and the ratio of water volume to bottom surface area. Second, the effect of sediment decay is compounded by warm water temperatures characteristic of the summer, often greater than 20°C, which support rapid growth and metabolism of benthic bacterial communities. Finally, the rate of reaeration from the atmosphere is low as a result of the sluggish water velocities.

Other water-quality issues in the Tualatin River include excessively high pH and potential ammonia toxicity. Under algal bloom conditions (low streamflow, sunny skies, and the coincident warm water temperatures), pH values increase in the lower river and occasionally violate the Oregon State maximum pH standard of 8.5 (fig. 8). Depletion of carbon dioxide from the water column by the high rate of algal growth is exacerbated by the low reaeration rate, which limits the replenishment of carbon dioxide from the atmosphere. Ammonia toxicity becomes a problem when inriver concentrations of ammonia increase to about 2 mg/L. The fraction of ammonia ($NH_3 + NH_4^+$) that is not ionized ($NH_3$) depends upon pH and water temperature, and poses a threat to aquatic organisms, especially fish, under certain conditions. This situation can occur when an algal bloom occurs and there is incomplete nitrification of ammonia in the WWTPs. Concentrations of ammonia at RM 8.7, just below the Durham WWTP, occasionally exceeded 1.5 mg/L under summer flow conditions during 1991 and 1993, and once exceeded 3 mg/L (fig. 9). On several occasions, the calculated values for concentrations of unionized ammonia at this site exceeded the U.S. Environmental Protection Agency toxicity criteria for 4-day average concentrations (U.S. Environmental Protection Agency, 1986) (fig. 9).

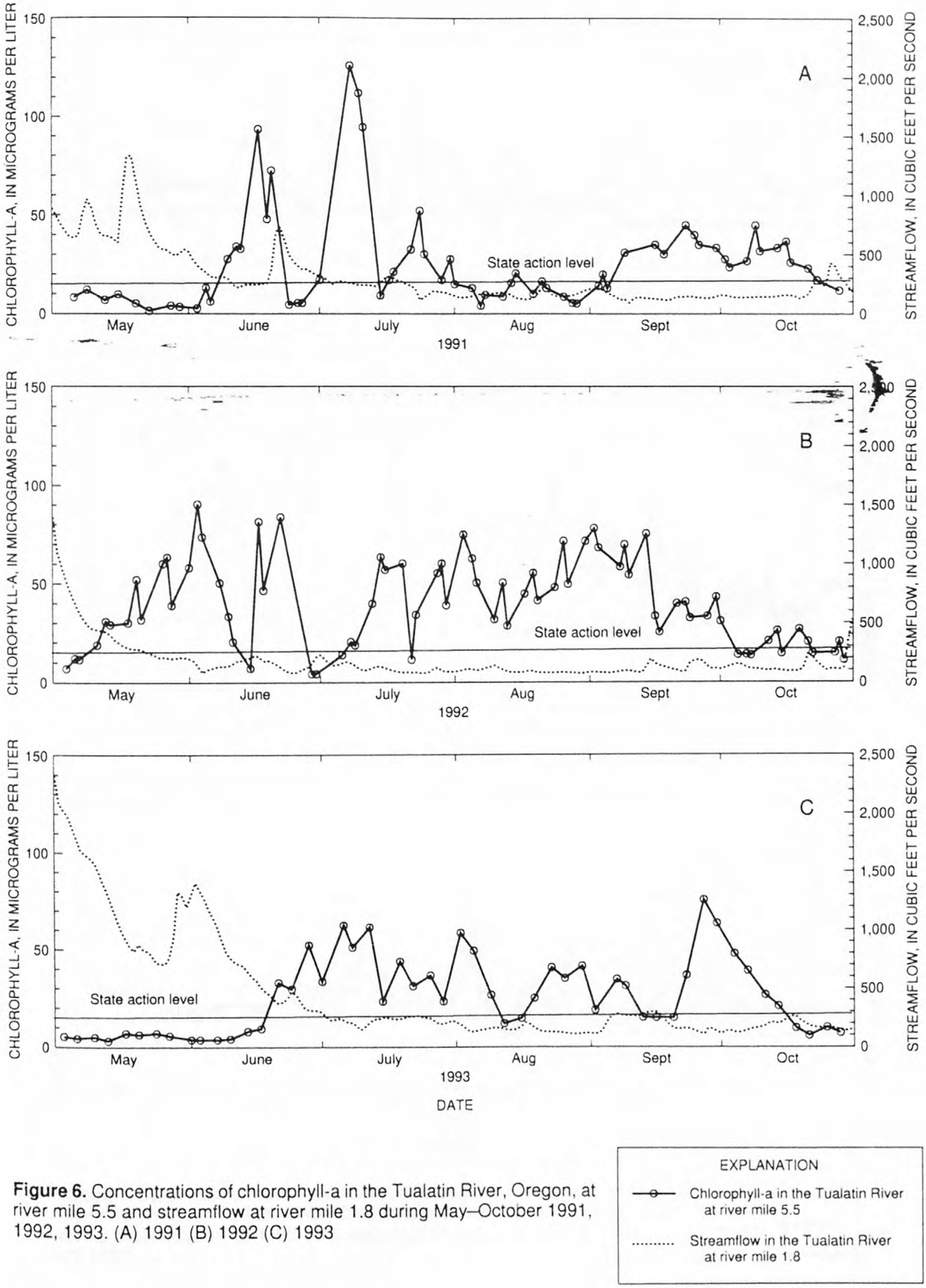



**Figure 6.** Concentrations of chlorophyll-a in the Tualatin River, Oregon, at river mile 5.5 and streamflow at river mile 1.8 during May–October 1991, 1992, 1993. (A) 1991 (B) 1992 (C) 1993

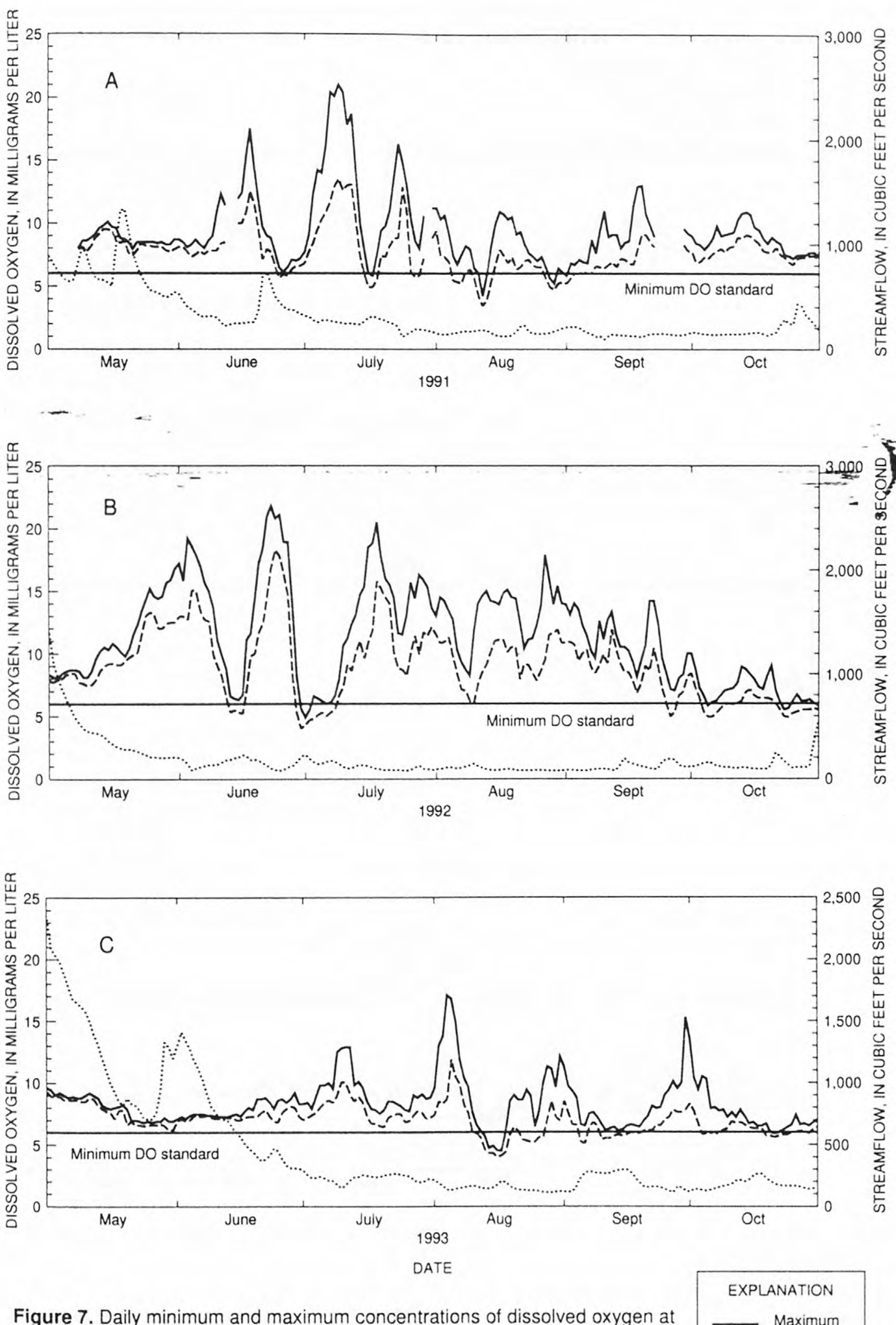



**Figure 7.** Daily minimum and maximum concentrations of dissolved oxygen at river mile 3.4 in the Tualatin River, Oregon, and streamflow at river mile 1.8 during May–October 1991–93. (DO, dissolved oxygen) (A) 1991 (B) 1992 (C) 1993

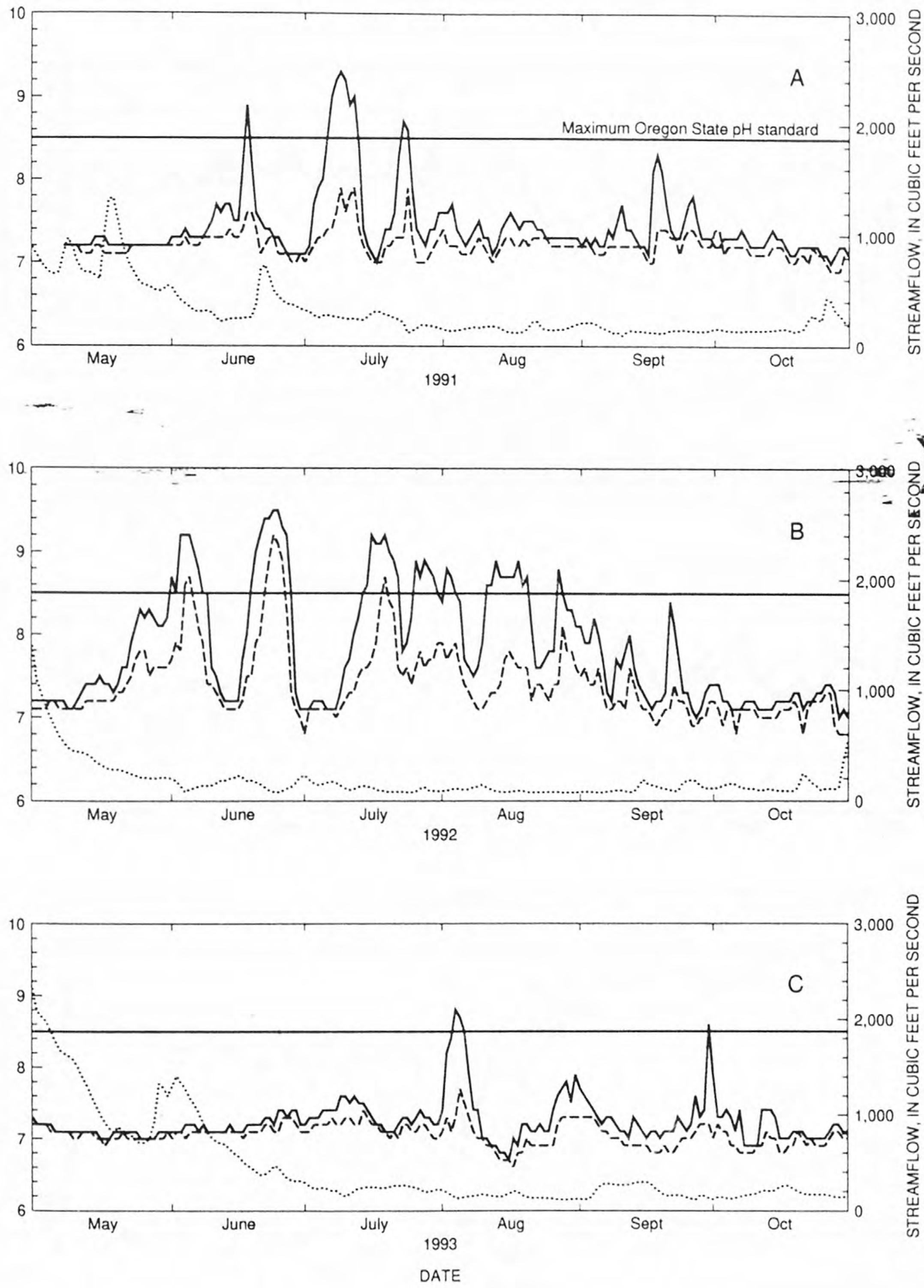



**Figure 8.** Daily minimum and maximum pH at river mile 3.4 in the Tualatin River, Oregon, and streamflow at river mile 1.8 during May–October 1991–93. (A) 1991 (B) 1992 (C) 1993

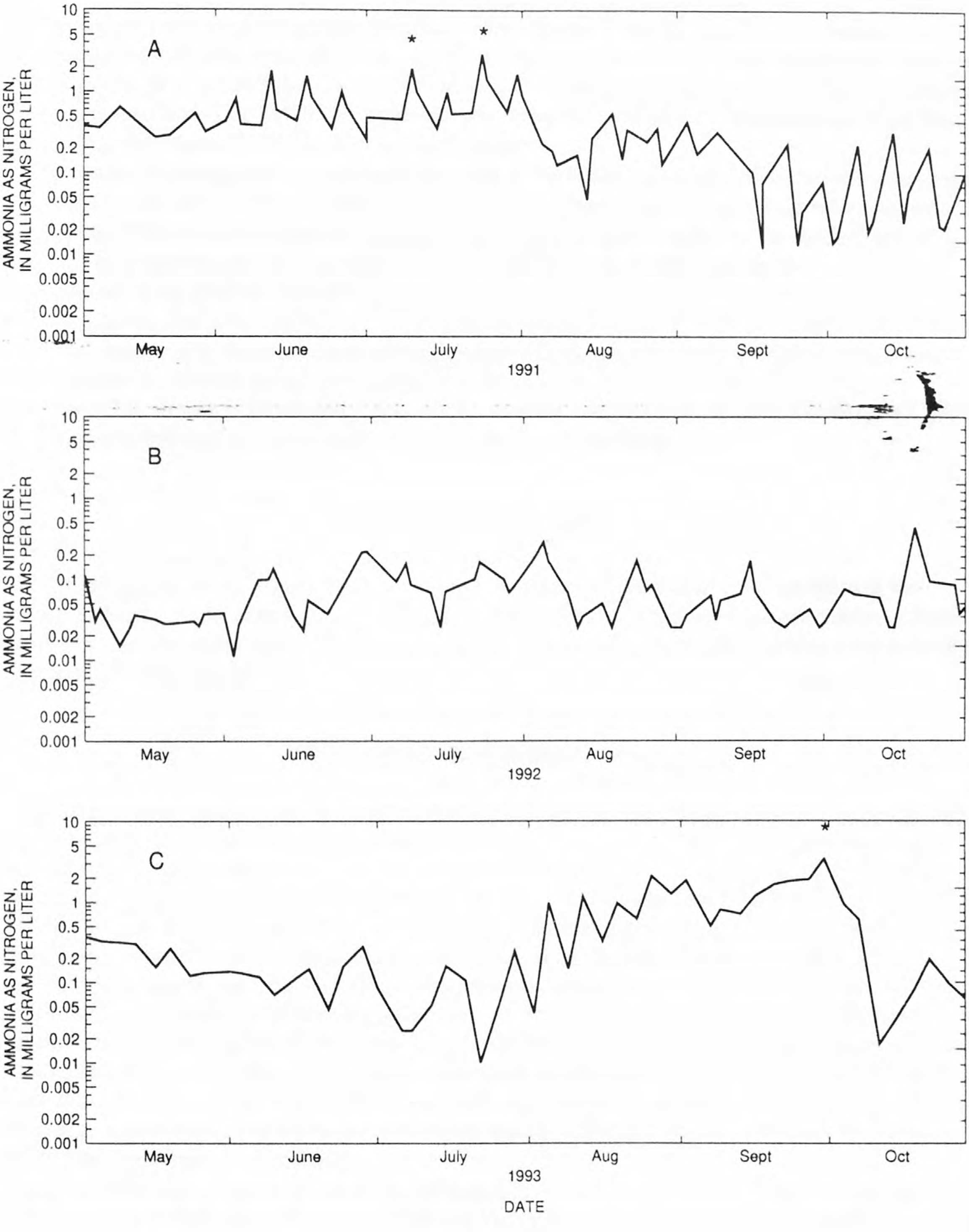



**Figure 9.** Concentrations of ammonia as nitrogen in the Tualatin River, Oregon, at river mile 8.7 during May–October 1991–93. * indicates samples where calculated concentrations of un-ionized ammonia exceeded the U.S. Environmental Protection Agency ammonia toxcity criteria for 4-day average concentrations (EPA, 1986). (A) 1991 (B) 1992 (C) 1993

The Tualatin River was listed in 1984 and 1986 as "Water-Quality Limited" by the Oregon Department of Environmental Quality (ODEQ) in response to the Federal Clean Water Act. The rationale for the listing was nuisance algal blooms and low concentrations of DO. Total maximum daily loads (TMDLs) were developed for total phosphorus and ammonia in the Tualatin River by the ODEQ in September 1988 (Oregon Department of Environmental Quality, 1997). The phosphorus TMDL was designed to limit the growth of algae in the river, and thereby protect the aesthetic qualities of the river and reduce the exceedances of the pH standard. The TMDL for ammonia was designed to reduce oxygen demand within the river by limiting the extent of inriver ammonia nitrification.

In response, the designated management agencies in the basin, including USA, the various counties and cites in the basin, and the Oregon Departments of Forestry and Agriculture, developed management plans to meet the TMDL load allocations. Between 1988 and 1990, USA upgraded the Rock Creek WWTP to meet its point-source wasteload allocation for ammonia and total phosphorus. In 1992, a pilot project was implemented at the Durham WWTP that allowed it to meet its wasteload allocation for both ammonia and total phosphorus that year. During 1993, the permanent upgrades were being installed at the Durham WWTP; as a consequence, the wasteload allocations were not met at the Durham WWTP until construction was complete in 1994. In addition to the point-source reductions, Best Management Practices were developed by the designated management agencies to meet the nonpoint-source total phosphorus TMDL by minimizing the delivery of total phosphorus to the streams in the basin.

# METHODS OF STUDY

The sampling approach was designed to quantify the sources and transport of nutrients in the Tualatin River during summer low-flow conditions. Complete documentation of sampling sites, streamflow measurement, and techniques of field-measurement, sampling, and laboratory analysis are provided in Doyle and Caldwell (1996).

## Streamflow and Withdrawals

Streamflow sites were chosen at key locations in the basin to describe major inputs and withdrawals of water throughout the length of the main-stem river (fig. 10). Continuous streamflow gaging stations were maintained at 5 main-stem river sites and 4 major tributary sites (table 2). In addition, Oregon Water Resources Department (OWRD) maintained gaging stations at Rock Creek and Chicken Creek; staff gages were located at these stations, and periodic discharge measurements were made by OWRD personnel to develop rating tables. Incidental gage height readings at these sites were made concurrent with the collection of water-quality samples and reflect instantaneous streamflow. Streamflow in Jackson Slough and Miller Swale was measured at the time of sample collection using a pygmy flow meter. Streamflow in other selected tributaries was based on biweekly to monthly streamflow measurements, with intermittent values estimated by hydrographic comparison with similar streams in the basin. Daily mean effluent discharge data from the two large WWTPs (Rock Creek and Durham) were provided by USA from continuous discharge monitors; during the summer low-flow season, effluent from the smaller WWTPs was diverted to land for irrigation purposes.

Large withdrawals of water occur at the Springhill Pumping Plant (RM 56.1), and at Oswego Canal (RM 6.7) (table 2). Withdrawals of water by Tualatin Valley Irrigation District at the Springhill Pumping Plant were monitored by an acoustic velocity meter; measured values were used directly in this study. Streamflow in the Oswego Canal was measured by OWRD.

Measurements of the volume of water withdrawn by direct pumping from the main-stem river for irrigation were not available. Estimates of these withdrawals were calculated based upon the observed ratio between the rate of water withdrawal and the number of acres irrigated by pipeline from the Springhill Pumping Plant. It was assumed that this ratio was similar for all the acreages with water rights within the basin. Two groups of water rights were identified: those defined by permits from Tualatin Valley Irrigation District, and those administered by OWRD (Watermaster District 19). The calculations assumed that 100 percent of Tualatin Valley Irrigation District acres and 50 percent of OWRD acres were irrigated with Tualatin River water (Jerry Rodgers, OWRD, oral commun.,1992). For the purpose of the water budgets, the water volumes for these withdrawals were summed over several subreaches.

## Seepage Measurements

To determine whether ground water discharges to the main stem of the Tualatin River during summer low-flow periods, and to roughly measure that discharge rate, seepage meters were installed at five main-stem sites in September of 1993. Measurement sites were located at RMs 43.4, 36.8, 27.0, 20.3, and 11.7; these locations were both within and above the reservoir reach of the river, and were within a reach that was suspected to receive regional ground-water discharge. Three seepage meters were placed in different locations at each site: (1) in shallow water near the river bank; (2) in deep water at the middle of the channel; and (3) in medium-depth water between the first two. Measurements of seepage were obtained from each meter throughout the months of September and October, 1993.

The difficulty of accurately measuring seepage rates is compounded by the problems inherent to extrapolating measurements to the entire sediment surface area of the river. A simple seepage meter design was chosen because the primary task was to detect seepage rather than measure its rate precisely. Fifteen seepage meters were constructed from the ends of 55-gallon steel drums, using a design similar to that of drum-type meters from other studies (Carr and Winter, 1980; Woessner and Sullivan, 1984).

Each seepage meter used half of a 55-gallon drum. On top of the half-drum, a short length of 3/8-inch (outside diameter) steel tubing was attached to a Swagelok fitting that was tapped into the drum-top and sealed on the outside with silicone epoxy. Other ports on top of the meter were sealed shut with silicone epoxy. A length of 3/8-inch (inside diameter) plastic tubing was connected to the steel tube with a tubing clamp. A 2-liter plastic bag was attached to the other end of the plastic tube using another tube and clamp assembly. Large U-bolts were attached to the drum-top as handles; silicone was used to seal the drum-top around the handles. The diameter of each meter was roughly 1.8 feet (0.56 meters), giving a cross-sectional area of 2.7 square feet (0.25 square meters).

The seepage meters were installed by scuba divers. Each meter was pushed into the sediment to a depth of at least 4 inches, leaving the drum-top at a higher level than the sediment surface. Excellent seals to the sediment were obtained in all cases. Care was taken to make sure that no air pockets remained in the seepage meter before it was installed. A rope was attached to one handle so that the meter could be retrieved at a later date. The plastic tube leading from the drum-top to the plastic bag was long enough so that the bag could be accessed from the river surface. The bag was attached to the tubing while both were under the river surface; the bag was initially empty of both water and air. To prevent the river current from exerting a back-pressure on the bag, the bag was shielded inside a bottomless, plastic milk jug. The rope and the plastic tubing were both tied to a buoy with a length of cord to provide easy access from the river surface.

These seepage meters measure ground-water discharge by simple displacement. Water that enters the drum displaces water into the tube and then into the bag. The time of bag attachment was recorded. After a period ranging from minutes to days, the bag, while still underwater, was removed from the end of the tube, taking care not to allow the captured water to escape. After measuring the volume of water in the bag, the seepage rate was calculated based upon the elapsed time and the area of sediment intercepted by the drum.

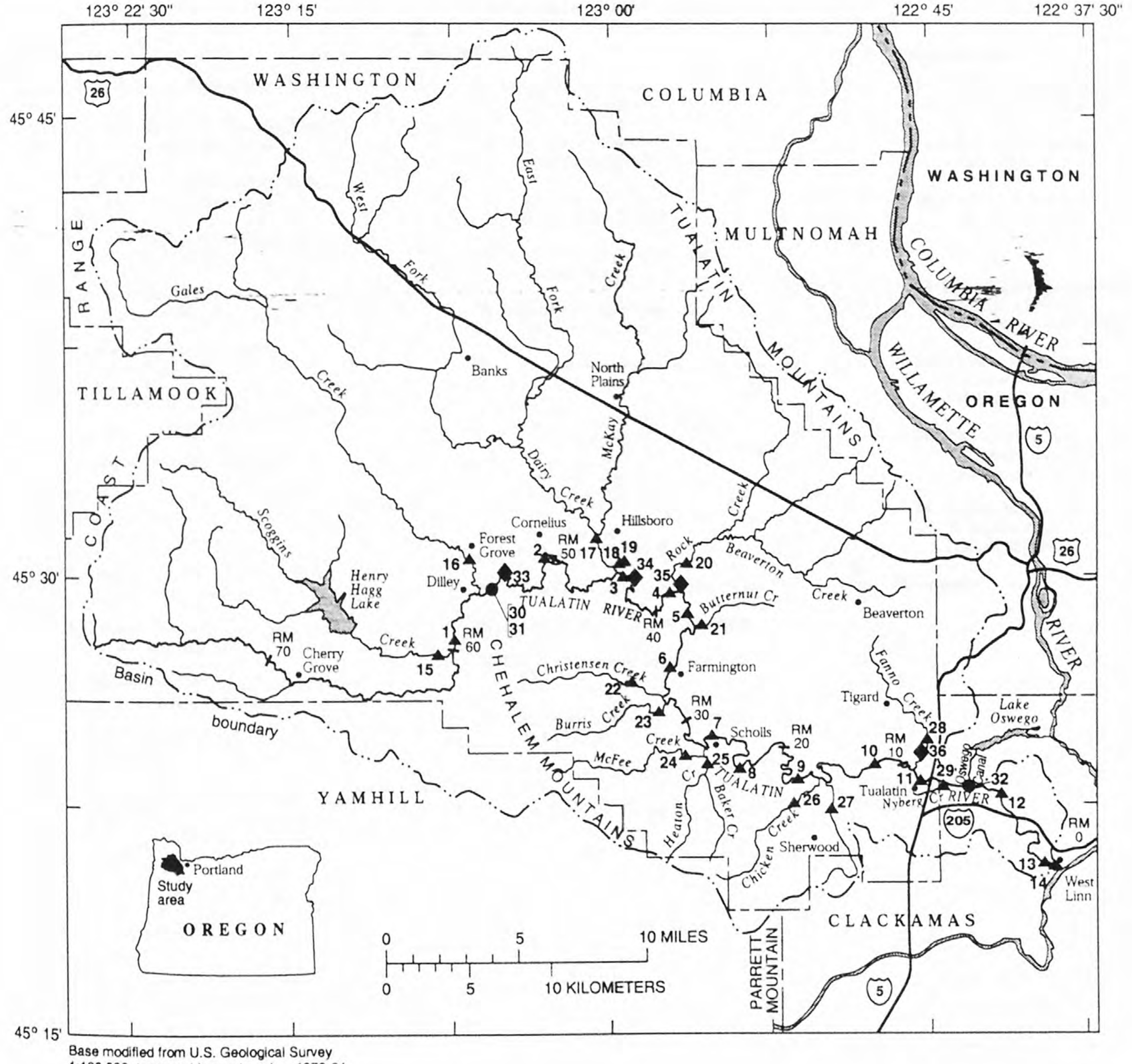



**Figure 10.** Tualatin River Basin, Oregon, with water-quality sampling sites.

## EXPLANATION

2 ▲ **River site**

1 Tualatin River at Dilley (RM 58.8)

2 Tualatin River at Golf Course Road near Cornelius (RM 51.5)

3 Tualatin River above Jackson Bottom near Hillsboro (RM 44.4)

4 Tualatin River at Rood Bridge at Hillsboro (RM 38.4)

5 Tualatin River at Meriwether irrigation pump (RM 36.8)

6 Tualatin River at Farmington (RM 33.3)

7 Tualatin River at Highway 210 bridge, near Scholls (RM 26.9)

8 Tualatin River near Scholls (RM 23.2)

9 Tualatin River at Elsner Road near Sherwood (RM 16.2)

10 Tualatin River near Highway 99W bridge near King City (RM 11.7)

11 Tualatin River at Boones Ferry Road at Tualatin (RM 8.7)

12 Tualatin River at Stafford Road near Lake Oswego (RM 5.5)

13 Tualatin River at West Linn (RM 1.8)

14 Tualatin River at Weiss Bridge (RM .2)

22 ▲ **Tributary site**

15 Scoggins Creek at Old Highway 47 (RM 60.0)

16 Gales Creek at Route 47 at Forest Grove (RM 56.7)

17 Dairy Creek at Highway 8 near Hillsboro (RM 44.8)

18 Jackson Slough at mouth near Hillsboro (RM 43.8)

19 Unnamed tributary near Hillsboro (RM 43.5)

20 Rock Creek near Hillsboro (RM 38.1)

21 Butternut Creek at River Road near Farmington (RM 35.7)

22 Christensen Creek near Farmington (RM 31.9)

23 Burris Creek near Farmington (RM 31.6)

24 McFee Creek near Scholls (RM 28.2)

25 Baker Creek near Scholls (RM 28.2)

26 Chicken Creek near Sherwood (RM 15.2)

27 Rock Creek (South) near Sherwood (RM 15.2)

28 Fanno Creek at Durham (RM 9.3)

29 Nyberg Creek at Tualatin (RM 7.5)

32 ● **Withdrawal site**

30 Springhill Pumping Plant on Tualatin River (RM 56.1)

31 Joint Water Commission Plant (RM 56.1)

32 Oswego Canal near Lake Oswego (RM 3.4)

33 ◆ **Discharge site**

33 Forest Grove Wastewater Treatment Plant at Forest Grove (RM 55.2)

34 Hillsboro Wastewater Treatment Plant at Hillsboro (RM 42.8)

35 Rock Creek Wastewater Treatment Plant at Hillsboro (RM 38.1)

36 Durham Wastewater Treatment Plant near Durham (RM 9.3)

RM 10 **River mile**

**Table 2.** Sampling sites and periods of record for continuous discharge and water-quality sampling in the main-stem Tualatin River (Oregon), its tributaries, and major diversions during May–October in 1991–93
[Map number, see fig. 10; tributary river miles represent the river mile in the Tualatin River main stem at the confluence; Q, continuous discharge record; WQ, water-quality sampling record]

| Map number | USGS station number | Station name | River mile | Q | WQ |
|---|---|---|---|---|---|
| | | **Main stem** | | | |
| 1 | 14203500 | Tualatin River near Dilley | 58.8 | 91–93 | 91–93 |
| 2 | 14204800 | Tualatin River at Golf Course Road near Cornelius | 51.5 | 92–93 | 91–93 |
| 3 | 14206250 | Tualatin River above Jackson Bottom near Hillsboro | 44.4 | | 91–93 |
| 4 | 14206440 | Tualatin River at Rood Bridge at Hillsboro | 38.4 | 91–93 | 91–93 |
| 5 | 14206460 | Tualatin River at Meriwether irrigation pump | 36.8 | | 91–93 |
| 6 | 14206500 | Tualatin River at Farmington | 33.3 | 91–93 | |
| 7 | 14206690 | Tualatin River at Highway 210 bridge, near Scholls | 26.9 | | 91–93 |
| 8 | 14206700 | Tualatin River near Scholls | 23.2 | | 91–93 |
| 9 | 14206740 | Tualatin River at Elsner Road near Sherwood | 16.2 | | 91–93 |
| 10 | 14206785 | Tualatin River at Highway 99W bridge near King City | 11.7 | | 91–93 |
| 11 | 14206960 | Tualatin River at Boones Ferry Road at Tualatin | 8.7 | | 91–93 |
| 12 | 14207050 | Tualatin River at Stafford Road near Lake Oswego | 5.5 | | 91–93 |
| 13 | 14207500 | Tualatin River at West Linn | 1.8 | 91–93 | |
| 14 | 14207600 | Tualatin River at Weiss Bridge | .2 | | 91–93 |
| | | **Tributaries** | | | |
| 15 | 14203000 | Scoggins Creek at Old Highway 47 | 60.0 | 91–93 | 91–93 |
| 16 | 14204530 | Gales Creek at Route 47 at Forest Grove | 56.7 | 91–93 | 91–93 |
| 17 | 14206200 | Dairy Creek at Highway 8 near Hillsboro | 44.8 | 91–93 | 91–93 |
| 18 | 14206255 | Jackson Slough at mouth near Hillsboro | 43.8 | | 91–93 |
| 19 | 14206270 | Unnamed tributary near Hillsboro (Miller Swale) | 43.5 | | 91–93 |
| 20 | 14206450 | Rock Creek near Hillsboro | 38.1 | | 91–93 |
| 21 | 14206490 | Butternut Creek at River Road near Farmington | 35.7 | | 91–92 |
| 22 | 14206600 | Christensen Creek near Farmington | 31.9 | | 91–93 |
| 23 | 14206650 | Burris Creek near Farmington | 31.6 | | 91–93 |
| 24 | 14206670 | McFee Creek near Scholls | 28.2 | | 91–93 |
| 25 | 14206680 | Baker Creek near Scholls | 28.2 | | 91–93 |
| 26 | 14206750 | Chicken Creek near Sherwood | 15.2 | | 91–93 |
| 27 | 14206760 | Rock Creek (South) near Sherwood | 15.2 | | 91–93 |
| 28 | 14206950 | Fanno Creek at Durham | 9.3 | 91–93 | 91–93 |
| 29 | 14206970 | Nyberg Creek at Tualatin | 7.5 | | 91–92 |
| | | **Diversions** | | | |
| 30 | 14204650 | Springhill Pumping Plant | 56.1 | 91–93 | |
| 31 | 14204648 | Joint Water Commission Plant | 56.1 | 91–93 | |
| 32 | 14207000 | Oswego Canal near Lake Oswego | 6.7 | 91–93 | |

## Water-Quality Sampling

Because flow measurements are required for the calculation of nutrient loads, water-quality sampling sites were colocated with streamflow sites wherever possible. The water-quality sampling strategy was designed to provide a comprehensive survey of the nutrient inputs from surface-water sources, and estimates of inputs from ground-water sources to the river.

Most of the water-quality samples were collected by the joint efforts of personnel from the USGS and USA. Other agencies that were involved with certain components of the sampling program on occasion included Tualatin Valley Irrigation District, the City of Beaverton, and the Oregon Department of Agriculture. Surface-water sampling included a fixed-station routine for main-stem and tributary sites, which was maintained throughout the 3-year study period, and a synoptic survey of small tributaries, tile drains, and surface seeps, which occurred during 1992. Ground-water sampling included data collected during the study period, as well as data collected in 1990 and 1994.

### Fixed Stations

Twelve sites on the main-stem Tualatin River and 1 site each near the mouths of the 5 major tributaries and 10 smaller tributaries were sampled throughout the 3-year period of the project (fig. 10, table 2). In addition, composite daily mean effluent samples were obtained for the WWTPs by USA personnel. The fixed-station sites were chosen on the basis of their location upstream and downstream from major WWTP and tributary sources, as well as their accessibility for sampling from bridges. Samples were collected in the morning and afternoon at most sites in the lower river to estimate any diel variations of WWTP loading or algal productivity on nutrient and chlorophyll-a concentrations.

Vertically and horizontally integrated samples were collected by USGS personnel, sampling at five points in a cross section primarily using a weighted bottle sampler. Because of sluggish streamflow (even in the tributaries), and the lack of sand in the samples, weighted bottle samples were considered to be representative. When wading sections were available, and streamflow velocity was less than 1 foot per second, a D81 sampler was used (Edwards and Glysson, 1988). Sampling was integrated from the surface to within 1 foot from the bottom in shallow sections and limited to the upper 10 feet in deeper sections. Integration below 10 feet was avoided to prevent sampling cooler, hypolimnetic waters that may not have been representative of the free-flowing part of the river. Samples were composited in a churn splitter and dispensed directly into bottles, which were field rinsed with native water before being filled. Periodically, hypolimnetic water was sampled separately with a Van Dorn bottle and filtered immediately.

During 1991, single samples from the river centroid, integrated over the top 3 feet only, were collected by USA personnel, whereas USGS personnel used the method described above. USA samples were dispensed directly from the 2-liter sampler bottle after shaking. Although these USA samples were not ideal, nutrient concentrations in samples collected by the two agencies during 1991 were essentially identical. During 1992 and 1993, USA personnel switched to the sampling techniques used by the USGS.

Field measurements of pH, water temperature, specific conductance, and DO were taken by USGS personnel using a Hydrolab$^{TM}$ multiparameter water-quality sensor. Readings were taken in the centroid, with vertical profiles at 3-foot intervals measured when the depth was sufficient. Periodically, cross-sectional measurements were made to verify that centroid measurements were representative of the river. Generally, measurements were within 0.2 units for pH, 0.5°C for water temperature, 0.5 mg/L for DO, and 2 μS/cm (microsiemens per centimeter) for specific conductance. Field instruments were calibrated prior to each sampling trip, and post-calibrations were done within one day following every trip. Calibration for pH and specific conductance was checked against standards that bracketed the anticipated values in the river; calibration for DO was done using an air-calibration technique. In addition to the weekly field measurements, continuous measurements of pH, water temperature, specific conductance, and DO were obtained from a four-parameter field monitor that was installed and maintained at RM 3.4 (fig. 10).

During 1991 only, field measurements of pH, water temperature, specific conductance, and DO were taken from the surface (3-foot depth) by USA personnel with separate instruments as follows: pH, Orion™ model 250; water temperature and specific conductance, YSI™ model 3000; DO, YSI™ models 57 and 58. Field measurements during 1992 and 1993 by USA personnel were taken using a Hydrolab™ multiparameter water-quality sensor, as previously described.

Sites at Jackson Bottom were not included in the original sample design, although sampling was initiated in July 1991 to assess the importance of the area as a source of nutrients to the main-stem river. Samples were taken by USGS personnel from Jackson Slough and Miller Swale once per month during July through October in 1991, and once or twice per month during May through October in 1992 and submitted to the USGS National Water Quality Laboratory in Denver, Colorado. During the summer of 1993, Jackson Slough and Miller Swale became part of the fixed-station sampling program and were sampled biweekly; these samples were submitted to the USA Water Quality Laboratory.

### Synoptic Survey

A synoptic survey of surface-water inputs to the upper river (RM 51.6 to 27.0) was conducted between June 1–8, 1992 to determine the importance of tile drain inputs, small tributaries, and visible ground-water seeps on the nutrient budget of the river. An effort was made to sample most surface-water inputs that entered the river in that reach. Although not all inputs could be found or sampled (some were too small), 57 samples were obtained to characterize the quality of inputs to this stretch of the river.

Seeps were easily identified as diffuse inputs from the banks. Most were too small to sample, seen only as damp banks located most often along the outside bends of the river. When possible, larger seeps were sampled using a 2-foot piece of stainless steel flashing that was folded into a "V" shape and pushed into the bank to funnel adequate water into a bottle for analysis. This method of collecting water also allowed quantification of seeps when they were localized. Seeps often occurred continuously along banks over tens to hundreds of feet, however, and thus their flow rates could not be quantitatively measured.

Water from small tributaries and tile drains could generally be collected directly into a bottle or beaker. Typically, the smaller inputs would enter the river by dropping several feet down the bank, thus allowing a "clean" sample to be easily collected and discharge to be measured volumetrically. Larger inputs were obtained by dipping the sample bottle into the stream. Discharge of larger inputs were measured using a pygmy meter on a wading rod.

Tile drains and small tributary inputs sometimes could not be readily distinguished from each other during the synoptic survey. In some cases, a pipe could be seen directly discharging to the river; these were obviously tile drains. But small surface-water inputs could be found that were probably fed by tile drains or represented a mixture of natural drainage and tile drains.

### Ground Water

Ground-water quality in the Tualatin Basin was investigated during the 1990–94 period to assess the importance of ground-water inputs on the nutrient budget, with particular emphasis on concentrations of phosphorus. Fifty-one relatively shallow (20–200 ft) wells were sampled once during this period to determine the regional distribution of phosphorus (Doyle and Caldwell, 1996) and to ascertain any relation between phosphorus concentration and geology. After it was determined that regional ground water could be a large source of phosphorus to the river, 15 piezometers (inchannel wells) were installed in the Tualatin stream bed between RM 52 and 20 to determine concentrations of phosphorus in ground water just below the river bed (Doyle and Caldwell, 1996) and, by measuring water levels, the potential for ground-water discharge into the river channel. To evaluate the local effect of ground-water drainage from the Jackson Bottom wetland, several inchannel wells were installed at the edge of the channel at two sites, RM 43.5 and 44.2.

Most wells sampled during this survey were used for domestic or agricultural purposes. Driller's logs were examined to determine screen depths and local geologic strata. Samples were obtained by pumping at least three well volumes and were rapidly filtered and processed. Inchannel wells that were installed in the stream bed were constructed of stainless steel screens and PVC casing. A peristaltic pump was used to collect the sample, taking care to prevent exposing the sample to air so as not to oxidize the sample before filtration.

### Sample Preparation and Analysis

Filtered samples were obtained for the USA Water Quality Laboratory using 12 mL (milliliter) plastic syringes and Gelman nylon Acrodisc filters (0.45 µm (micrometer) pore size). All samples were immediately placed on ice and transported to the laboratory within 5 hours for preservation (if necessary) and analysis. WWTP samples were 24-hour flow-weighted composite samples collected by personnel from the respective WWTP and analyzed by the USA Water Quality Laboratory. Filtered samples sent to the USGS National Water Quality Laboratory were filtered through a 0.45 µm membrane filter that had been pre-treated with deionized water and sample water. Nutrient samples sent to USGS National Water Quality Laboratory were preserved with mercuric chloride; samples for cations and dissolved iron and manganese were acidified to less than pH 2.0 with nitric acid. Details on laboratory methods are provided in Doyle and Caldwell (1996).

### Quality Assurance

The laboratory quality assurance (QA) program was designed to quantify estimates of bias and variability in the sampling and analytical processes. The QA program was administered by USGS Oregon District personnel and consisted of weekly quality-control (QC) samples that were submitted to the three USA laboratories responsible for generating the chemical data. A mix of laboratory and field QC samples were included to test both the methods of laboratory analysis and field sample collection.

The potential for bias or systematic error in the analytical methods was measured with blank samples, field-spiked samples, and standard reference samples. Results indicate that little bias occurred for total phosphorus, orthophosphate, nitrate, or ammonia. Positive bias, on the order of 25 to 35 percent, was occasionally observed for total phosphorus and ammonia at concentrations less than 0.05 mg/L. Nonetheless, the data for these constituents were considered acceptable because the errors were small (generally less than 0.01 mg/L) and sources with concentrations in this low range did not contribute large loads so that analytical uncertainties had a negligible effect on the budget calculation.

Large biases, on the order of 100 percent or more, were observed for total Kjeldahl nitrogen (TKN) in the low-level range (approximately 0.1 mg/L and below), although no bias was measured in the mid- to high-level samples. These data reflect the considerable analytical "noise" for TKN analyses near the reporting limit. Despite these observed biases, the quality of the ambient TKN data was considered to be adequate for the purpose of this study because ambient TKN concentrations tend to be much larger than those in the low-level QC samples.

Variability or precision in the sampling and analytical process was defined by field duplicates, and was generally found to be within 10 percent for most constituents, slightly higher (within 20 percent) for TKN and total phosphorus.

A complete discussion of the results from the laboratory QA program is contained in Appendix A.

## STREAMFLOW CONDITIONS

Streamflow in the Tualatin River during the months May through October is typically characterized by higher flows in the early season, followed by an extended period of low flow that often persists through the end of October. A comparison of median streamflow (May through October) in the Tualatin River at RM 1.8 in 1991, 1992, and 1993 with the years 1976–93 provides context for the evaluation of hydrologic conditions during the period of this study (table 3). Median streamflows were consistently highest during May and June, fed by late spring rains and snowmelt in the upper regions of the basin. The reduction of flow later in the summer was most pronounced in August and September. Streamflow conditions during 1991 were most similar to the longer period of record; after the unusually wet spring of 1993, conditions later in the summer of that year were also fairly typical. Median streamflows during 1991 and 1993 were 214 and 236 $ft^3/s$, only slightly higher than the median for the reference period of 193 $ft^3/s$. In contrast, hydrologic conditions during 1992 were significantly drier relative to the other 2 years in the study. The median flow of 118 $ft^3/s$ during 1992 represents nearly a 40 percent reduction from the median of the reference period.

The proportion of streamflow volume contributed by the major tributaries to the Tualatin River typically varies over the course of the summer. During 1991–93, Dairy Creek contributed the largest volume of streamflow during May and June, occasionally exceeding the streamflow in the main-stem river at RM 58.8 (table 4). Scoggins Creek contributed a relatively small component of streamflow during this period, and inputs from the other tributaries also comprised a lesser proportion of main-stem flow. Later in the summer (July–September), during the period of low rainfall and intense irrigation, tributary input to the upper river was dominated by water released from Henry Hagg Lake via Scoggins Creek. The proportion of streamflow contributed by Dairy Creek was much reduced, frequently less than 20 percent of the main-stem flow at RM 58.8. Inflow from the upper main-stem river and Gales and Rock Creeks was similarly reduced.

The contribution of WWTP effluent to the water volume in the Tualatin River during the summer low-flow period also tends to vary as the summer progresses. When streamflow is naturally higher in the Tualatin River in the early summer, effluent from the WWTPs generally contributes only a small component of the streamflow in the river. Later in the summer, however, when streamflow is greatly reduced and withdrawals for irrigation are high, effluent discharge typically constitutes a larger fraction of main-stem river flow. During May and June in 1991–93, mean effluent discharge from the Rock Creek WWTP (RM 38.1) equalled 18 Mgal/d (million gallons per day), or 28 $ft^3/s$, which was about 5 percent of the mean streamflow measured in the river at RM 33.3. Similarly, daily mean effluent discharged from the Durham WWTP (RM 9.3) during the same period equalled 17.5 Mgal/d (27 $ft^3/s$) or 3 percent of the main-stem river flow leaving the basin. In contrast, effluent from these WWTPs each averaged about 10–15 percent of the streamflow in the river during July–October in 1991–93.

Monthly mean withdrawals for irrigation by Tualatin Valley Irrigation District from the Springhill Pumping Plant (RM 56.6) ranged from less than 10 $ft^3/s$ in May and June to greater than 40 $ft^3/s$ during July and August for 1991–93 (table 5). Similarly, withdrawals for drinking water supply by the Joint Water Commission tended to be smallest in May, averaging 23.3 $ft^3/s$ for the years 1991–93, and largest in August, averaging 35.0 $ft^3/s$ (table 5). Nearly 40 percent of the volume of water in the upper river was removed by the combined withdrawals at the Springhill Pumping Plant during July and August in 1991–93. In the lower river, streamflow in the Oswego Canal was generally in the range of 50 to 60 $ft^3/s$ throughout the summer (table 5).

Time-of-travel estimates for the range of streamflow characteristic of summer low-flow conditions were determined from dye studies conducted by USA during the summers of 1987 and 1988 (Jan Miller, USA, unpub. data, 1994) and by the USGS during the summer of 1992 (Lee, 1995). These estimates provide a useful general description of the relation between streamflow and travel time within the various river reaches. For streamflow between 300 and 100 $ft^3/s$, travel times from RM 58.8 to the mouth vary by more than twofold, from 10 days to 24 days (fig. 11). The increase in travel time at low streamflow is especially pronounced in the lower river, between RM 26.9 and the diversion dam at RM 3.4. Within this reach, when streamflow decreases from 300 to 100 $ft^3/s$, the travel time increases from about 6 days to more than 14 days.

**Table 3.** Median streamflow in the Tualatin River, Oregon, at river mile 1.8 (West Linn) for May–October for the years 1976–93, and 1991, 1992, and 1993
[Streamflow in cubic feet per second]

| Years | May | June | July | August | September | October | May–October |
|---|---|---|---|---|---|---|---|
| 1976–93 | 548 | 263 | 149 | 130 | 166 | 187 | 193 |
| 1991 | 676 | 338 | 244 | 147 | 131 | 139 | 214 |
| 1992 | 330 | 142 | 110 | 84 | 96 | 110 | 118 |
| 1993 | 1,200 | 580 | 235 | 141 | 176 | 172 | 236 |

## Water Balance

Because of the variability of streamflow during higher flow conditions, data from high-flow periods during the early summer were not suitable for the calculation of a water budget. Additionally, water-quality problems are more pronounced during the periods of relatively low flow. For the purpose of the water and nutrient budgets, therefore, low-flow periods ranging from 12 to 17 weeks in length were identified for each year (fig. 12). These periods were defined by streamflow that was predominantly less than the median summer flow for that year. The water balances were calculated from site to site in a pseudo-Lagrangian manner, taking the approximate time of travel between main-stem river sampling sites into consideration. Mean streamflows during the selected low-flow periods were determined for tributary and WWTP inputs, irrigation withdrawals and other diversions, as well as gaged sites along the main-stem river.

Calculated streamflow was determined by the sum of measured sources and diversions, including estimates for irrigation withdrawals directly from the main-stem river. Surplus streamflow was determined as the difference between the volume of water actually measured in the river at gaged sites and the calculated volume for that site. Possible sources for the streamflow surpluses include inputs such as small tributaries, surface seeps, tile drains, and direct ground-water discharge. Comparisons of observed and calculated flows indicate that consistent streamflow surpluses occur over the length of the river from RM 58.8 to the mouth (table 6). Streamflow surpluses ranging from 25 to 44 $ft^3/s$ occurred during the selected low-flow periods in 1991, 1992, and 1993, and represent 17, 36, and 24 percent of the observed streamflow, respectively. In all 3 years, the surpluses were largely established upstream of RM 33.3.

For the purpose of calculating loads for the nutrient budget, it was necessary to estimate streamflow for main-stem river sample sites that were ungaged. Observed streamflow was routed downstream, balanced by measured inputs and withdrawals. To account for the surplus flows, it was necessary to estimate additional water input which was not accounted for by the measured sources and sinks. Estimates of surplus flows at ungaged sites were made by interpolating between observed surplus flows at the gaged sites (fig. 13). Confidence intervals for the observed mean streamflows were determined based on the standard error of the mean ($\alpha$=0.05). The error in the calculated streamflow was defined by standard propagation of error techniques (Miller and Miller, 1988).

**Table 4.** Monthly mean streamflow in major and minor tributaries and at gaged sites in the main-stem Tualatin River, Oregon, during May–October for the years 1991, 1992, and 1993

[ [1]Mean of miscellaneous streamflow measurements made during the month; --, no data available; river mile for tributaries equals location of confluence with Tualatin River]

| Site | Tualatin River mile | Monthly mean streamflow (cubic feet per second) | | | | | |
|---|---|---|---|---|---|---|---|
| | | May | June | July | August | September | October |
| **1991** | | | | | | | |
| Scoggins Creek | 60.0 | 49 | 25 | 141 | 190 | 150 | 113 |
| Tualatin River near Dilley | 58.8 | 156 | 74 | 153 | 193 | 161 | 121 |
| Gales Creek | 56.7 | 99 | 52 | 26 | 15 | 8.6 | 6.7 |
| Dairy Creek | 44.8 | 185 | 102 | 42 | 19 | 19 | 23 |
| Tualatin River at Rood Bridge | 38.4 | 523 | 242 | 145 | 146 | 135 | 140 |
| Rock Creek | 38.1 | 39 | 52 | 16 | 12 | 8.7 | 12 |
| Butternut Creek [1] | 35.7 | -- | 3.1 | -- | -- | -- | -- |
| Tualatin River at Farmington | 33.3 | 636 | 302 | 188 | 181 | 172 | 180 |
| Christensen Creek [1] | 31.9 | -- | 6.8 | .8 | .2 | .2 | .1 |
| Burris Creek [1] | 31.6 | -- | 3.5 | .9 | .5 | .5 | .5 |
| McFee Creek [1] | 28.2 | -- | 7.1 | 3.4 | 1.2 | .9 | 1.7 |
| Baker Creek [1] | 28.2 | -- | 7.7 | 2.4 | 1.0 | .9 | 1.0 |
| Chicken Creek [1] | 15.2 | 18 | 11 | 4.2 | 2.5 | 2.2 | 2.2 |
| Rock Creek South [1] | 15.2 | -- | 2.9 | 1.1 | .7 | .7 | .7 |
| Fanno Creek | 9.3 | 40 | 36 | 8.3 | 8.2 | 3.9 | 12 |
| Nyberg Creek [1] | 7.5 | -- | 1.4 | 1.1 | 1.1 | -- | 1.1 |
| Tualatin River at West Linn | 1.8 | 751 | 366 | 236 | 156 | 141 | 189 |
| **1992** | | | | | | | |
| Scoggins Creek | 60.0 | 30 | 121 | 153 | 174 | 110 | 68 |
| Tualatin River near Dilley | 58.8 | 112 | 143 | 148 | 154 | 109 | 86 |
| Gales Creek | 56.7 | 72 | 21 | 14 | 6.1 | 7.7 | 13 |
| Dairy Creek | 44.8 | 92 | 37 | 22 | 10 | 14 | 20 |
| Tualatin River at Rood Bridge | 38.4 | 301 | 120 | 120 | 113 | 111 | 105 |
| Rock Creek | 38.1 | 19 | 14 | 9.4 | 4.6 | 11 | 14 |
| Butternut Creek [1] | 35.7 | 1.0 | .3 | .8 | .2 | -- | -- |
| Tualatin River at Farmington | 33.3 | 374 | 160 | 152 | 138 | 127 | 151 |
| Christensen Creek [1] | 31.9 | 1.6 | .2 | .2 | -- | .04 | -- |
| Burris Creek [1] | 31.6 | 2.5 | 2.1 | 1.1 | .9 | .6 | -- |
| McFee Creek [1] | 28.2 | 5.7 | 4.2 | 2.0 | .4 | 1.3 | -- |
| Baker Creek [1] | 28.2 | 4.0 | 2.6 | 1.7 | .62 | .9 | -- |
| Chicken Creek [1] | 15.2 | 7.9 | 3.4 | 2.4 | 1.7 | 1.6 | 2.9 |
| Rock Creek South [1] | 15.2 | 2.7 | .9 | .5 | .2 | .8 | -- |
| Fanno Creek | 9.3 | 15 | 8.6 | 5.6 | 3.4 | 6.7 | 18 |
| Nyberg Creek [1] | 7.5 | 1.2 | 1.0 | 1.3 | .9 | .9 | -- |
| Tualatin River at West Linn | 1.8 | 444 | 147 | 118 | 90.2 | 112 | 142 |

**Table 4.** Monthly mean streamflow in major and minor tributaries and at gaged sites in the main-stem Tualatin River, Oregon, during May–October for the years 1991, 1992, and 1993—Continued

[ [1]Mean of miscellaneous streamflow measurements made during the month; --, no data available; river mile for tributaries equals location of confluence with Tualatin River]

| Site | Tualatin River mile | Monthly mean streamflow (cubic feet per second) | | | | | |
|---|---|---|---|---|---|---|---|
| | | May | June | July | August | September | October |
| | | | | 1993 | | | |
| Scoggins Creek | 60.0 | 92.5 | 39 | 52 | 123 | 206 | 115 |
| Tualatin River near Dilley | 58.8 | 251 | 125 | 92 | 125 | 206 | 135 |
| Gales Creek | 56.7 | 182 | 114 | 36 | 17 | 16.5 | 16 |
| Tualatin River at Golf Course | 51.5 | 470 | 216 | 90 | 82 | 169 | 115 |
| Dairy Creek | 44.8 | 312 | 220 | 67 | 40 | 22.4 | 27 |
| Tualatin River at Rood Bridge | 38.4 | 890 | 464 | 168 | 124 | 172 | 148 |
| Rock Creek | 38.1 | 85.4 | 74 | 22 | 12 | 10.3 | 17 |
| Butternut Creek [1] | 35.7 | -- | -- | -- | -- | -- | -- |
| Tualatin River at Farmington | 33.3 | 1,040 | 569 | 222 | 162 | 218 | 199 |
| Christensen Creek [1] | 31.9 | 8.6 | 4.1 | .3 | .5 | .4 | .4 |
| Burris Creek [1] | 31.6 | 8.0 | 3.4 | 1.5 | 1.0 | 1.2 | .7 |
| McFee Creek [1] | 28.2 | 31 | 10 | 4.9 | 1.6 | 1.5 | 1.6 |
| Baker Creek [1] | 28.2 | 23 | 6.2 | 3.0 | 1.5 | 1.1 | 1.4 |
| Chicken Creek [1] | 15.2 | 15 | 6.8 | 6.0 | 4.8 | 4.5 | 1.1 |
| Rock Creek South [1] | 15.2 | 8.8 | 4.5 | 1.9 | 1.1 | 1.5 | 1.2 |
| Fanno Creek | 9.3 | 49 | 25 | 12 | 4.8 | 3.6 | 9.9 |
| Nyberg Creek [1] | 7.5 | -- | -- | -- | -- | -- | -- |
| Tualatin River at West Linn | 1.8 | 1,280 | 686 | 229 | 145 | 202 | 173 |

**Table 5.** Monthly mean flow in the major withdrawals from the Tualatin River, Oregon, during May–October for the years 1991–93

[TVID, Tualatin Valley Irrigation District]

| Withdrawals | Tualatin River mile | Monthly mean flow (cubic feet per second) | | | | | |
|---|---|---|---|---|---|---|---|
| | | May | June | July | August | September | October |
| | | | | 1991 | | | |
| TVID | 56.1 | 1.6 | 12.1 | 46.1 | 44.5 | 25.3 | 13.1 |
| Joint Water Commission | 56.1 | 16.6 | 21.0 | 31.5 | 32.4 | 27.9 | 24.7 |
| Oswego Canal | 6.7 | 56.2 | 54.4 | 55.6 | 50.1 | 59.3 | 57.9 |
| | | | | 1992 | | | |
| TVID | 56.1 | 20.4 | 40.5 | 48.6 | 45.9 | 20.6 | 8.3 |
| Joint Water Commission | 56.1 | 29.9 | 37.4 | 33.0 | 37.9 | 30.9 | 25.6 |
| Oswego Canal | 6.7 | 44.3 | 56.1 | 63.0 | 64.7 | 61.6 | 51.8 |
| | | | | 1993 | | | |
| TVID | 56.1 | 2.5 | 6.2 | 26.5 | 43.1 | 31.0 | 9.2 |
| Joint Water Commission | 56.1 | 23.3 | 26.1 | 27.4 | 34.6 | 32.9 | 23.0 |
| Oswego Canal | 6.7 | 35.5 | 35.9 | 51.6 | 51.7 | 51.2 | 52.1 |

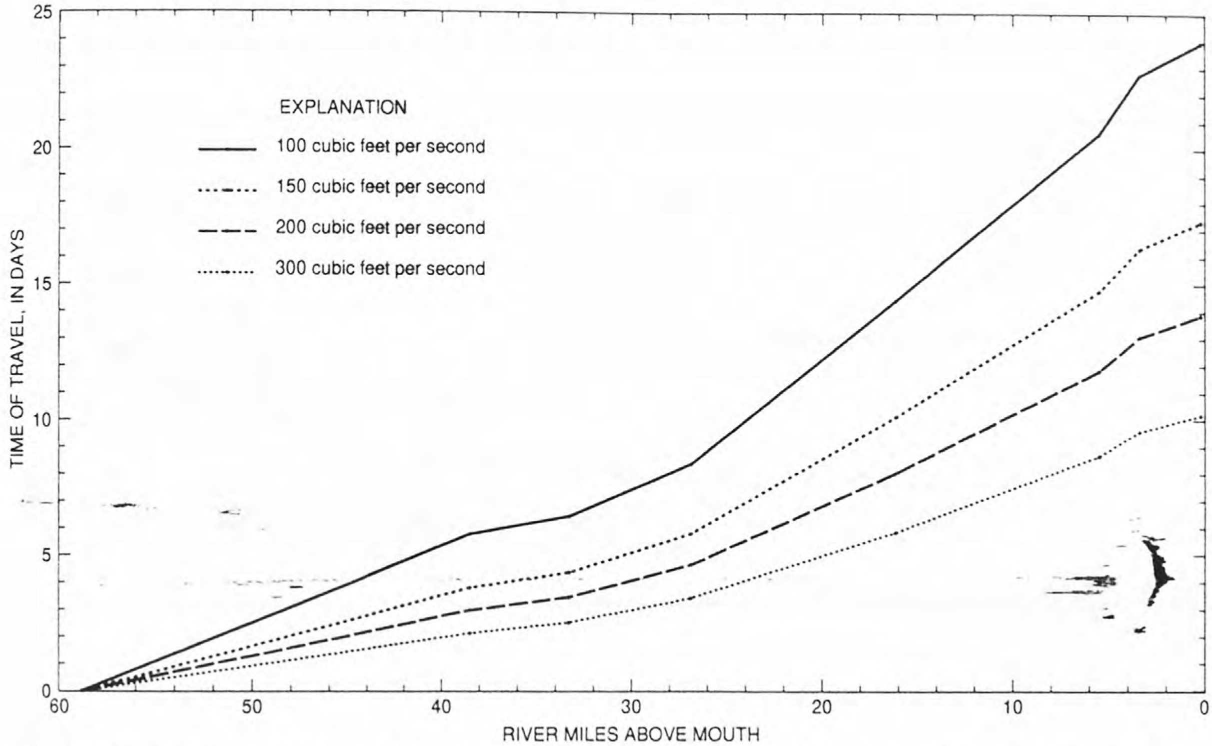



**Figure 11.** Estimated times-of-travel from river mile 58.8 to selected downstream locations in the Tualatin River, Oregon, for a range of streamflows characteristic of summer flow conditions.

Flow data from the synoptic survey in June 1992 were summed to evaluate the importance of the various minor surface-water inputs in the water budget. This survey covered nearly 25 miles of the river, between RMs 51.6 and 27.0, incorporating the reach where the largest proportion of the surplus flows were observed. The combined input from 48 surface-water sources (excluding inputs that were regularly sampled during the routine sampling program) totalled approximately 3 $ft^3/s$. While these results represent conditions during an unusually dry year, they clearly suggest that inputs from unmeasured surface seeps, tile drains, and small tributaries do not account for more than a small fraction of the surplus streamflow in the main-stem river.

In contrast, the potential for direct ground-water discharge to the main-stem river channel was observed to be high. Positive upward pressure was observed in all the inchannel wells, although the amount of water actually entering the river remains difficult to quantify because of the physical characteristics of the streambed in the Tualatin River. Bottom characteristics are somewhat variable, but in most places the bed has a large amount of silt and organic material on top of a tighter material composed in part of clays. These sediments tend to retard ground-water movement because the hydraulic conductivity of the clays and silts is very low. The low hydraulic conductivity contributes to the positive heads observed in the inchannel wells, several feet above the river surface in many cases.

The actual movement of ground water into the main-stem river was measured with inchannel seepage meters in 1993. While positive seepage was observed at every site, rates ranged over several orders of magnitude, from greater than 200 $L/m^2/d$ (liters per square meter per day) to less than 0.1 $L/m^2/d$ (fig. 14). The observed rates were significantly higher at the uppermost site, and tended to decrease in the downstream direction, which is consistent with the observed streamflow surpluses that developed in the upper river above RM 38.4. It is impossible to describe the seepage trend with any certainty based upon these seepage data; however; the bottom surface area that was sampled during this survey was only a tiny fraction (about 0.0003 percent) of the total surface area of the river bottom in the reach. Nonetheless, these data indicate that seepage into the river channel does occur, although it is clearly not an easily characterized phenomenon. Localized regions of high seepage are likely to be separated by many regions of lower seepage.

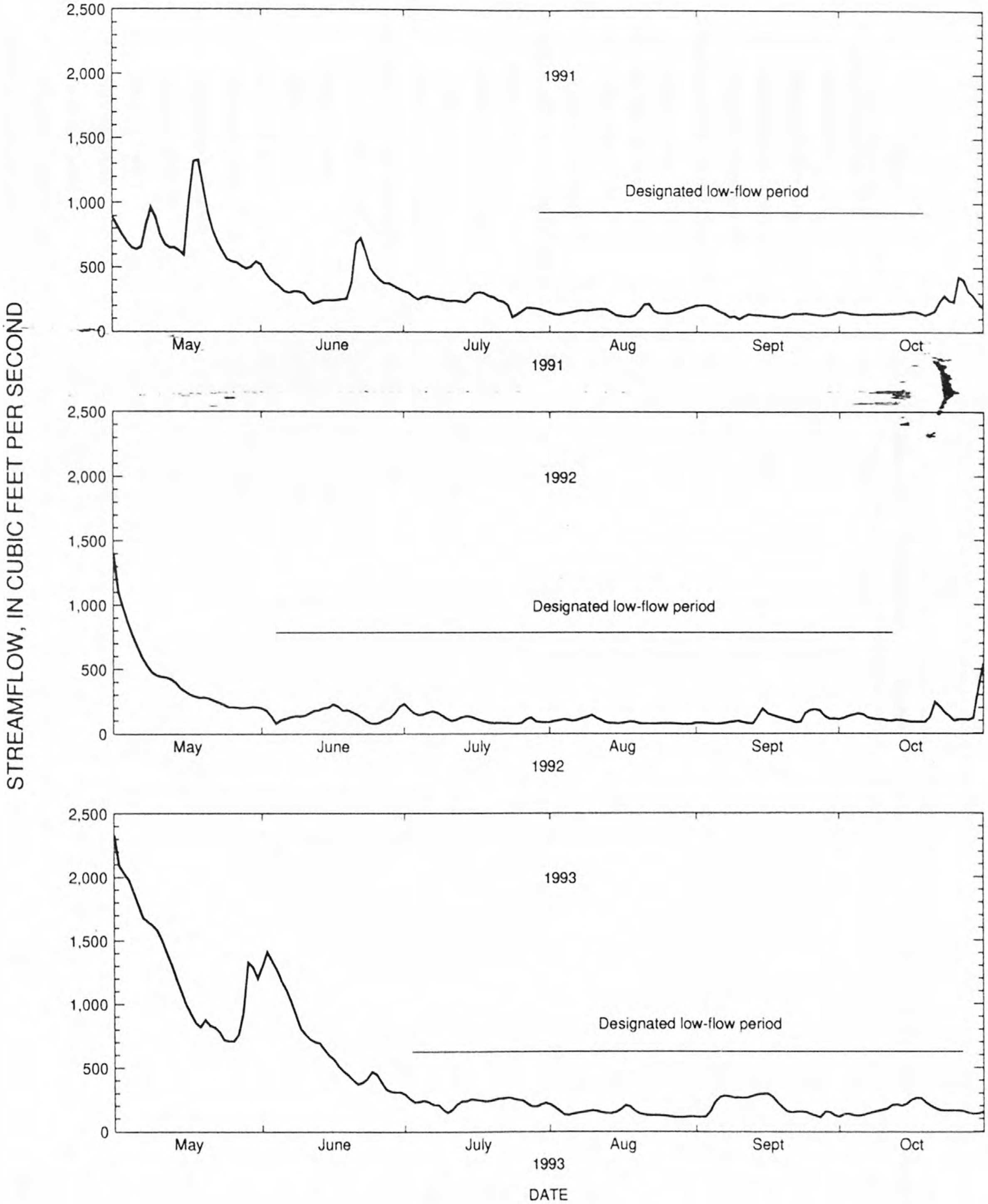



**Figure 12.** Daily mean streamflow in the Tualatin River, Oregon, at river mile 1.8 during May through October 1991–93, and the corresponding low-flow periods designated for calculation of water and constituent budgets in this study.

**Table 6.** Summary of mean measured streamflow in surface-water inputs and diversions in the Tualatin River Basin, Oregon, and comparison of measured and calculated streamflow at gaged main-stem sites during selected low-flow periods in 1991, 1992, and 1993

[Tributary river miles represent the river mile in the Tualatin River main stem at the confluence; streamflow in cubic feet per second; WWTP, wastewater treatment plant; surplus, measured-calculated; n.d., no data; see text and figure 12 for definition of low-flow periods]

| Site | Tualatin River mile | 1991 | | | 1992 | | | 1993 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Measured | Calculated | Surplus | Measured | Calculated | Surplus | Measured | Calculated | Surplus |
| Tualatin River near Dilley | 58.8 | 175 | 175 | 0 | 139 | 139 | 0 | 141 | 141 | 0 |
| Gales Creek | 56.7 | 14 | | | 14 | | | 25 | | |
| Springhill Pumping Plant | 56.1 | -37 | | | -39 | | | -30 | | |
| Joint Water Commission | 56.1 | -30 | | | -35 | | | -31 | | |
| Irrigation withdrawals | | -5.4 | | | -5.4 | | | -4.4 | | |
| Tualatin River at Golf Course Rd. | 51.5 | n.d. | | | 96 | 74 | +22 | 114 | 101 | +13 |
| Dairy Creek | 44.8 | 22 | | | 20 | | | 37 | | |
| Jackson Slough | 43.8 | .3 | | | .3 | | | .6 | | |
| Miller Swale | 43.5 | .7 | | | .9 | | | .8 | | |
| Irrigation withdrawals | | -10 | | | -11 | | | -8.6 | | |
| Tualatin River at Rood Bridge | 38.4 | 139 | 129 | +10 | 116 | 84 | +32 | 151 | 131 | +20 |
| Rock Creek | 38.1 | 12 | | | 9.8 | | | 15 | | |
| Rock Creek WWTP | 38.1 | 21 | | | 22 | | | 23 | | |
| Butternut Creek | 35.7 | .5 | | | .4 | | | n.d. | | |
| Irrigation withdrawals | | -4.7 | | | -4.9 | | | -4.1 | | |
| Tualatin River at Farmington | 33.3 | 176 | 157 | +19 | 144 | 111 | +33 | 200 | 165 | +35 |
| Christensen Creek | 31.9 | .2 | | | .2 | | | .4 | | |
| Burris Creek | 31.6 | .5 | | | 1.1 | | | 1.1 | | |
| Baker Creek | 28.2 | 1.0 | | | 1.2 | | | 1.8 | | |
| McFee Creek | 28.2 | 1.2 | | | 1.6 | | | 2.4 | | |
| Chicken Creek | 15.2 | 2.8 | | | 2.5 | | | 2.3 | | |
| Rock Creek (South) | 15.2 | .7 | | | .5 | | | 1.4 | | |
| Durham WWTP | 9.3 | 21 | | | 20 | | | 24 | | |
| Fanno Creek | 9.3 | 4.3 | | | 5.8 | | | 7.7 | | |
| Nyberg Creek | 7.5 | 1.0 | | | 1.0 | | | n.d. | | |
| Oswego Canal | 6.7 | -58 | | | -60 | | | -53 | | |
| Irrigation withdrawals | | -14 | | | -15 | | | -12 | | |
| Tualatin River at West Linn | 1.8 | 143 | 118 | +25 | 109 | 70 | +39 | 185 | 141 | +44 |

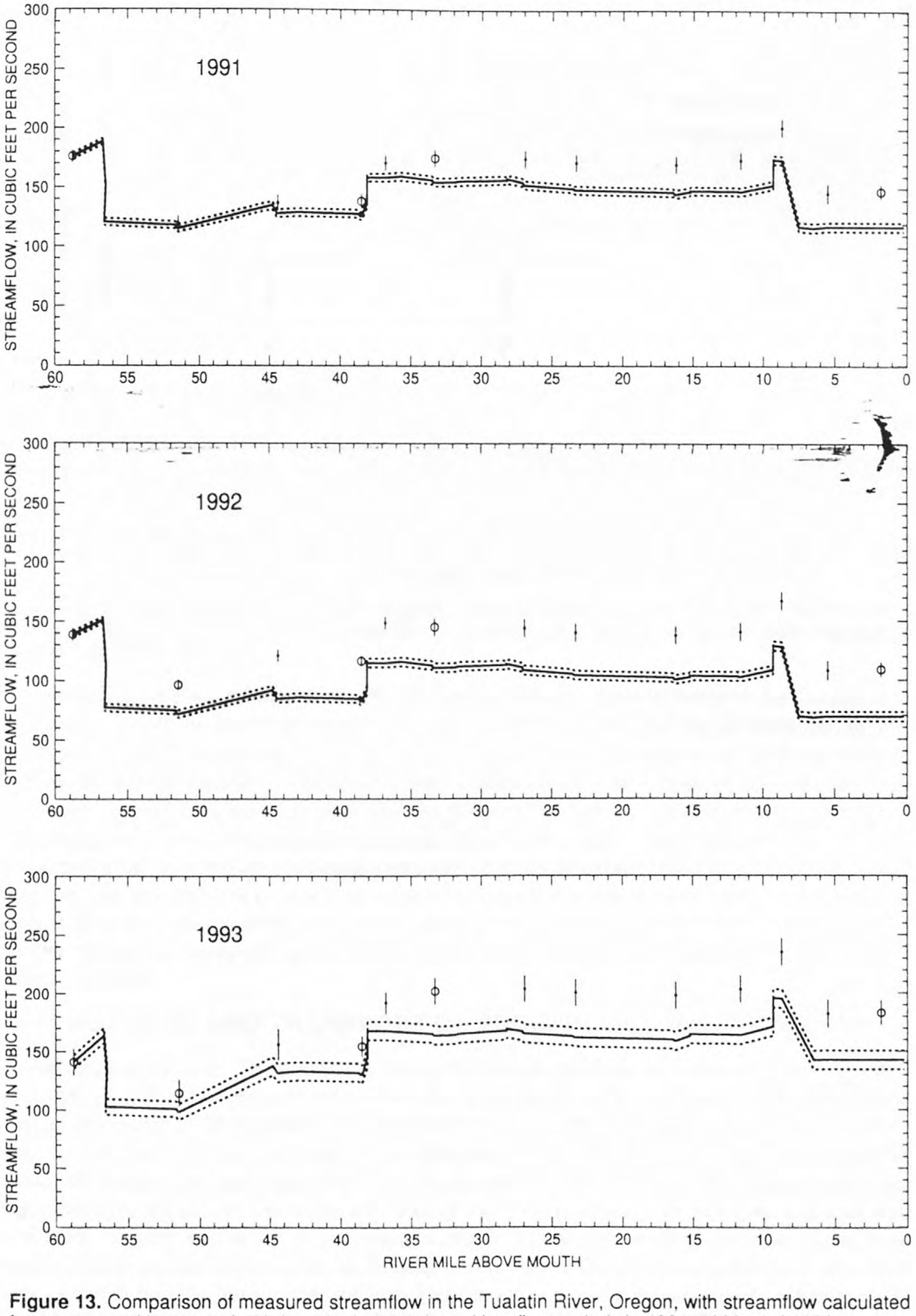



**Figure 13.** Comparison of measured streamflow in the Tualatin River, Oregon, with streamflow calculated from measured inputs and withdrawals during selected low-flow periods in 1991, 1992, and 1993. (EXPLANATION: Circles represent measured mean streamflow; dots represent estimated streamflow between gaged sites; error bars represent 95 percent confidence limits; the solid lines represent calculated streamflow; the dotted lines represent errors in the calculation propagated downstream.)

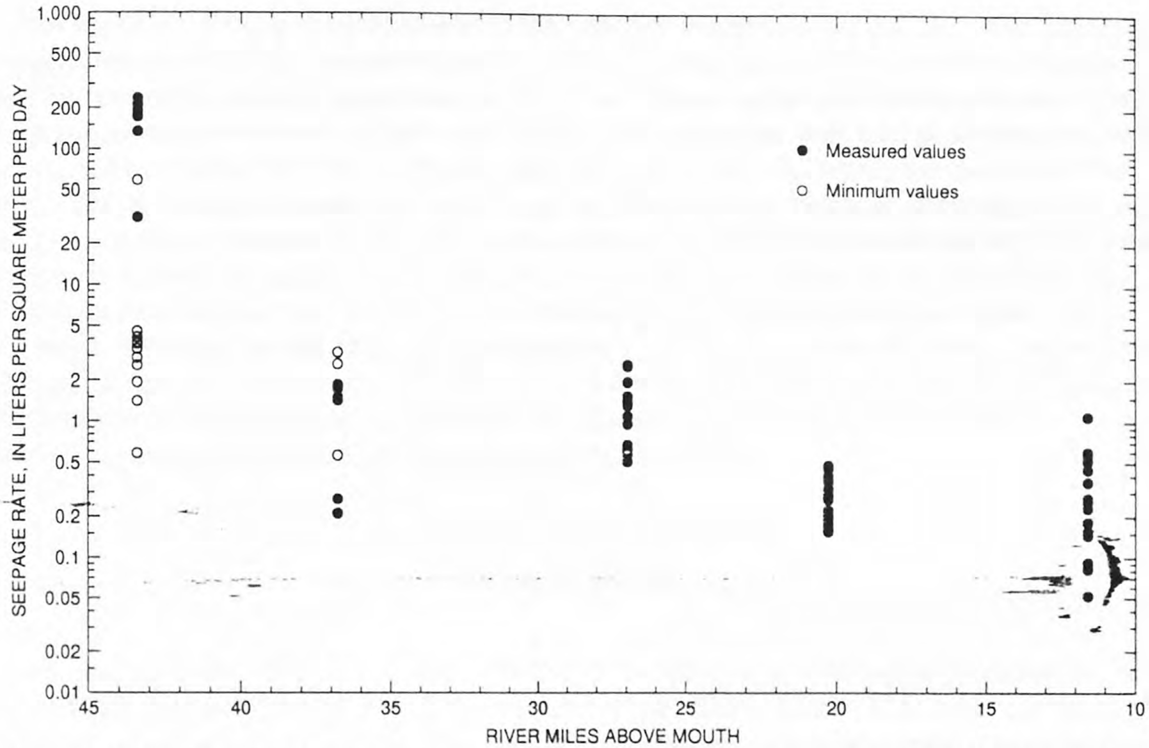



**Figure 14.** Seepage into the Tualatin River, Oregon, during the late summer and fall of 1993. Minimum values were obtained when the collection apparatus was full at the time of sampling, so that the actual seepage rate could not be measured.

Results from the water balance clearly indicate that a large source of water to the Tualatin River during summer low-flow conditions, between 20 and 37 percent of flow leaving the basin during the period of this study, cannot be accounted for by inputs from surface water. Ground-water discharge directly to the main-stem river channel is a credible source for the missing water. Positive upward pressure of ground water beneath the channel indicate that the potential for direct ground-water discharge is high. Additionally, the measurement of positive seepage over a wide range of rates suggests that local zones of higher permeability or conductivity can deliver large volumes of ground water directly to the main-stem river, despite the tendency for the hydraulic characteristics of the channel bed to retard ground-water movement in many areas. Notwithstanding the difficulty in quantifying ground-water inputs, it is clear that ground water must be considered as an important source of water to the Tualatin River during summer low-flow conditions.

## SOURCES AND TRANSPORT OF PHOSPHORUS AND NITROGEN

Nutrient supply to the Tualatin River during the summer months is affected by many factors. While the underlying geology is a primary factor determining the quality of ground water in the basin, the quality of water in tributaries is determined by the interaction between the characteristics of ground-water discharge, soils, and land-use practices. Effluent discharged from WWTPs also contributes potentially large nutrient loads to the main-stem river. Conversely, withdrawals of water for irrigation, drinking water supplies, and hydroelectric power (diversion through the Oswego Canal) are important sinks for water and nutrient loads in the river. Finally, the release of nutrients from decomposition processes in the bottom sediments during thermal stratification in the deep reaches of the lower river is potentially an important nutrient source during the hot summer months. This section contains a discussion of each of these factors, followed by a mass balance or nutrient budget including all measured inputs of phosphorus and nitrogen to the Tualatin River. These budgets provide a summary of the sources and transport of these constituents through the river system, so that the relative importance of the various inputs can be evaluated for the purpose of effective water-quality management in the basin.

The regulated instream concentrations (TMDL criterion concentrations) that have been established by Oregon Department of Environmental Quality (ODEQ) for the Tualatin River provide an important context for considering nutrient concentrations within the various sources to the main-stem river. These criterion concentrations were set in 1988 when TMDLs were defined for both total phosphorus and ammonia in selected tributaries and sites on the main stem. For total phosphorus within the main-stem river reach, the TMDL criterion concentration is 0.04 mg/L at RM 58.8, incrementally increasing to 0.07 mg/L at RM 33.3 and points downstream. Criterion concentrations for total phosphorus in the major tributaries are defined as follows: Scoggins Creek (0.06 mg/L), Gales and Dairy Creeks (0.045 mg/L), Rock and Fanno Creeks (0.07 mg/L). The TMDL criterion concentrations for ammonia are more varied over the river's length: 0.03 mg/L at RM 58.8, increasing gradually to 0.05 mg/L at RM 38.5 with a sharp increase to 1.0 mg/L at RM 33.3, and decreasing to 0.85 mg/L at RM 16.2 and downstream. In the tributaries, the TMDL criterion for ammonia is set at 0.04 mg/L for Gales and Dairy Creeks, and 0.10 mg/L for Rock and Fanno Creeks (Oregon Department of Environmental Quality, 1997).

## Ground Water

Because the quality of ground water is affected by the chemical and biological processes that occur in the soils and rock beds through which the water moves, the residence time of the water and the mineral composition influence the chemical characteristics of ground water. As a consequence, the two layers of valley fill deposits in the Tualatin Basin, the shallow catastrophic flood deposits and the deeper Sandy River Mudstone equivalent, are important controlling factors in determining ground-water quality in the basin.

The survey of 51 domestic wells indicated that elevated concentrations of phosphorus are found in ground water throughout the basin. In nearly every sample, concentrations were higher than 0.07 mg/L, the TMDL criterion concentration for total phosphorus in the lower main-stem river (fig. 15). The wells were categorized by depth relative to the interface between the catastrophic flood deposits (top) and the Sandy River Mudstone equivalent (bottom) using data both from well logs and geological data summarized by Madin (1990). Wells with the highest concentrations of total dissolved phosphorus, ranging up to 2.5 mg/L, tended to be completed at depths relatively close to the interface. Median total dissolved phosphorus concentrations ranged from 0.15 mg/L in shallow wells (completed within the catastrophic flood deposits) to 0.34 mg/L in the deep ground water (wells completed at the interface or below the catastrophic flood deposits).

These results were corroborated by a chemical and mineralogical analysis of drilling cores collected throughout the basin by researchers at Oregon Graduate Institute and Portland State University (Wilson, 1997). In that study, core subsamples were extracted with distilled water (at saturation) to determine the equilibrium concentrations of water-soluble phosphorus, thereby simulating pore-water phosphorus concentrations as a function of core depth. The results from most of their core extractions were very similar to those obtained in the USGS domestic well survey. The extractable phosphorus concentrations produced by core samples of the catastrophic flood deposits were in the range of 0.1 to 0.2 mg/L. Near the interface of the flood deposits with the Sandy River Mudstone equivalent, extractable phosphorus concentrations ranged from 0.4 to 0.7 mg/L. The deepest core, obtained near the center of the basin at the Hillsboro airport, produced extractable phosphorus concentrations as high as 3.2 mg/L within the Sandy River Mudstone equivalent. These results indicate that large amounts of highly mobile phosphorus exist in the upper 500 feet of valley-fill sediments throughout the Tualatin Basin. Mineralogical analysis of the cores obtained during the same study clearly showed the presence of vivianite, a ferrous phosphate mineral ($Fe_3(PO_4)_2 \cdot 8H_2O$) at different depths in the cores, generally below 500 feet.

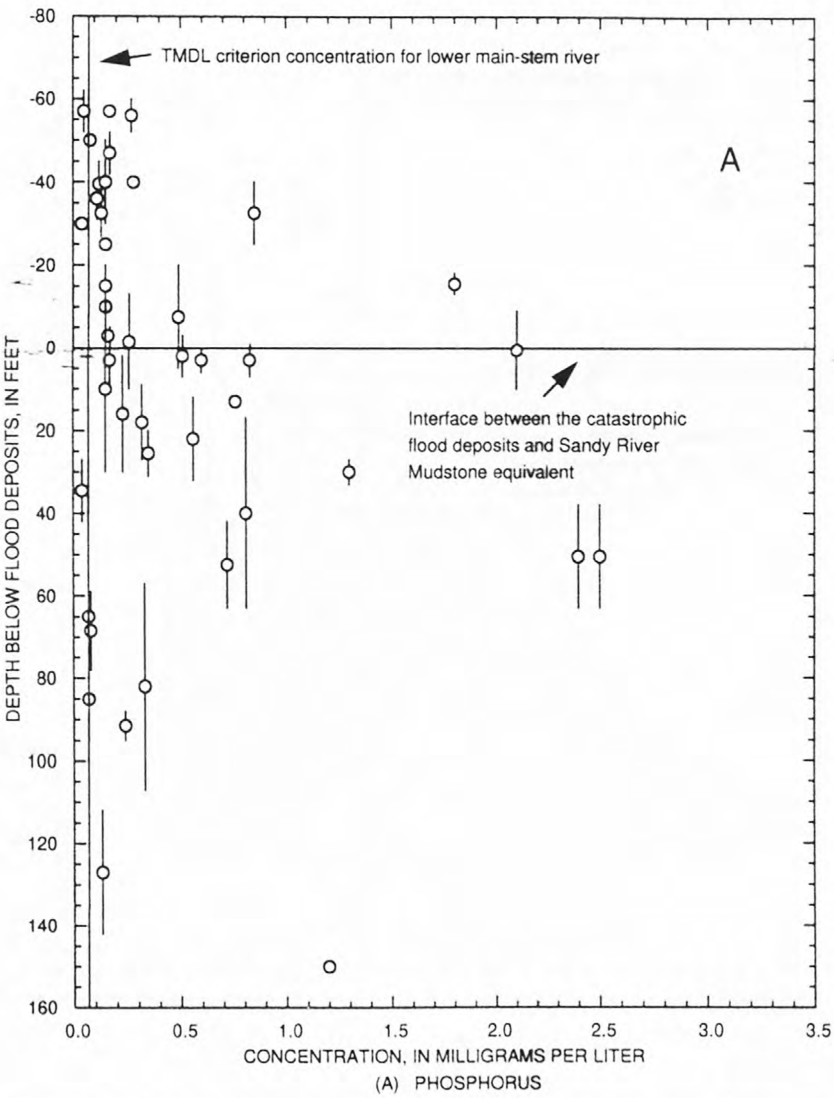



**Figure 15.** Concentrations of total dissolved phosphorus and ammonia as nitrogen in shallow domestic wells finished in unconsolidated materials throughout the Tualatin River Basin, Oregon, sampled during 1990 and 1993. (TMDL, Total Maximum Daily Load) The vertical lines show the screened interval of each well. The depth below the flood deposits was determined for each sample from well logs and geological data summarized by Madin (1990). (A) Total dissolved phosphorus (B) Ammonia as nitrogen

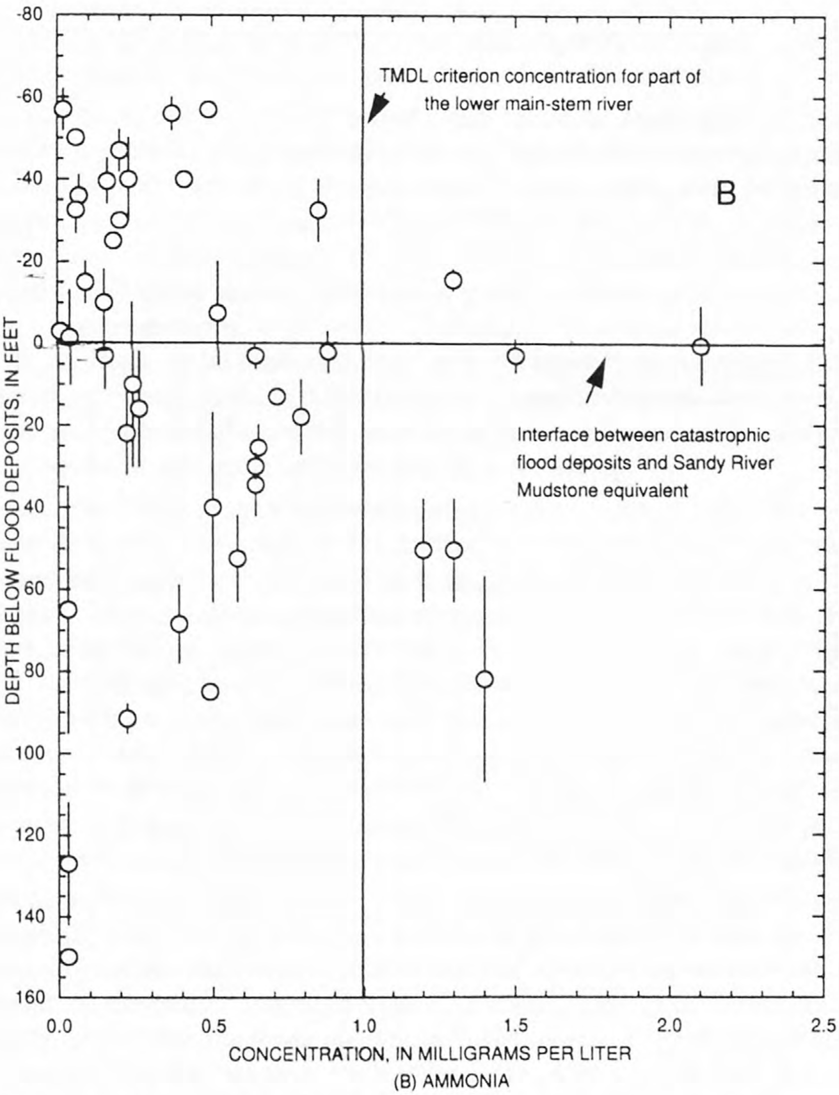



**Figure 15.** Concentrations of total dissolved phosphorus and ammonia as nitrogen in shallow domestic wells finished in unconsolidated materials throughout the Tualatin River Basin, Oregon, sampled during 1990 and 1993—Continued. (TMDL, Total Maximum Daily Load) The vertical lines show the screened interval of each well. The depth below the flood deposits was determined for each sample from well logs and geological data summarized by Madin (1990). (A) Total dissolved phosphorus (B) Ammonia as nitrogen

Ammonia concentrations observed in the USGS domestic well survey also tended to be higher in wells finished near the interface between the flood deposits and the Sandy River Mudstone equivalent, although most of the observed values were less than the TMDL criterion concentration for the lower main-stem river (fig. 15). The median ammonia concentration in the shallow wells was 0.22 mg/L, accounting for approximately 60 percent of the median concentration of total nitrogen (0.35 mg/L). The balance of total nitrogen was split between organic nitrogen and nitrate in most of the shallow wells. In the deeper wells, the median ammonia concentration was higher, 0.55 mg/L, and comprised more than 90 percent of the total nitrogen (0.60 mg/L). In general, nitrate concentrations were less than 0.1 mg/L in all the wells, although elevated concentrations (>3.0 mg/L) were observed in a few samples.

Decomposition of organic material in the sediments below the catastrophic flood deposits filling the Tualatin River valley is probably a key element governing the elevated concentrations of total phosphorus and ammonia in deep ground water. Extensive amounts of organic matter were buried at the interface between the two geologic strata during the catastrophic Missoula Floods. Oxygen is the preferred electron acceptor for the process of organic decomposition, and oxygen is not replenished in deep ground-water systems that are isolated from the surface. Ammonia is typically released during the decay process and will accumulate under anoxic conditions, when nitrate is commonly used as an electron acceptor. Nitrification, a common sink for ammonia under oxic conditions, does not occur in anoxic water. The combination of these decomposition processes results in the depletion of oxygen and nitrate, the attainment of anoxic conditions, and the accumulation of ammonia. Such conditions were commonly observed in water samples collected from deeper wells during the domestic ground-water survey.

The presence of vivianite in the valley sediments provides a mineral source for phosphorus that can be mobilized under these anoxic conditions. The presence of vivianite, as well as concentrations of total dissolved iron observed in both the shallow and deep ground water (median concentrations equalling 0.195 mg/L and 0.320 mg/L, respectively), suggests that vivianite, rather than siderite ($FeCO_3$) controls the solubility of iron in these ground waters. Concentrations of phosphorus also suggest equilibrium with a vivianite mineral phase. In addition, phosphorus concentrations observed in ground water reflect the relative abundance of phosphorus in the basin as a whole. The larger values for total phosphorus and dissolved iron in the deep ground water, relative to shallow ground water, probably reflect the longer flow paths characteristic of regional flow systems, which increase the potential for geochemical alteration of water quality and the solubilization of minerals present in the aquifer. In addition, the longer flow paths are more likely to bring the water through a zone that is affected by the decomposition of buried organic material.

The results from the survey of inchannel wells located in the middle of the channel characterize nutrient concentrations in regional ground water that discharges to the main-stem river. In contrast, the data from the edge-of-channel wells located near the Jackson Bottom wetland provide insight on the local effect of the wetland on the quality of ground water discharging to the river. Concentrations of total phosphorus significantly greater than the lower main-stem TMDL criterion concentration of 0.07 mg/L were observed in all samples from the inchannel wells (table 7). In general, the lowest mean concentrations of total phosphorus, ranging from 0.56 to 0.74 mg/L, were observed in the edge-of-channel wells, coincident with elevated mean concentrations of dissolved iron (frequently >15 mg/L). Mean concentrations of total phosphorus in all the wells located in the middle of the streambed channel, on the other hand, were consistently on the order of 1.0 mg/L or greater, occasionally exceeding 2.0 mg/L. Mean concentrations of dissolved iron were much less in the midchannel wells, typically less than 1.0 mg/L, although somewhat higher values were observed at RM 27.0.

Concentrations of ammonia also tended to be high in many wells relative to the instream TMDL criteria, and the highest concentrations were generally observed in those wells located near the edge of the channel at Jackson Bottom. The mean ammonia concentration in the midchannel wells was 0.99 mg/L, compared to the mean from the channel edge of 4.42 mg/L. The highest ammonia concentrations were observed at RM 43.5, where ammonia concentrations were greater than 6.0 mg/L in the two wells located at the channel edge. In contrast, the ammonia concentration in the midchannel well at this site was 1.90 mg/L. Mean concentrations of nitrate were consistently low (0.02 mg/L) in all of the inchannel wells.

**Table 7.** Summary of results from inchannel wells in the Tualatin River, Oregon, sampled during 1992–94 (Doyle and Caldwell, 1996)

[Tributary river miles represent the river mile in the Tualatin River main stem at the confluence; depth and water level in feet; specific conductance in microsiemens per centimeter at 25 degrees Celsius; concentration in milligrams per liter; >, greater than; --, no data; N between 2–6]

| Tualatin River mile | Station I.D. | Depth into sediments | Representative water level above river | Mean specific conductance | Mean chloride | Mean total dissolved phosphorus | Mean dissolved iron | Mean ammonia, as nitrogen |
|---|---|---|---|---|---|---|---|---|
| | | | | **Midchannel wells** | | | | |
| 20.8 | 452421122523101 | 7.2 | 4.3 | 290 | 3.40 | 1.23 | 0.510 | 0.96 |
| 20.8 | 452421122523102 | 5.4 | -- | 302 | 2.70 | 1.09 | <.012 | .26 |
| 27.0 | 452453122551501 | 9.2 | 3.5 | 304 | 6.70 | 0.96 | 2.70 | .89 |
| 27.0 | 452453122551502 | 11.5 | 3.6 | 302 | 6.95 | 1.01 | 2.75 | .90 |
| 33.4 | 452700122565701 | 8.2 | >4.7 | 308 | 3.83 | 2.10 | .252 | 1.39 |
| 33.4 | 452700122565702 | 11.4 | >4.6 | 307 | 3.83 | 2.35 | .063 | .80 |
| 36.8 | 452843122562601 | 11.8 | 4.0 | 305 | 3.15 | 2.43 | .770 | 1.24 |
| 36.8 | 452843122562602 | 8.6 | 2.2 | 308 | 2.30 | 2.00 | .170 | 1.43 |
| 43.5 | 452959122584803 | 8.2 | 1.9 | 454 | 3.75 | 2.90 | 1.10 | 1.90 |
| 51.7 | 453005123031601 | 9.2 | 1.2 | 225 | 1.50 | 1.08 | .072 | .47 |
| 51.7 | 453005123031602 | 6.8 | .9 | 222 | 1.67 | 1.04 | .117 | .63 |
| | | | | **Wells at channel edge at Jackson Bottom area** | | | | |
| 43.5 | 452959122584801 | 7.6 | .5 | 648 | 16.3 | .74 | 23.7 | 6.80 |
| 43.5 | 452959122584802 | 14.0 | 1.4 | 570 | 3.80 | 1.15 | 8.02 | 6.06 |
| 44.2 | 452955122591701 | 7.5 | .6 | 746 | 10.1 | .56 | 15.6 | 4.06 |
| 44.2 | 452955122591702 | 12.0 | 5.4 | 652 | 11.3 | .75 | 15.3 | .76 |

The variability in nutrient concentrations observed in the inchannel wells is a likely consequence of the complexity of flow lines converging in zones of regional ground-water discharge (fig. 4). Ground-water flow to regional discharge areas is delivered from both regional and local flow systems in relative proportions that depend upon hydraulic gradient and conductivity. In a stream that is the center for regional ground-water discharge, midchannel wells would be expected to intercept ground water at the end of a regional flow path. In the Tualatin Basin, this water corresponds to the deep ground water that flows through the Sandy River Mudstone equivalent. In fact, the pattern of data from the midchannel wells was similar to that of the deep-ground-water data from the domestic well survey, supporting this assumption, although actual concentration ranges for both phosphorus and ammonia in the midchannel wells were higher (table 7 and fig. 15). In this respect, the midchannel wells were most comparable to wells finished at depths close to the interface between the two geologic strata. The relatively high phosphorus concentrations are consistent with the discharge of regional ground water that has had the opportunity to be affected by the dissolution of vivianite and the general reducing conditions of the deeper strata. Even relatively small input volumes of such water during low-flow conditions can result in disproportionate effects on the water chemistry of the system.

In contrast, the quality of water from wells at the channel edge near Jackson Bottom reflects the quality of shallower ground water, indicating that these wells probably intercept more water from the local ground-water system in the Jackson Bottom area (fig. 4). The relatively shallow edge-of-channel wells (RMs 43.5 and 44.2, depths less than 9 feet) showed elevated values for chloride and specific conductance, reflecting the influence of WWTP effluent used for irrigation (table 7). Concentrations of total phosphorus measured in these wells were among the lowest, possibly reflecting the efficiency of phosphorus removal by the wetland soils. Ammonia concentrations were large relative to the other wells, suggesting that nitrification was blocked by oxygen depletion in this local ground-water system. A lack of nitrate, as well as the high concentrations of total iron, are also a consequence of anoxic conditions.

## Surface Water

Surface-water inflows from tributaries are important sources of phosphorus and nitrogen to the Tualatin River. For the purpose of this analysis, tile drains are included in the discussion of surface-water sources, even though they essentially serve to drain shallow ground water from agricultural fields. The inputs from WWTPs in the basin must also be considered as major sources of nutrient loads, especially nitrate, to the river. Surface-water sinks in the basin include the many diversions of water, which act to reduce both streamflow volume and nutrient loads at the point of diversion. The effect of these reductions on water quality downstream as other inputs enter the river varies with the location of the diversion point within the river.

### Tributaries and Tile Drains

The range in concentrations of total phosphorus in the tributaries during the study period spanned several orders of magnitude, with median concentrations less than the TMDL criterion concentrations only in Scoggins Creek and occasionally in Gales Creek (fig. 16). Median concentrations in the other major tributaries (Dairy, Rock, and Fanno Creeks) and all the smaller tributaries and tile drains were consistently greater than 0.07 mg/L, the TMDL criterion concentration for the lower main-stem Tualatin River (fig. 16, table 8). Values ranged between 0.10 and 0.30 mg/L for most streams. Higher concentrations were observed in Jackson Slough, Miller Swale, Christensen, and Burris Creeks, especially during 1991 and 1992. The highest total phosphorus concentrations were observed in Jackson Slough and Miller Swale, both of which drain Jackson Bottom; median concentrations ranged from 0.70 to nearly 2 mg/L. A large fraction of the total phosphorus in all the streams was in the form of orthophosphate, from 25 to more than 60 percent.

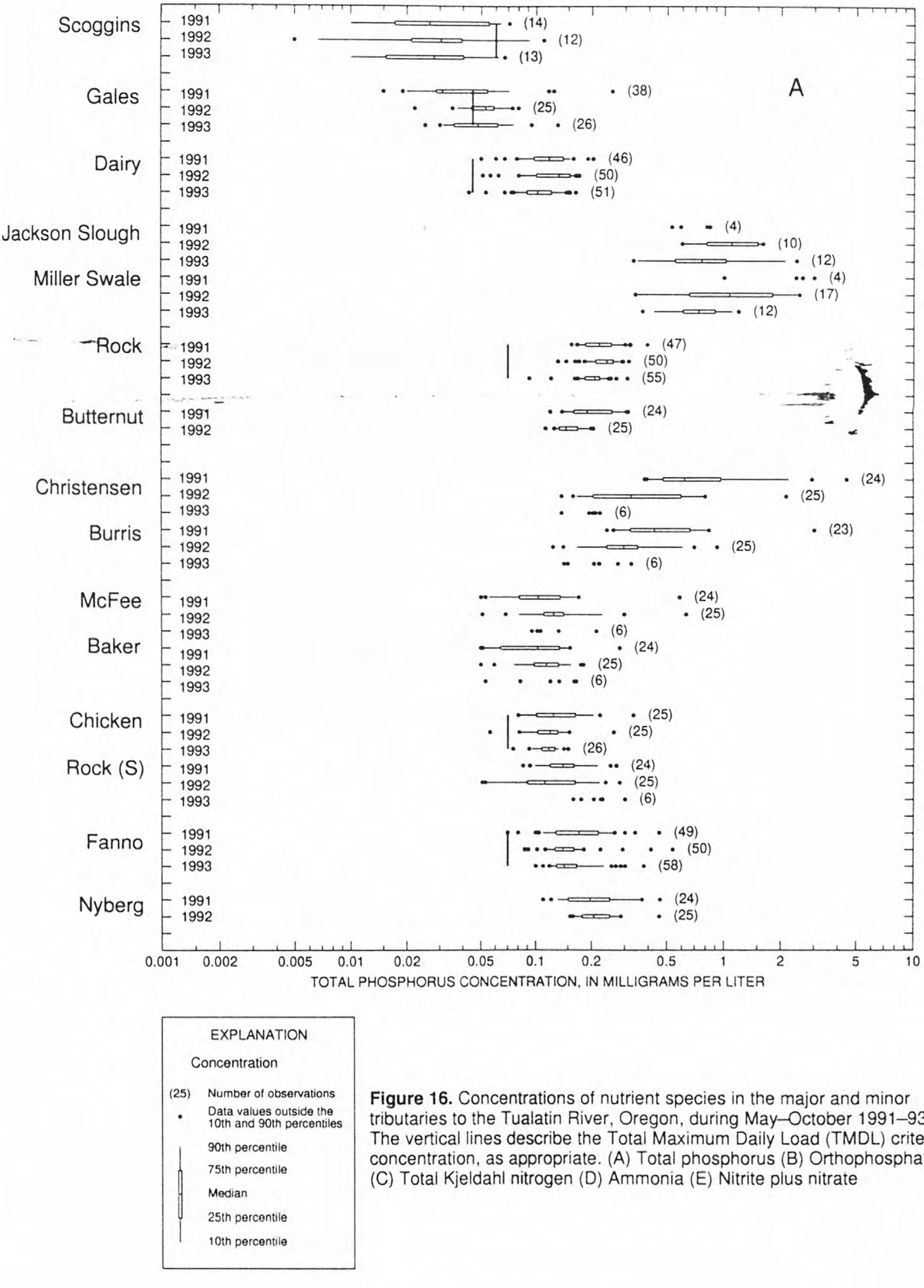



**Figure 16.** Concentrations of nutrient species in the major and minor tributaries to the Tualatin River, Oregon, during May–October 1991–93. The vertical lines describe the Total Maximum Daily Load (TMDL) criterion concentration, as appropriate. (A) Total phosphorus (B) Orthophosphate (C) Total Kjeldahl nitrogen (D) Ammonia (E) Nitrite plus nitrate

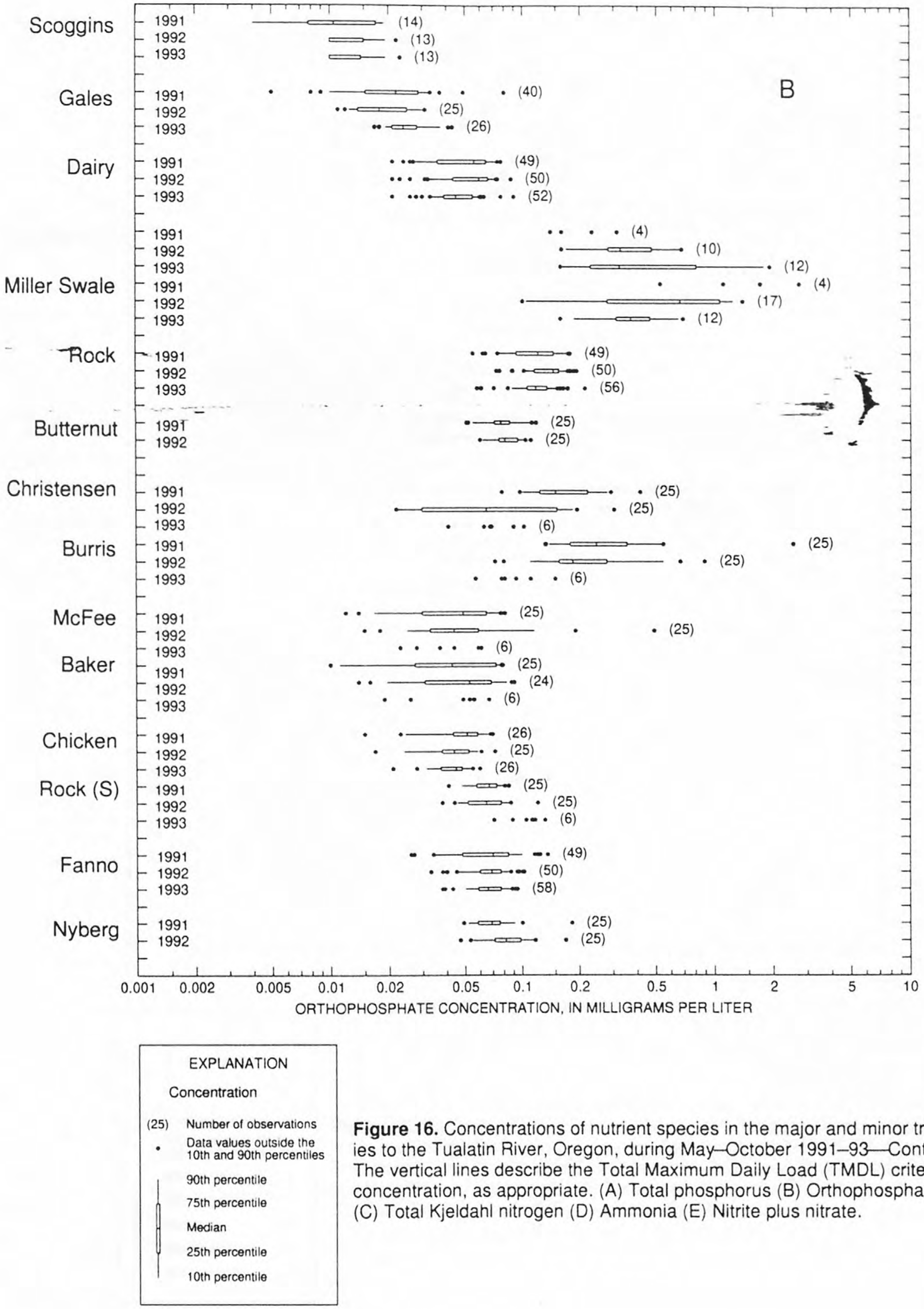
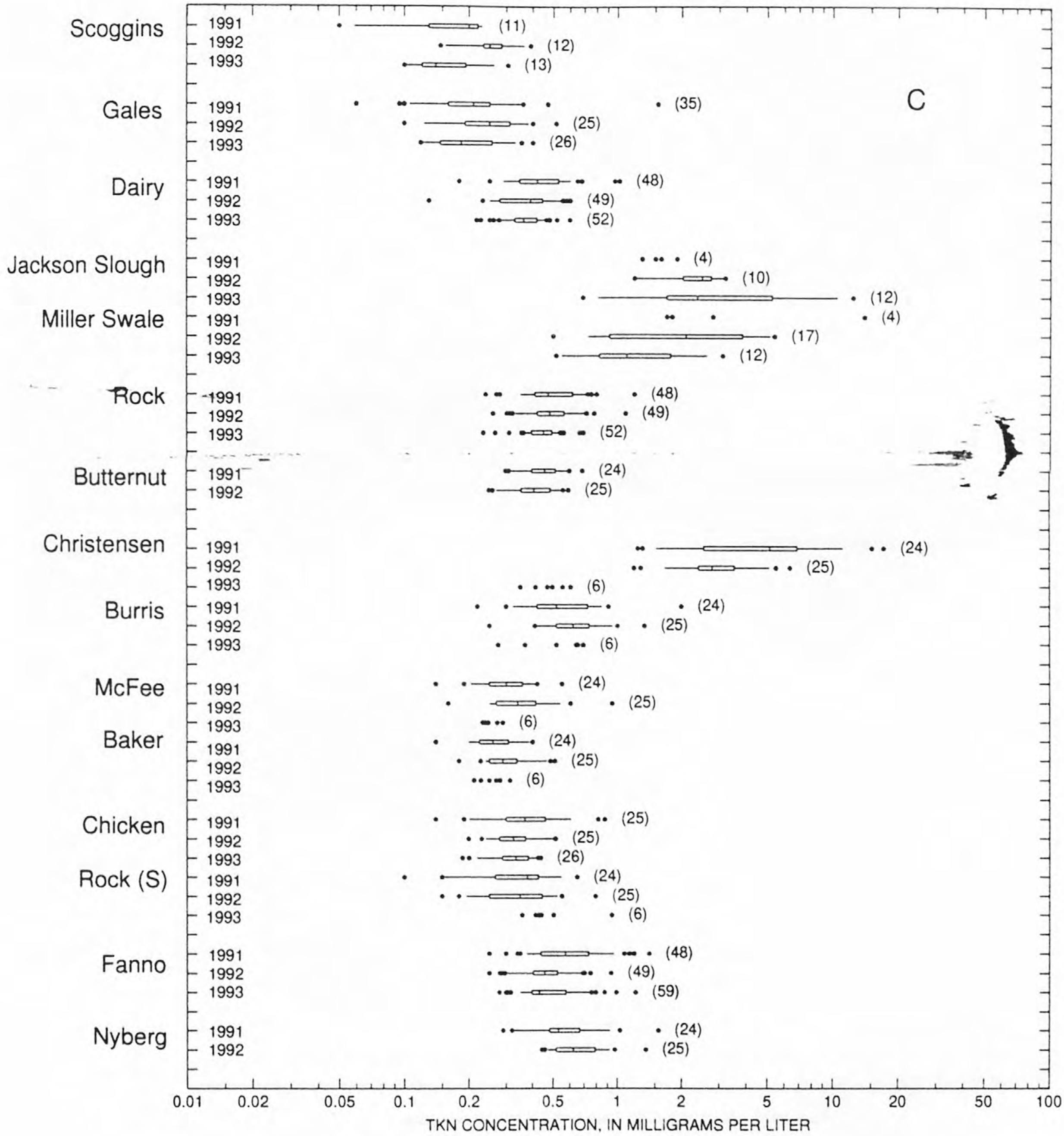



**Figure 16.** Concentrations of nutrient species in the major and minor tributaries to the Tualatin River, Oregon, during May–October 1991–93—Continued. The vertical lines describe the Total Maximum Daily Load (TMDL) criterion concentration, as appropriate. (A) Total phosphorus (B) Orthophosphate (C) Total Kjeldahl nitrogen (D) Ammonia (E) Nitrite plus nitrate.



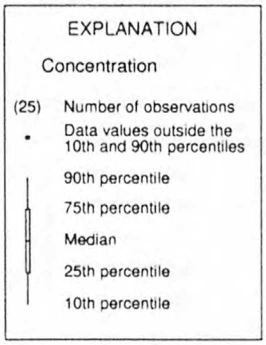
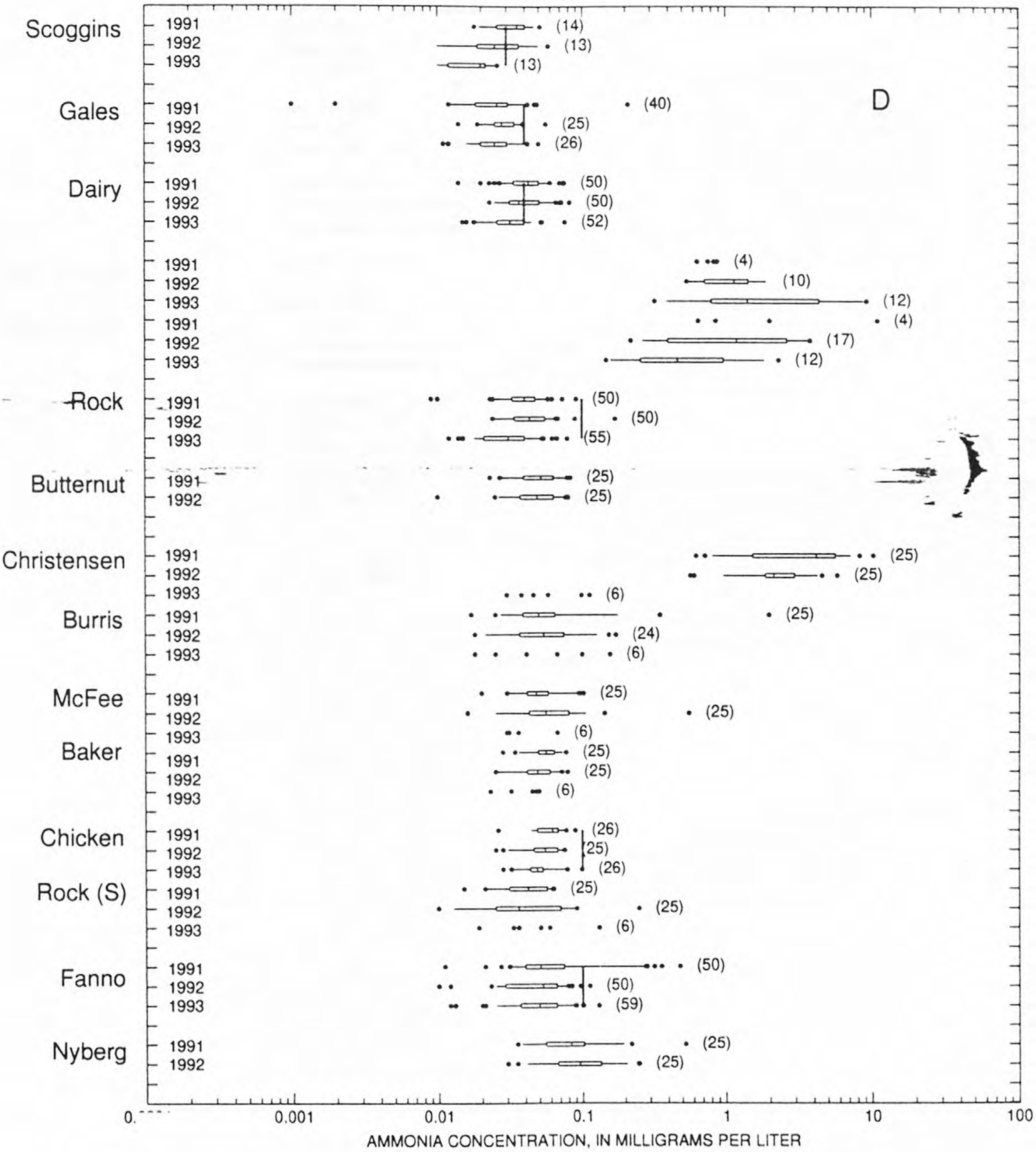




**Figure 16.** Concentrations of nutrient species in the major and minor tributaries to the Tualatin River, Oregon, during May–October 1991–93—Continued. The vertical lines describe the Total Maximum Daily Load (TMDL) criterion concentration, as appropriate. (A) Total phosphorus (B) Orthophosphate (C) Total Kjeldahl nitrogen (D) Ammonia (E) Nitrite plus nitrate



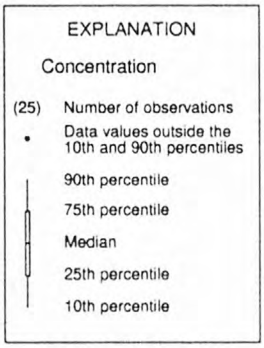




**Figure 16.** Concentrations of nutrient species in the major and minor tributaries to the Tualatin River, Oregon, during May–October 1991–93—Continued. The vertical lines describe the Total Maximum Daily Load (TMDL) criterion concentration, as appropriate. (A) Total phosphorus (B) Orthophosphate (C) Total Kjeldahl nitrogen (D) Ammonia (E) Nitrite plus nitrate

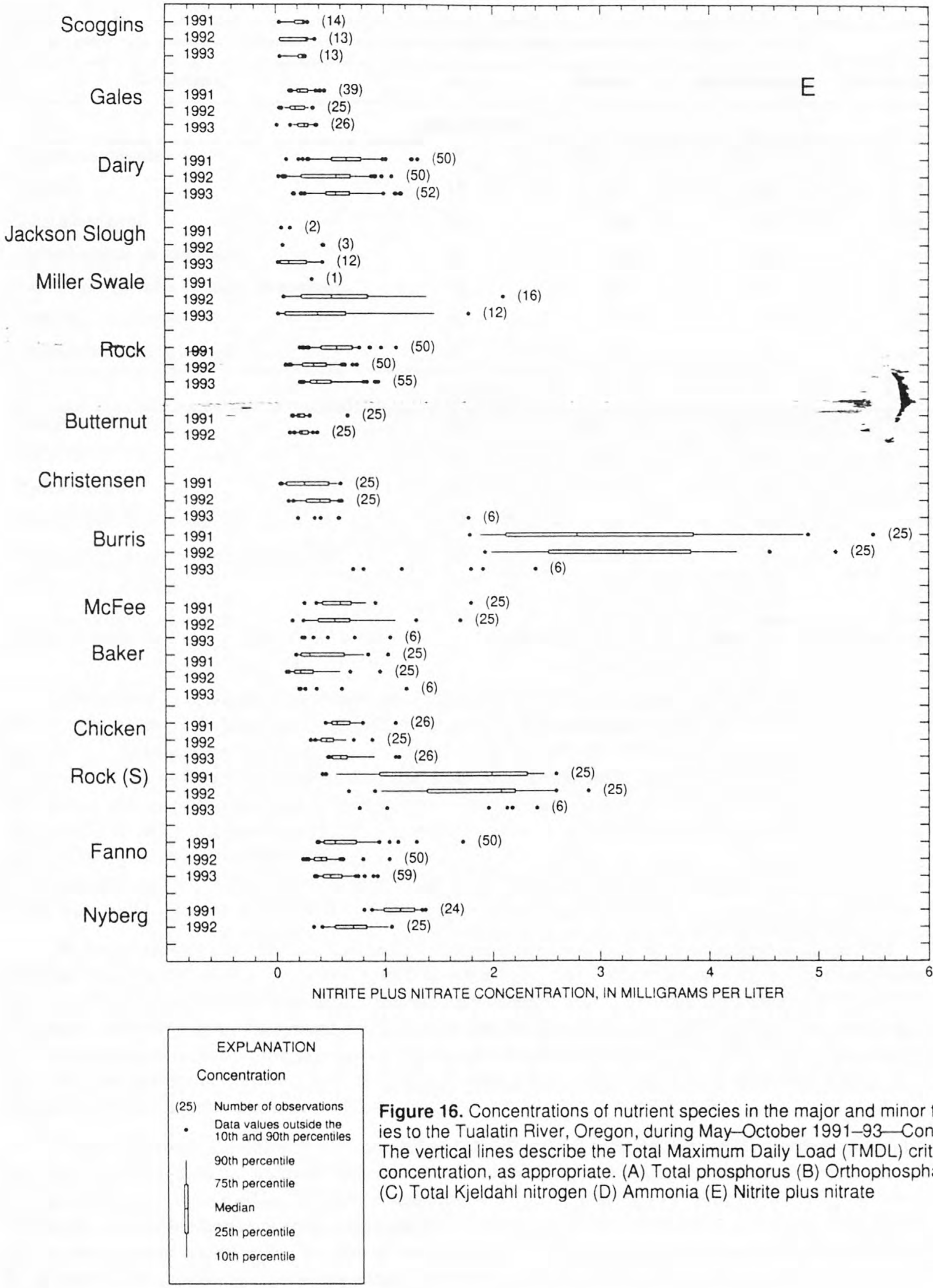



**Figure 16.** Concentrations of nutrient species in the major and minor tributaries to the Tualatin River, Oregon, during May–October 1991–93—Continued. The vertical lines describe the Total Maximum Daily Load (TMDL) criterion concentration, as appropriate. (A) Total phosphorus (B) Orthophosphate (C) Total Kjeldahl nitrogen (D) Ammonia (E) Nitrite plus nitrate

**Table 8.** Summary of nutrient data from small tributaries and tile drains into the Tualatin River, Oregon, observed during the synoptic survey between river miles 51.6 and 27.0 in June 1992

[N, number of observations; small tributaries, tributaries mapped on a scale of 1:24,000; tile drains, tile drains plus tributaries too small to be mapped at 1:24,000 scale; specific conductance in microsiemens per centimeter at 25 degrees Celsius; concentrations in milligrams per liter]

| Constituent | N | Median | 25th Percentile | 75th Percentile |
|---|---|---|---|---|
| **Small tributaries** | | | | |
| Specific conductance | 9 | 304 | 276 | 331 |
| Chloride | 13 | 7.00 | 5.50 | 9.30 |
| Total phosphorus | 16 | .132 | .106 | .252 |
| Orthophosphate, as phosphorus | 16 | .100 | .055 | .150 |
| Organic nitrogen plus ammonia, as nitrogen | 9 | .40 | .30 | .50 |
| Ammonia, as nitrogen | 16 | .040 | .035 | .080 |
| Nitrite plus nitrate, as nitrogen | 16 | .395 | .265 | 1.24 |
| **Tile drains** | | | | |
| Specific conductance | 33 | 306 | 259 | 338 |
| Chloride | 21 | 12.0 | 6.30 | 21.0 |
| Total phosphorus | 36 | .125 | .095 | .290 |
| Orthophosphate, as phosphorus | 36 | .095 | .065 | .190 |
| Organic nitrogen plus ammonia, as nitrogen | 36 | .40 | .20 | .70 |
| Ammonia, as nitrogen | 36 | .045 | .030 | .105 |
| Nitrite plus nitrate, as nitrogen | 36 | 2.15 | .800 | 5.55 |

Median concentrations of total nitrogen in the major tributaries ranged from about 0.4 mg/L to greater than 1.0 mg/L, while concentrations in the smaller tributaries and tile drains were generally larger, ranging up to greater than 5.0 mg/L (fig. 16, table 8). Concentrations of TKN and nitrate were lowest in Scoggins and Gales Creeks, similar to the pattern observed for phosphorus. In general, organic nitrogen and nitrate accounted for more than 90 percent of total nitrogen. Ammonia concentrations were fairly consistent and generally less than TMDL criteria at all sites except for Jackson Slough, Miller Swale, and Christensen Creek. At these three sites in 1991 and 1992, ammonia was an important component of total nitrogen (more than 50 percent) and median concentrations were generally greater than 1.0 mg/L, exceeding the TMDL criterion concentration for the lower main-stem river.

A comparison of chloride and nutrient concentrations among the various categories of sources provides insight into the relation between surface-water and ground-water sources in the Tualatin Basin (fig. 17). For the purpose of this analysis, the tributary category combines data from small unnamed tributaries sampled during the synoptic survey with data for the larger tributaries, sampled on June 4 and 2 in 1992, respectively, within the same river reach as the synoptic survey (RMs 51.6 to 27.0). Drainage from Jackson Bottom is excluded from this analysis and is discussed separately. The ground-water categories include all the domestic well data.

Large differences in chloride concentrations were observed, ranging over several orders of magnitude (fig. 17A). Median chloride concentrations were highest in the tile drains and surface seeps, about 10 mg/L or greater. The median chloride concentration in the tributaries was approximately 7 mg/L, comparable to the median concentration in shallow ground water. Chloride concentrations tended to be less in deep ground water, with a median of about 3.5 mg/L. The largest chloride concentration observed for ground water (>300 mg/L) was associated with a specific conductance measurement of more than 1,500 μS/cm, suggesting the influence of localized brines.

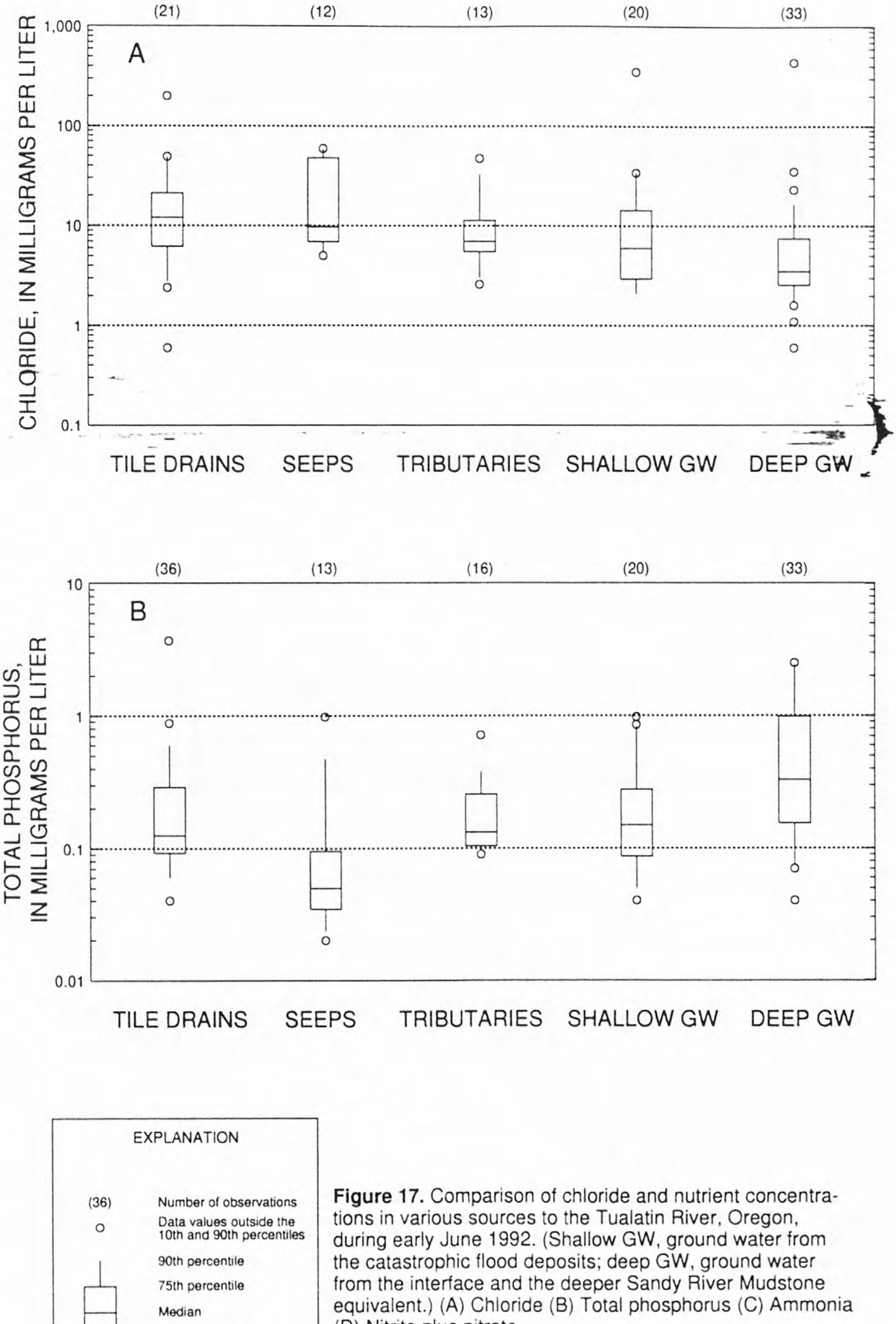
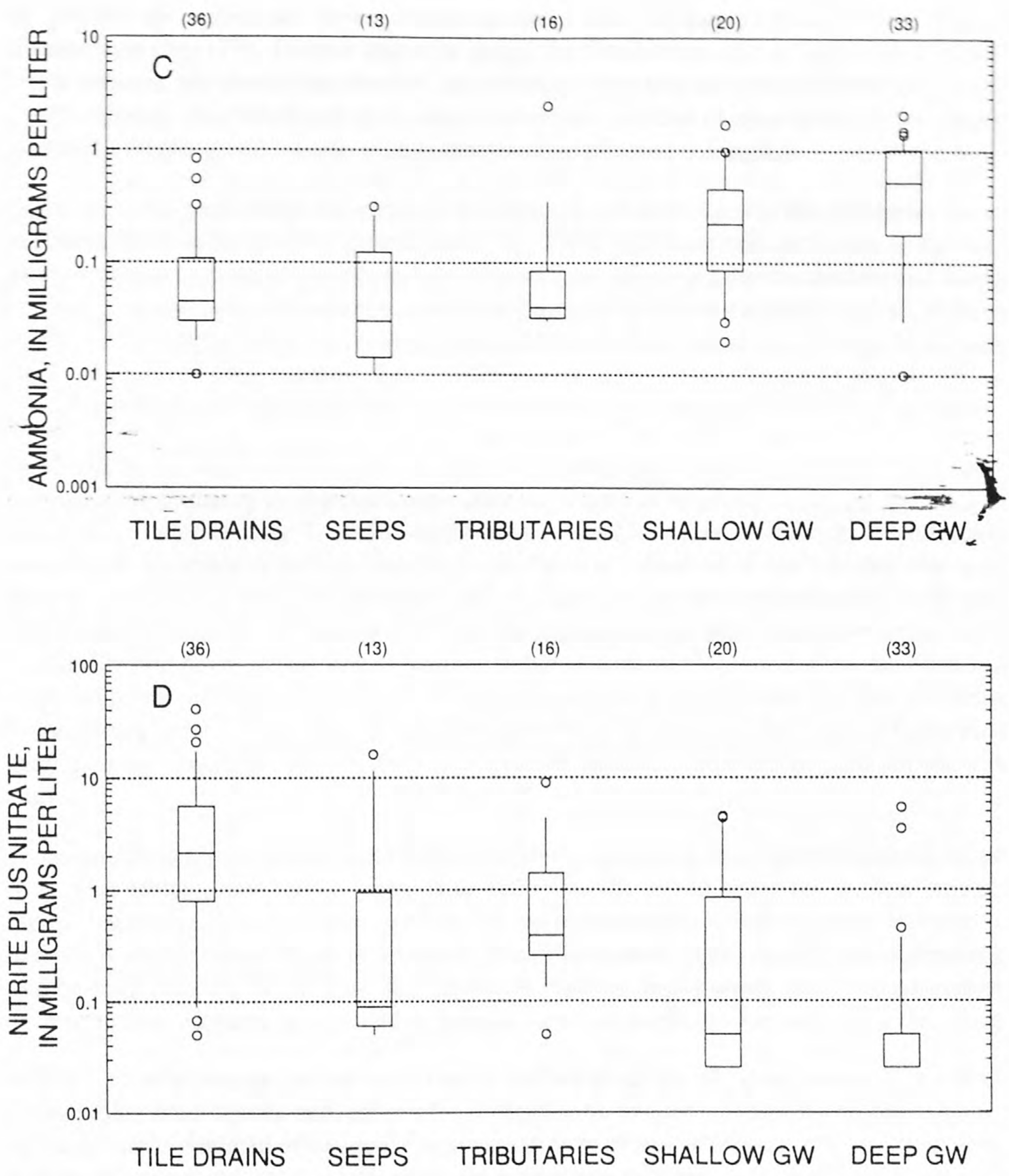



**Figure 17.** Comparison of chloride and nutrient concentrations in various sources to the Tualatin River, Oregon, during early June 1992. (Shallow GW, ground water from the catastrophic flood deposits; deep GW, ground water from the interface and the deeper Sandy River Mudstone equivalent.) (A) Chloride (B) Total phosphorus (C) Ammonia (D) Nitrite plus nitrate



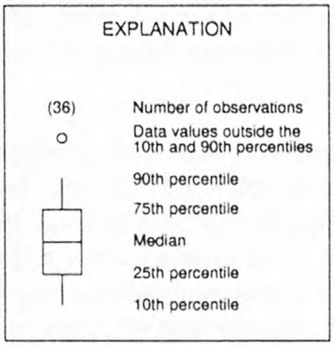




**Figure 17.** Comparison of chloride and nutrient concentrations in various sources to the Tualatin River, Oregon, during early June 1992—Continued. (Shallow GW, ground water from the catastrophic flood deposits; deep GW, ground water from the interface and the deeper Sandy River Mudstone equivalent.) (A) Chloride (B) Total phosphorus (C) Ammonia (D) Nitrite plus nitrate

Considerable variability was also observed in nutrient concentrations among the various sources. The range between the highest and lowest concentrations of total phosphorus spanned more than two orders of magnitude (fig. 17B). Despite that wide range, the distributions of total phosphorus concentrations in the tributaries, tile drains, and shallow ground water were similar (medians between 0.1 and 0.2 mg/L). Phosphorus concentrations in the seeps were lower (median of approximately 0.05 mg/L), while those in the deeper ground water were higher (median of about 0.3 mg/L).

In contrast to the phosphorus concentrations, ammonia concentrations in the tributaries were much lower than those found in the shallow ground water (fig. 17C). Ammonia concentrations in the tile drains and seeps were similar to those in the tributaries, while concentrations in both the shallow and deep ground water were significantly higher. Nitrate concentrations generally followed the pattern of DO. Ground water was typically low in oxygen; therefore, nitrogen was most likely to be found in a reduced form (ammonia) rather than in an oxidized form (nitrate) (fig. 17D). Similarly, water in the tributaries and tile drains was usually well oxygenated, and nitrogen, therefore, was more likely to be found in an oxidized form.

The similarity between total phosphorus concentrations in the tributaries and shallow ground water, corresponding to the similarity in chloride concentrations, is indicative of the direct link between shallow ground water and tributaries in the Tualatin Basin during summer low-flow conditions. The relatively large proportions of total phosphorus as dissolved phosphate that were observed in the tributary data is also consistent with large inputs of phosphorus from ground water, transported predominantly in the dissolved phase. Concentrations of total phosphorus in the tile drains were comparable to the tributaries. In fact, these data indicate that percolation from agricultural fields was essentially identical to that from shallow ground water with respect to phosphorus concentrations, although it was elevated in other constituents such as chloride and nitrate. These data suggest that agricultural practices in the Tualatin Basin did not significantly increase concentrations of phosphorus in water entering streams during the low-flow period of this study.

In contrast, these result suggest that the form of the nitrogen species in the tributaries is influenced primarily by other factors, especially oxygen status, rather than by conditions in the shallow ground water. The ammonia delivered to the tributaries from ground water probably is nitrified quickly by bacteria growing in the shallow stream beds. Nitrate generated by this process tends to be retained in oxygenated surface waters, and be augmented by nitrate from the tile drains, resulting in the observed nitrate concentrations that were intermediate between those found in ground-water and surface-water sources to the tributaries.

The low total phosphorus concentrations in the surface seeps is a plausible consequence of several processes, including plant uptake and, especially, adsorption by or coprecipitation with ferric hydroxides. In ground water that is depleted of oxygen, the dominant form of iron is ferrous iron ($Fe^{+2}$), which is highly soluble. When ground water is exposed to the atmosphere in a seep, however, ferrous iron is rapidly oxidized to the ferric form, $Fe^{+3}$, and insoluble ferric hydroxides precipitate. Phosphorus is easily removed from the water as phosphate ions adsorb readily onto the surface of precipitating ferric hydroxides. Phosphate may also coprecipitate with the ferric hydroxides (Mayer and Jarrell, 1995). Additional phosphorus may be removed in ground water that is close to the surface by plant uptake, similar to the effect observed in soils.

The oxygen gradient that develops in a surface seep is also an important factor regulating the cycling of the nitrogen species in the water. Ammonia concentrations are decreased in the presence of oxygen by the process of bacterial nitrification, which transforms ammonia to nitrate. Although nitrate typically accumulates in a surface system under these conditions, when oxygenated conditions exist in close proximity to anoxic conditions, nitrate can be removed to the atmosphere by denitrification. Because this process acts as a sink for total nitrogen, it is consistent with the observed reduction in total nitrogen in the seeps relative to the shallow ground water.

### Effect of Land Use

The effect of land use on nutrient concentrations in streams in the Tualatin Basin is superimposed on the influence of geology and ground water, and is probably less important during the low-flow summer season because of low surface runoff. The lowest nutrient concentrations were associated with Scoggins and Gales Creeks, which are located primarily in the mountainous regions of the basin. Because these upland regions in the basin serve as regions of ground-water recharge, the extent of ground-water inflow to these streams is limited and local. In addition, nutrient inputs to these streams are small because their drainage basins are mostly forested and contain few point sources of nutrients. Finally, the soils in the upland regions of the basin also tend to have higher affinities to sorb phosphorus than soils in the valley.

The other major tributaries, Dairy, Rock, and Fanno Creeks, and all the smaller tributaries sampled during this study flow through the valley plain and contain relatively high nutrient concentrations. The influence of ground water during summer low-flow conditions is largest on these flatland streams, which are the primary recipients of shallow ground-water discharge in the basin. Still, agricultural and urban land use predominates in these watersheds, so the potential for surface runoff and erosion to contribute large nutrient loads to these streams during periods of higher streamflow is a concern. While streamflow in the Tualatin Basin is much reduced during the summer relative to the rest of the year, periods of stormy weather in the early summer occasionally result in flows much higher than those typically observed later in the summer. As a result, summer flows typically range over several orders of magnitude. For example, measured streamflow ranged from 6 $ft^3/s$ to 576 $ft^3/s$ in Dairy Creek, and from 1 $ft^3/s$ to 384 $ft^3/s$ in Fanno Creek during the summer season in the years 1991–93.

Little correlation between streamflow and nutrient concentrations in the tributaries was observed during this period, however, despite the wide range of flow. Total phosphorus concentrations increased with increasing streamflow only in Fanno Creek, and that increase was less than twofold). The primary effect was an increase in the proportion of particulate phosphorus; the fraction of particulate phosphorus increased from about one-half to two-thirds of the total phosphorus at the highest ranges of streamflow. Early summer storms are associated with increased surface runoff that washes particulate phosphorus into the streams or resuspends bed-sediment material, although the concentrations of total phosphorus are not necessarily increased. Under baseflow conditions later in the summer, dissolved phosphate becomes the predominant form of phosphorus, reflecting the primary influence of ground-water discharge to streams under these conditions.

Similarly, little increase in concentrations of total nitrogen was observed with increased streamflow in any of these streams except for Dairy Creek. The fraction of total nitrogen as nitrate also tended to be consistently larger with higher streamflow in Dairy Creek. The increase in nitrate with higher flows is probably associated with the migration of nitrate derived from nitrogen fertilizer. Because nitrate is very soluble in oxygenated waters, it is highly mobile in shallow ground water and tile drains.

The most significant effects of land use on nutrient concentrations in the Tualatin Basin occurred in small tributaries characterized by the highest nutrient concentrations: Christensen and Burris Creeks, Jackson Slough, and Miller Swale. These streams received relatively large nutrient loads as a result of specific land-use activities within their subbasins during the period of study.

The elevated concentrations of total phosphorus and ammonia in Christensen Creek were partly due to improper handling of manure used for fertilizer in a single confined animal feeding operation that caused large loads of both constituents to enter the stream (Mike Wolf, Oregon Department of Agriculture., oral commun, 1995). Similarly, surface runoff of irrigation water from a container nursery in the Burris Creek subbasin was part of the cause of the high concentrations of total phosphorus observed there (Mike Wolf, Oregon Department of Agriculture, oral commun., 1995). The significant concentration decrease in these constituents that was observed in Christensen and Burris Creeks over the period of this study can be attributed to the adoption of improved management practices within these individual facilities. Median concentrations of total phosphorus in both tributaries ranged between 0.45 and 0.60 mg/L in 1991, but dropped to about 0.20 mg/L during 1993. The median concentration of ammonia in Christensen Creek decreased from approximately 3.0 mg/L in 1991 to less than 0.1 mg/L in 1993. The data are limited by the fact that only 6 samples were collected in 1993, compared to more than 20 samples each in 1991 and 1992. Nonetheless, these results suggest that poorly handled nutrient sources can result in high instream nutrient concentrations, and that Best Management Practices can improve water quality in streams in the Tualatin Basin.

Because of the irrigation of effluent from the Hillsboro WWTP onto the Jackson Bottom experimental wetland, nutrient concentrations in Jackson Slough and Miller Swale reflect the efficiency of the wetland system in filtering and retaining nutrients from the wastewater. Several changes in the management of Hillsboro WWTP effluent during the study period resulted in significant overall reductions in nutrient loading to the river, especially from Miller Swale (table 9). The management changes included an increase in the number of acres irrigated between 1992 and 1993, from 168 to 338, and a reduction in the volume of effluent diverted through the cells of the Jackson Bottom Experimental Wetland (Jan Miller, USA, written commun., 1994).

Loading from Jackson Slough was relatively stable throughout most of the study period, with median concentrations of total phosphorus ranging from about 0.7 to 1.0 mg/L and median total nitrogen concentrations from 1.6 to 2.5 mg/L (fig. 16). The median ammonia concentration was consistently about 1.0 mg/L. Because the volume of streamflow was so small, generally less than 0.5 $ft^3/s$, nutrient loads remained relatively low throughout the period of this study (table 9). In contrast, median concentrations of total phosphorus in Miller Swale decreased significantly over the 3-year period, from 2.5 mg/L in 1991 to 0.73 mg/L in 1993 (fig. 16). Total nitrogen concentrations were also reduced, mostly due to a decrease in ammonia. An increase in nitrate concentrations was observed over the same period. The elevated concentrations of total phosphorus and ammonia in Miller Swale during 1991 were a consequence of problems in the experimental wetland that caused effluent to flow directly into the swale with minimal treatment (Jan Miller, USA, oral commun., 1994). In 1992 and 1993, the reduction in effluent volume passing through the experimental cells, coupled with an increase in the number of acres irrigated, resulted in greater effectiveness of nutrient removal by wetland processes. Streamflow in Miller Swale was also reduced by these changes, which further reduced the loads of both phosphorus and nitrogen (table 9).

**Table 9.** Mean streamflow and nutrient loads in streams draining Jackson Bottom during May–October in 1991, 1992, and 1993

[*Excludes 2 weeks in June, when Hillsboro Wastewater Treatment Plant effluent was diverted through Jackson Slough; streamflow in cubic feet per second; loads in pounds per day]

| Constituent | Jackson Slough | | | Miller Swale | | |
|---|---|---|---|---|---|---|
| | 1991 | 1992 | 1993* | 1991 | 1992 | 1993 |
| Streamflow | 0.38 | 0.30 | 0.51 | 1.4 | 0.92 | 0.91 |
| Total phosphorus | 1.4 | 1.7 | 2.4 | 19 | 7.8 | 3.7 |
| Total nitrogen | 3.1 | 3.9 | 9.3 | 65 | 20 | 8.7 |
| Ammonia, as nitrogen | 1.5 | 1.8 | 5.7 | 49 | 11 | 3.4 |
| Nitrite plus nitrate, as nitrogen | .09 | .22 | .39 | .73 | 2.5 | 1.9 |

## Wastewater Treatment Plants

Effluent discharge from the two large WWTPs, Rock Creek (RM 38.1) and Durham (RM 9.3), to the Tualatin River constitutes a significant component of main-stem streamflow during the late-summer low-flow period. In addition, nutrient concentrations in WWTP effluent historically had been very high, resulting in large loads to the river. Improvements in treatment efficiencies during recent years produced considerable reductions in nutrient loads as a result of lower concentrations in the effluent (fig. 18). Nonetheless, effects of the WWTPs on nutrient concentrations in the river remained large during the period of this study. Appendix B contains figures that show the composite daily mean concentrations of chloride, nitrogen, and phosphorus in WWTP effluent during the study period.

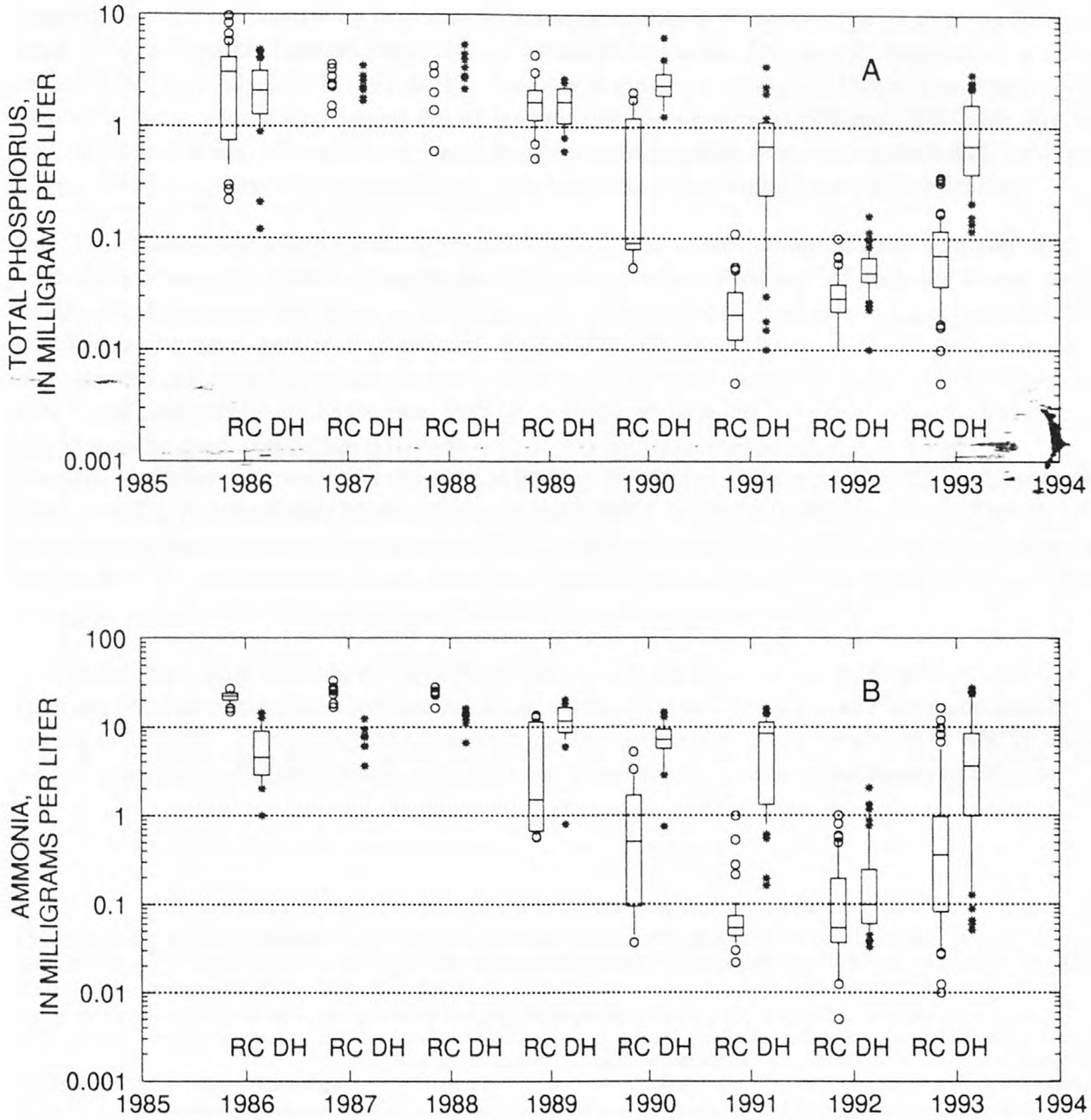
Advanced tertiary treatment for phosphorus removal, using a two-step alum addition, was added to the treatment process at the Rock Creek and Durham WWTPs in response to the establishment of the phosphorus TMDL in the Tualatin Basin. The upgrades at the Rock Creek WWTP were completed prior to the summer of 1991, and resulted in a significant decrease in total phosphorus concentrations in Rock Creek WWTP effluent (fig. 18A). Prior to the initiation of advanced treatment, daily mean concentrations were typically greater than 2.0 mg/L, while concentrations decreased to generally less than 0.10 mg/L during the period of this study. In fact, daily mean total phosphorus concentrations in Rock Creek effluent were less than the TMDL criteria concentration of 0.07 mg/L for most of 1991 and 1992. Because the concentrations of total phosphorus in the main-stem river typically exceeded the TMDL criteria, the Rock Creek WWTP effluent was actually diluting the receiving waters during those years.

Pilot testing of the advanced treatment process at the Durham WWTP was ongoing through the summer of 1992, when effluent concentrations were also generally less than 0.10 mg/L (fig. 18A). During 1991, and again in 1993 while the upgrades were being installed at the Durham WWTP, phosphorus concentrations in effluent were higher by up to one order of magnitude. The upgrades at the Durham WWTP were completed by the summer of 1994, allowing it to consistently discharge effluent with phosphorus concentrations less than 0.10 mg/L.

Similarly, additional treatment processes (termed biological nutrient removal, including inplant nitrification) were implemented at both the Rock Creek and Durham WWTPs for ammonia removal in response to the ammonia TMDL. The schedule for these upgrades at both WWTPs was approximately the same as for the two-stage alum process for phosphorus removal. With this additional treatment process in place, ammonia concentrations in effluent from the Rock Creek WWTP were reduced by more than an order of magnitude (fig. 18B). Median concentrations decreased from over 10.0 mg/L in 1986 to less than 1.0 mg/L during 1991–93. With the maximum treatment in effect at Durham during 1992, the median ammonia concentrations were about 0.10 mg/L, although they ranged much higher during 1991 and 1993.

Effluent concentrations of nitrate are very high when these WWTPs maintain nitrification for ammonia removal, making nitrate the largest component of total nitrogen in the effluent. As a consequence of the nitrification process, effluent from the Rock Creek WWTP consistently contained nitrate concentrations around 10 mg/L; similar concentrations of nitrate were observed in the Durham WWTP effluent during 1992 (Appendix B). In 1991 and 1993, however, nitrate concentrations fluctuated over an order of magnitude according to the efficiency of the WWTP nitrification process.

Specific conductance and chloride concentrations in WWTP effluent tend be relatively high compared to other major sources to the main-stem river. Because these constituents are associated primarily with WWTP effluent, they function as a useful signature for the influence of the WWTPs. In effluent from the Rock Creek and Durham WWTPs during this study, specific conductance was generally in the range between 500 and 800 μS/cm. Similarly, chloride concentrations were also elevated, ranging between 30 and 50 mg/L in effluent from the Rock Creek WWTP, and between about 40 to 70 mg/L in effluent from Durham.



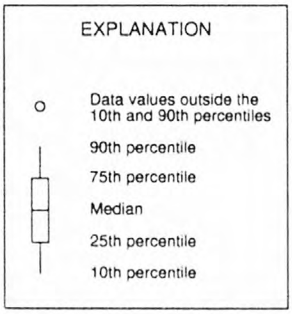




**Figure 18.** Concentrations of total phosphorus and ammonia nitrogen in effluent from the Rock Creek (RC) and Durham (DH) Wastewater Treatment Plants to the Tualatin River, Oregon, during May–October 1986–93. (A) Total phosphorus (B) Ammonia

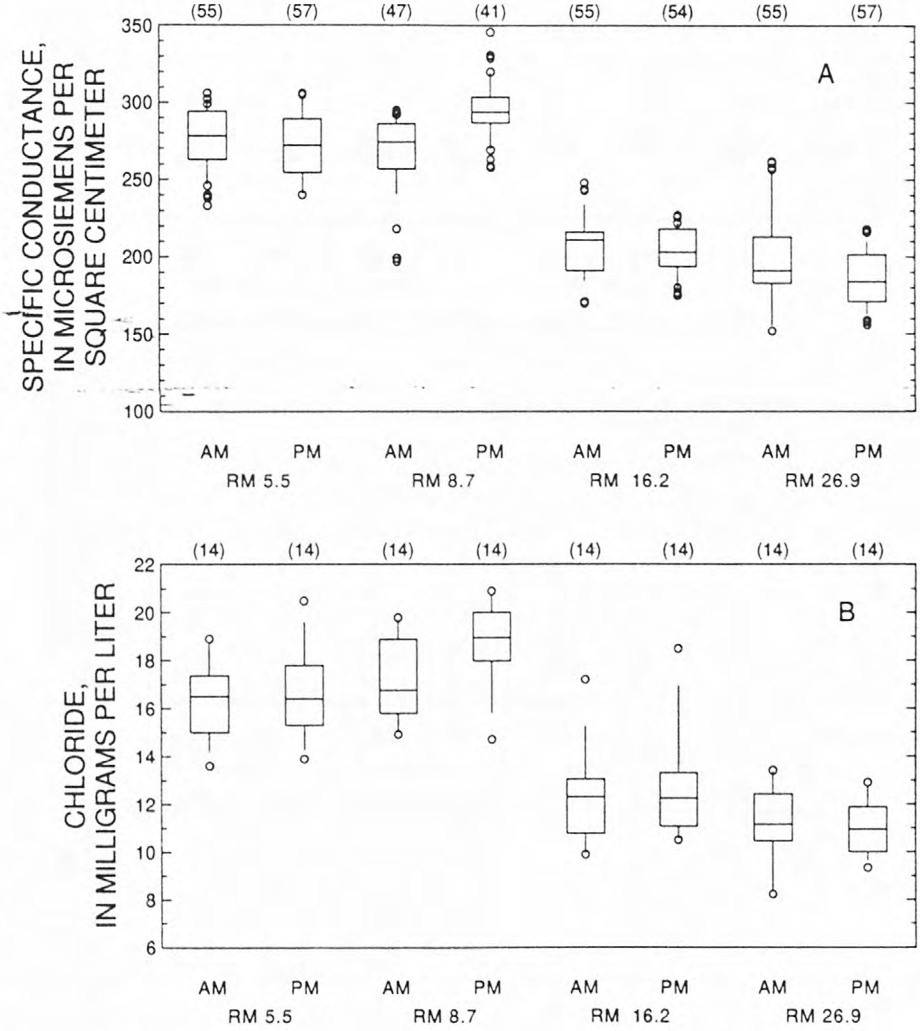
In addition to fluctuations in daily or seasonal nutrient loads, WWTPs also exhibit a diel fluctuation in loading. WWTP diel variability is primarily tied to variability in effluent discharge over the 24-hour period, although nutrient concentrations also vary throughout the day. During a 24-hour survey at the Durham WWTP on July 10–11, 1991, both the volume of effluent discharge and the concentrations of total phosphorus and ammonia were largest during the daylight hours between 0800 and 1900 (table 10). As a result, the largest loads of both constituents were observed during this time. During the night, between 2000 and 0700, discharge and concentrations were less, with a concomitant reduction in loading.

Diel variability in nutrient loading from WWTPs can be a potential sampling issue during low-flow periods when streamflow is sluggish, preventing longitudinal dispersion of loads for several miles downstream. To evaluate the extent of this effect, data were compared from morning and afternoon samples taken at four main-stem river sites during the low-flow period in 1992 (fig. 19). Large differences were observed in the median values for those constituents primarily associated with WWTP effluent at RM 8.7, just downstream of the Durham WWTP. A difference of about 25 μS/cm in the median measurement of specific conductance was observed, with higher values measured in samples taken during the afternoon. A similar difference was observed at this site for chloride (approximately 2.5 mg/L) and nitrate (about 1 mg/L). The travel time between Durham and RM 8.7 during this period was about 7 hours, so that samples taken during the morning reflected effluent discharged during the middle of the night, when loads from the WWTP were relatively small. In contrast, samples taken during the afternoon reflected effluent discharged around 0900 in the morning, when nutrient loads were relatively large.

Differences were not observed at any of the other sites for any of the nutrient species, with one exception. Median concentrations of ammonia and nitrate were reduced in the afternoon compared to the morning at RM 26.9. It is unlikely that these differences were a result of diel variability in WWTP loading, however, because no diel differences were observed at this site for specific conductance or chloride.

**Table 10.** Summary of hourly effluent discharge measurements, and concentrations and loads of total phosphorus and ammonia, as nitrogen, from a 24-hour survey at the Durham Wastewater Treatment Plant (The survey began at 0800 on July 10, 1991 and ended at 0700 on July 11, 1991.)
[Discharge in million gallons per day; mg/L, milligrams per liter; lb/d, pounds per day]

| Time period | Mean discharge | Total phosphorus (mg/L) | Total phosphorus (lb/d) | Ammonia nitrogen (mg/L) | Ammonia nitrogen (lb/d) |
|---|---|---|---|---|---|
| 0800-1300 | 15.9 | 2.80 | 372 | 15.9 | 2,110 |
| 1400-1900 | 17.3 | 1.30 | 188 | 13.4 | 1,940 |
| 2000-0100 | 15.2 | 0.89 | 113 | 13.0 | 1,650 |
| 0200-0700 | 10.0 | 1.13 | 94 | 12.7 | 1,060 |



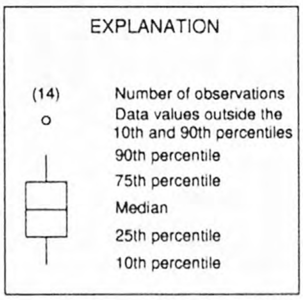
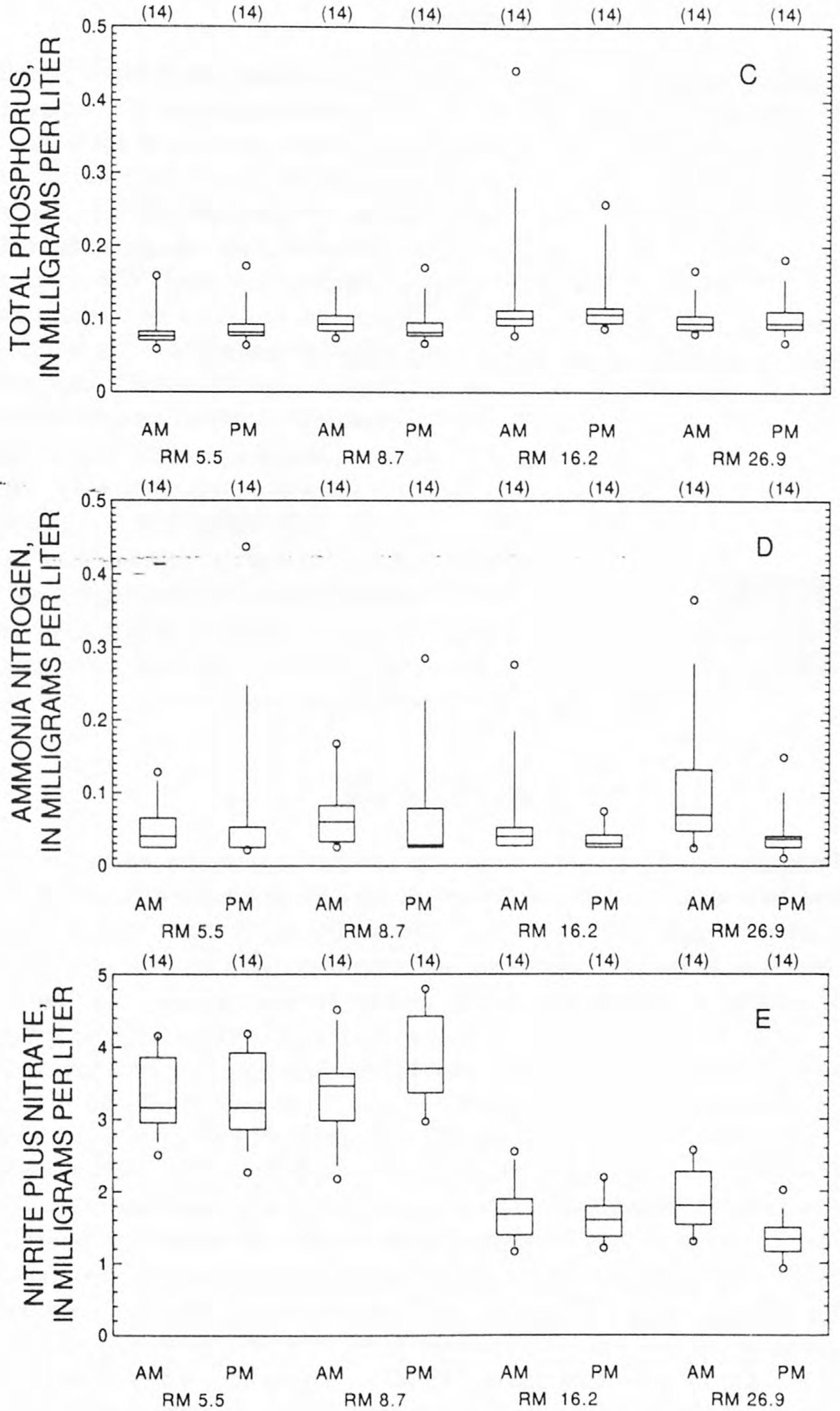




**Figure 19.** Comparison of specific conductance, chloride, total phosphorus, ammonia nitrogen, and nitrite plus nitrate from morning (AM) and afternoon (PM) samples taken at selected river miles (RM) in the Tualatin River, Oregon, during May–October 1992.
(A) Specific conductance (B) Chloride (C) Total phosphorus (D) Ammonia (E) Nitrite plus nitrate



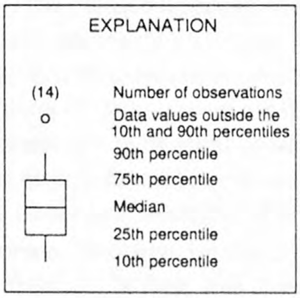




**Figure 19.** Comparison of specific conductance, chloride, total phosphorus, ammonia nitrogen, and nitrite plus nitrate from morning (AM) and afternoon (PM) samples taken at selected river miles (RM) in the Tualatin River, Oregon, during May–October 1992—Continued. (A) Specific conductance (B) Chloride (C) Total phosphorus (D) Ammonia (E) Nitrite plus nitrate

### Diversions

Diversion of water from a water body functions as a sink, resulting in a net loss of water and nutrients from the system. The largest diversion of water in the Tualatin River, ranging from 30 to 40 percent of the water volume in the upper river, occurs at the Springhill Pumping Plant (RM 56.1). Total nutrient concentrations are relatively low in this region of the river because the sources of water are typically the most dilute in the basin: the headwaters of the main-stem river, Gales Creek, and stored water from Henry Hagg Lake through Scoggins Creek. Below this point, inflows of water from Dairy Creek, Rock Creek, and the Rock Creek WWTP, as well as numerous smaller tributaries, are characterized by relatively large nutrient concentrations. As a result of the removal of such a large proportion of water volume in the upper main-stem river, the effect of the sources farther downstream on phosphorus concentrations in the river is increased. Diversion of water through the Springhill Pumping Plant, therefore, reduces the potential for dilution of nutrient sources farther downstream.

The second major diversion occurs in the lower river, at RM 6.7, where the Oswego Canal transfers water into Lake Oswego. At this point in the main-stem river, below all the major WWTP and tributary sources, nutrient concentrations are relatively high, especially phosphorus. Consequently, diversion of this water serves as a significant reduction in the phosphorus load. The overall effect on water quality in the main-stem river is slight, however, because the withdrawal does not directly affect nutrient concentrations.

Similarly, withdrawal of water directly from the river by individual water users has a negligible effect on nutrient concentrations because the total volume of water withdrawn is relatively small and distributed over many river miles instead of concentrated in one location.

## Main-Stem River

Water samples were routinely collected at main-stem river sites from the upper 10 feet of the water column. Data from these samples provide an overview of concentration patterns in the river over the length of the study reach and demonstrate the influence of major inputs, including tributaries and WWTPs. The extent of thermal stratification in the lower river, and the potential impact of stratification on loading of nutrients from the bottom sediments, were assessed with data from samples collected from the deeper water in the lower river during specific time periods.

Chloride concentrations in the surface waters of the Tualatin River during the summer months were governed primarily by effluent from the Rock Creek and Durham WWTPs (fig. 20A). The median value for chloride was low at RM 58.8 (less than 5 mg/L) because of the influence of water from Henry Hagg Lake. Farther downstream at RM 36.8, however, just below the Rock Creek WWTP, the median chloride concentration increased to about 10 mg/L. Median values remained fairly steady downstream until RM 8.7, below the Durham WWTP, where they increased again to nearly 15 mg/L or more.

In contrast, concentrations of total phosphorus in the upper 10 feet of the main-stem river during this study were governed largely by inputs between RMs 58.8 and 38.4, with negligible influence from the WWTPs (except for Durham in 1991 and 1993). Median concentrations of total phosphorus increased steadily in the upper river from 0.03 mg/L at RM 58.8 to approximately 0.1 mg/L at RM 38.4, exceeding the TMDL criterion concentration for the lower river of 0.07 mg/L during all 3 years (fig. 20B). Downstream of RM 38.4, the median concentration of total phosphorus remained nearly constant at about 0.1 mg/L during 1992, increasing to about 0.15 mg/L with the inflow of effluent from Durham in 1991 and 1993. A parallel pattern of increase in soluble orthophosphate in the upper river was observed (fig. 20C). Median concentrations of orthophosphate decreased somewhat in the lower river, especially during 1992, presumably as a consequence of algal uptake. The low streamflows and prevalent sunny skies during that year generated highly favorable conditions for the growth of algae in the lower river below RM 26.9, consistent with the observed depletion of orthophosphate concentrations.

Concentrations of nitrogen, on the other hand, were closely tied to WWTP effluent in a pattern similar to that for chloride. Nitrate was consistently the primary component of total nitrogen, comprising approximately 60 to 80 percent (fig. 20D, E, and F). Median nitrate concentrations increased from about 0.3 mg/L at RM 58.8 to greater than 1 mg/L below the Rock Creek WWTP, increasing still further downstream of the Durham WWTP to 2 to 3 mg/L. Ammonia concentrations, in contrast, were generally low relative to the TMDL criterion concentrations throughout the river (fig. 20E). Between RM 5.5 and the mouth, a distinct decline in median ammonia concentration was observed, more pronounced in 1991 when ammonia concentrations were relatively large, suggesting nitrification in the shallow reach below the diversion dam at RM 3.4. The corresponding increase in nitrate was not clearly detectable, however, because it was small relative to the nitrate concentration already present.

### Thermal Stratification

In the lower river (RM 33.3–3.4), thermal stratification can occur during the summer as a result of high solar insolation and sluggish streamflow. The stream depth is irregular in this reach of the river, especially downstream of RM 12, and characterized by pools deeper than 12 feet that are separated by relatively shallow sills. The extent of thermal stratification in these pools was estimated by the degree of oxygen depletion with depth, because sediment oxygen demand tends to deplete oxygen in the deeper water during extended periods of thermal stratification in the water column. To gauge the persistence of stratification through the night, oxygen measurements taken during the morning only were examined at four main-stem sampling sites (RMs 16.2, 11.6, 8.7, and 5.5). Depth profiles indicate that the streambed at these sites represents typical conditions within their respective regions of the river.

No evidence for persistent thermal stratification was observed at two of the sites, RM 16.2 and RM 8.7. At the other two sites, RM 11.6 and RM 5.5, morning concentrations of DO near the river bottom were observed on occasion to be less than 1 mg/L. The frequency of oxygen depletion was significantly greater at RM 5.5, observed on 46 percent of the sampling visits, compared to 10 percent of the sampling visits at RM 11.6. Streambed conditions at RM 5.5 generally represent average conditions for the reach between RM 3.8 and 6.5; the stratification observed at RM 5.5, therefore, presumably affects most of the 3-mile reach upstream of the diversion dam. Although shallow areas less than 12 feet in depth do occur periodically throughout this reach, they are uncommon. Most of this reach has depths greater than 15 feet, with some depths extending below 18 feet just upstream of the dam.

Routine temperature measurements taken throughout the study indicate that the duration of thermal stratification at RM 5.5 varied from year to year, with the longest period observed during 1992 (fig. 21). The maximum temperature difference that was observed was not large, with temperatures ranging between 22°C at the surface to 18°C near the stream bottom. Nonetheless, the density gradient was stable enough to create a distinct hypolimnion that was separated from the upper water for prolonged periods of time during June, July, and August in 1992. The length of time was less in 1991, although it extended through most of July and August. The period of stratification was limited to only a few weeks in August in 1993, presumably because of the higher streamflow early in the summer during that year. During these periods of thermal stratification, oxygen depletion in the deeper water was significant, typical of eutrophic systems (fig. 22). The extent of the anoxic zone was generally confined to depths below 12 feet.

### Loading from Sediments

Water samples were collected from the hypolimnion at six sites between RM 11.6 and the diversion dam at RM 3.4, on July 20, 1992, to evaluate the potential for significant loading of nutrients from the bottom sediment during stratified conditions (table 11). Discrete samples from various depths were taken at a number of sites in this reach. Thermal stratification and oxygen depletion in the deep water were well established at RM 5.5 on this date (figs. 21 and 22). Elevated concentrations of total phosphorus greater than 1.5 mg/L were observed at two sites, RM 5.5 and RM 4.0, at depths of 18 and 21 feet respectively.

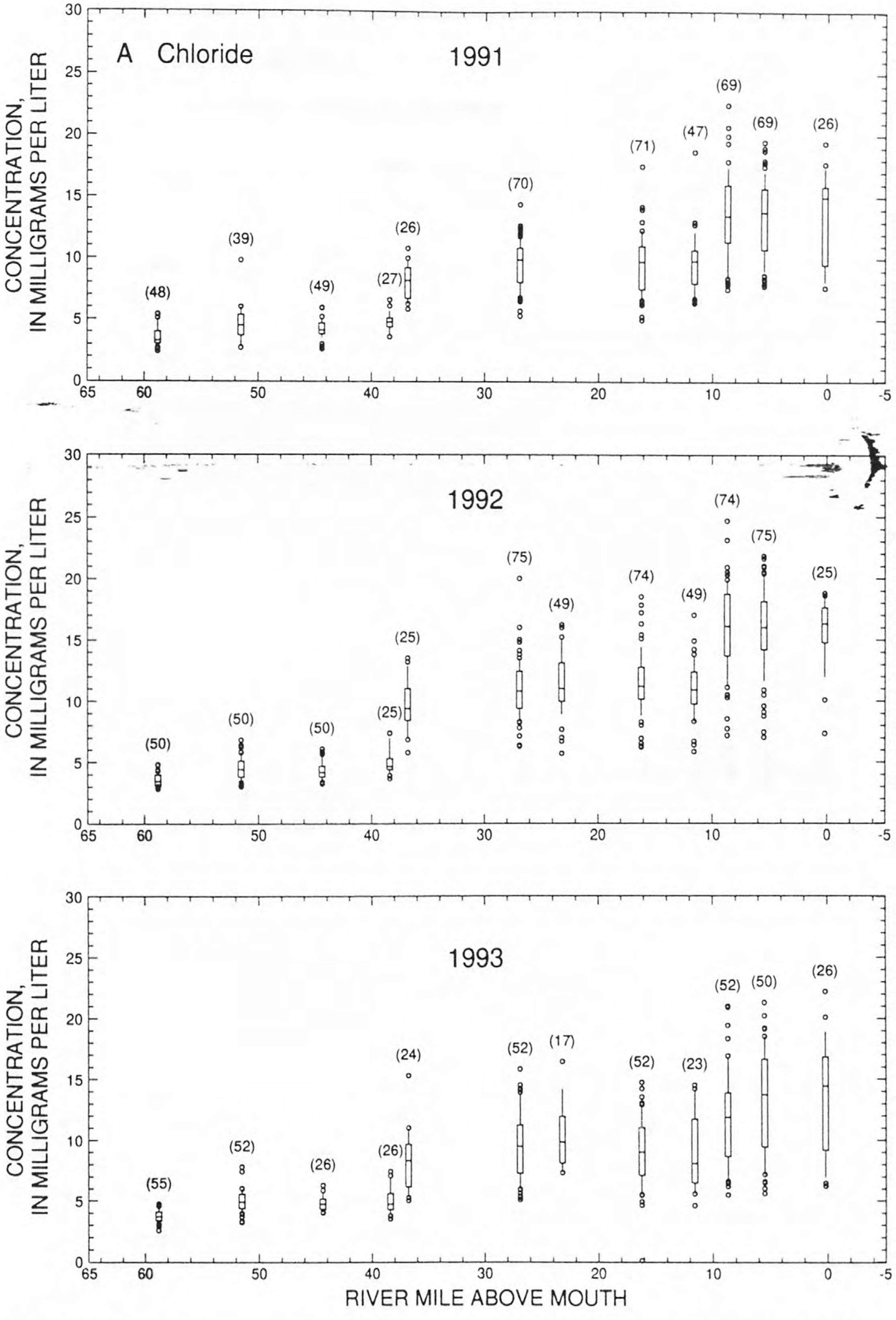



**Figure 20.** Concentrations of chloride and nutrients at selected sites in the main-stem Tualatin River, Oregon, during May through October 1991–93—Continued. Data are from the upper 10 feet. (TMDL, Total Maximum Daily Load) (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total Kjeldahl nitrogen, TKN (E) Ammonia (F) Nitrite plus nitrate

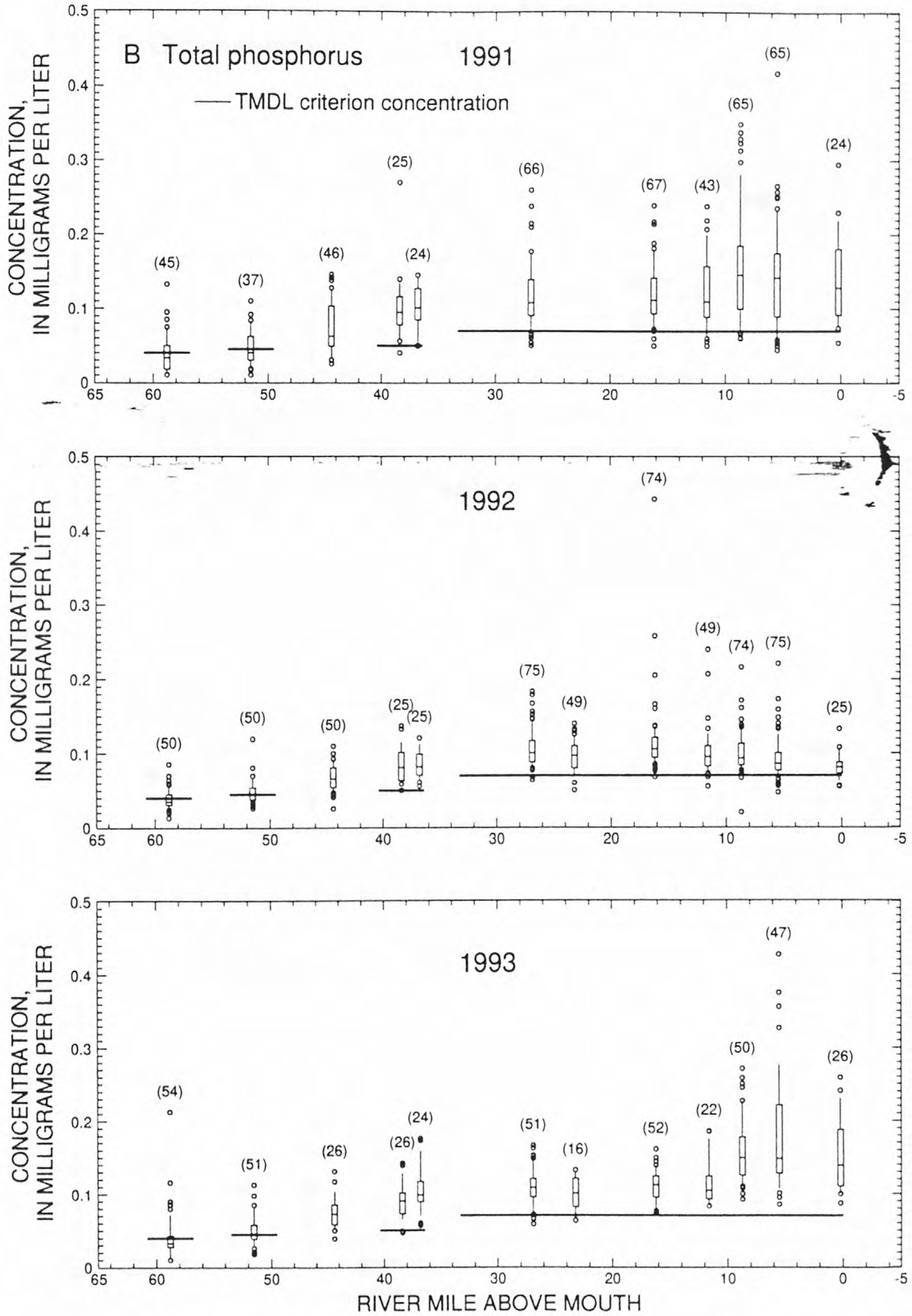



**Figure 20.** Concentrations of chloride and nutrients at selected sites in the main-stem Tualatin River, Oregon, during May through October 1991–93—Continued. Data are from the upper 10 feet—Continued. (TMDL, Total Maximum Daily Load) (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total Kjeldahl nitrogen, TKN (E) Ammonia (F) Nitrite plus nitrate

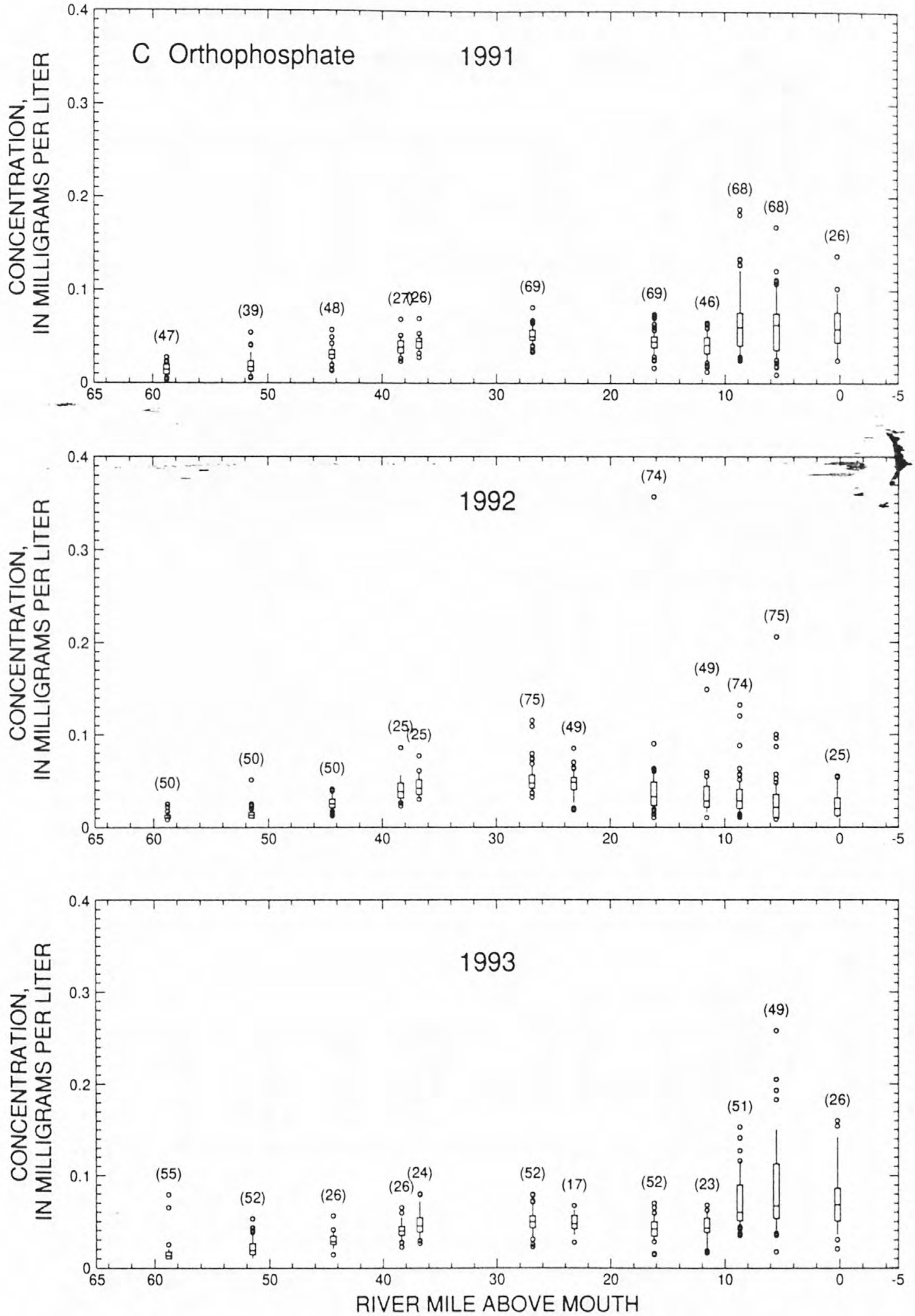



**Figure 20.** Concentrations of chloride and nutrients at selected sites in the main-stem Tualatin River, Oregon, during May through October 1991–93—Continued. Data are from the upper 10 feet—Continued. (TMDL, Total Maximum Daily Load) (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total Kjeldahl nitrogen, TKN (E) Ammonia (F) Nitrite plus nitrate

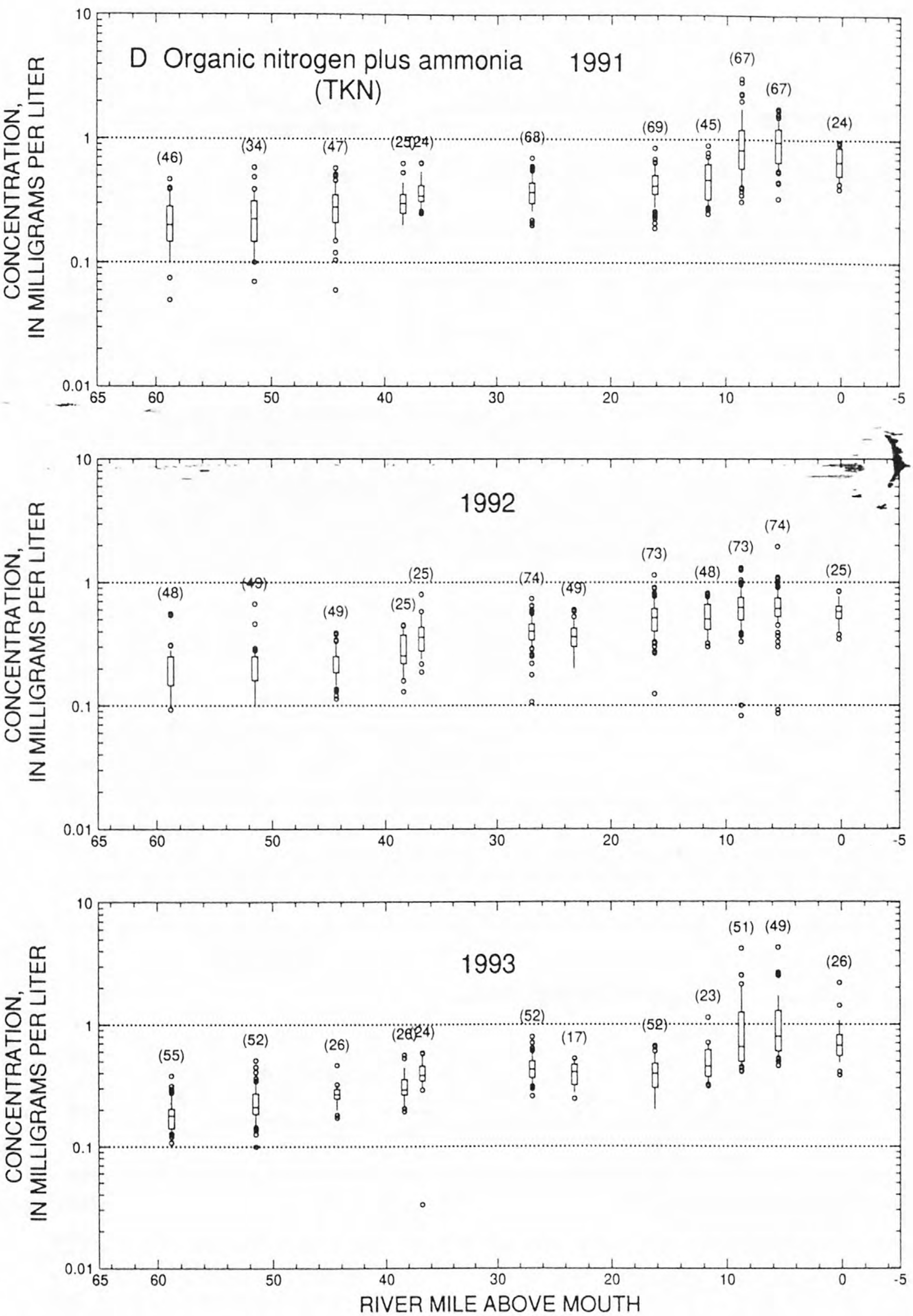



**Figure 20.** Concentrations of chloride and nutrients at selected sites in the main-stem Tualatin River, Oregon, during May through October 1991–93—Continued. Data are from the upper 10 feet—Continued. (TMDL, Total Maximum Daily Load) (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total Kjeldahl nitrogen, TKN (E) Ammonia (F) Nitrite plus nitrate

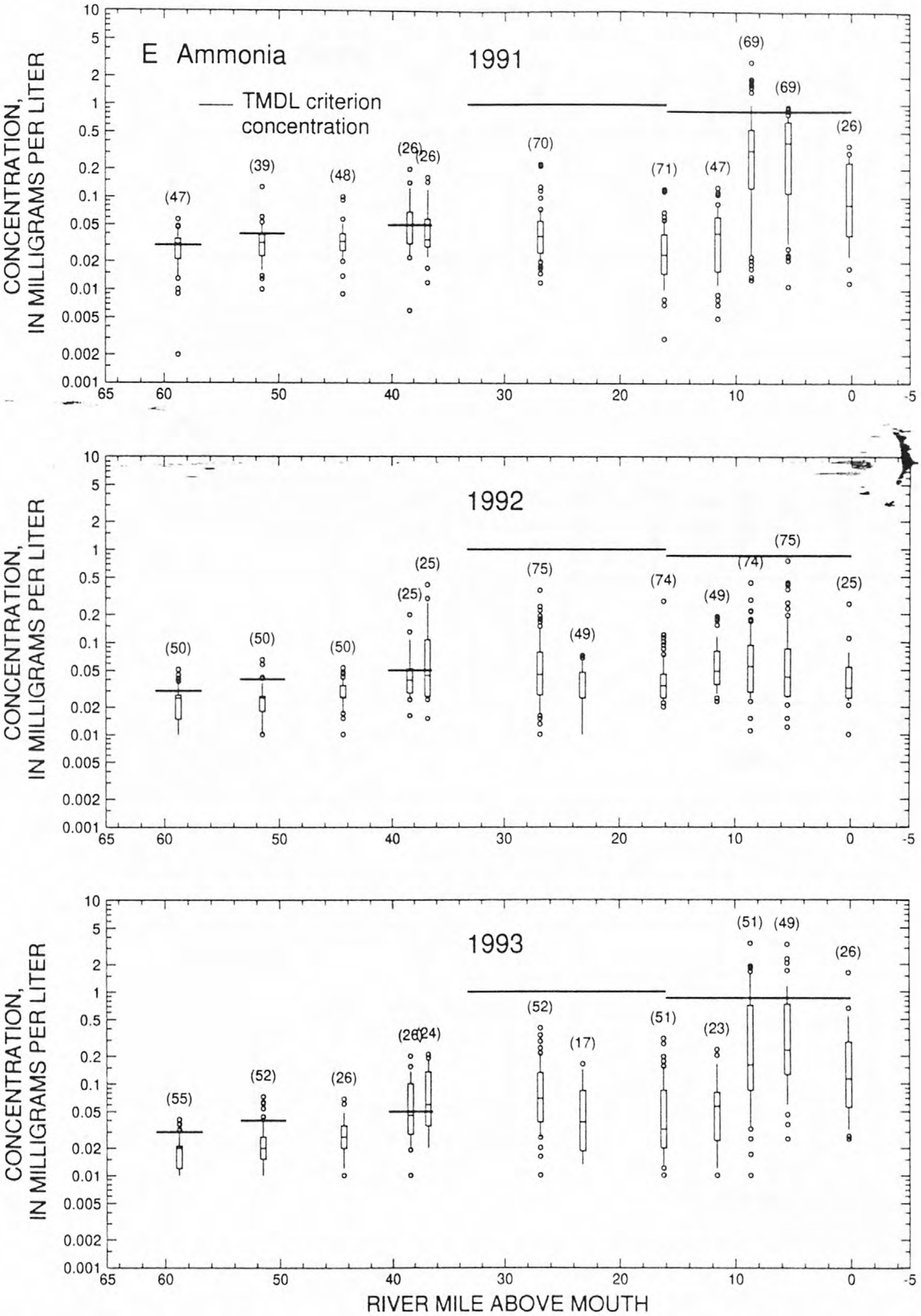



**Figure 20.** Concentrations of chloride and nutrients at selected sites in the main-stem Tualatin River, Oregon, during May through October 1991–93—Continued. Data are from the upper 10 feet—Continued. (TMDL, Total Maximum Daily Load) (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total Kjeldahl nitrogen, TKN (E) Ammonia (F) Nitrite plus nitrate

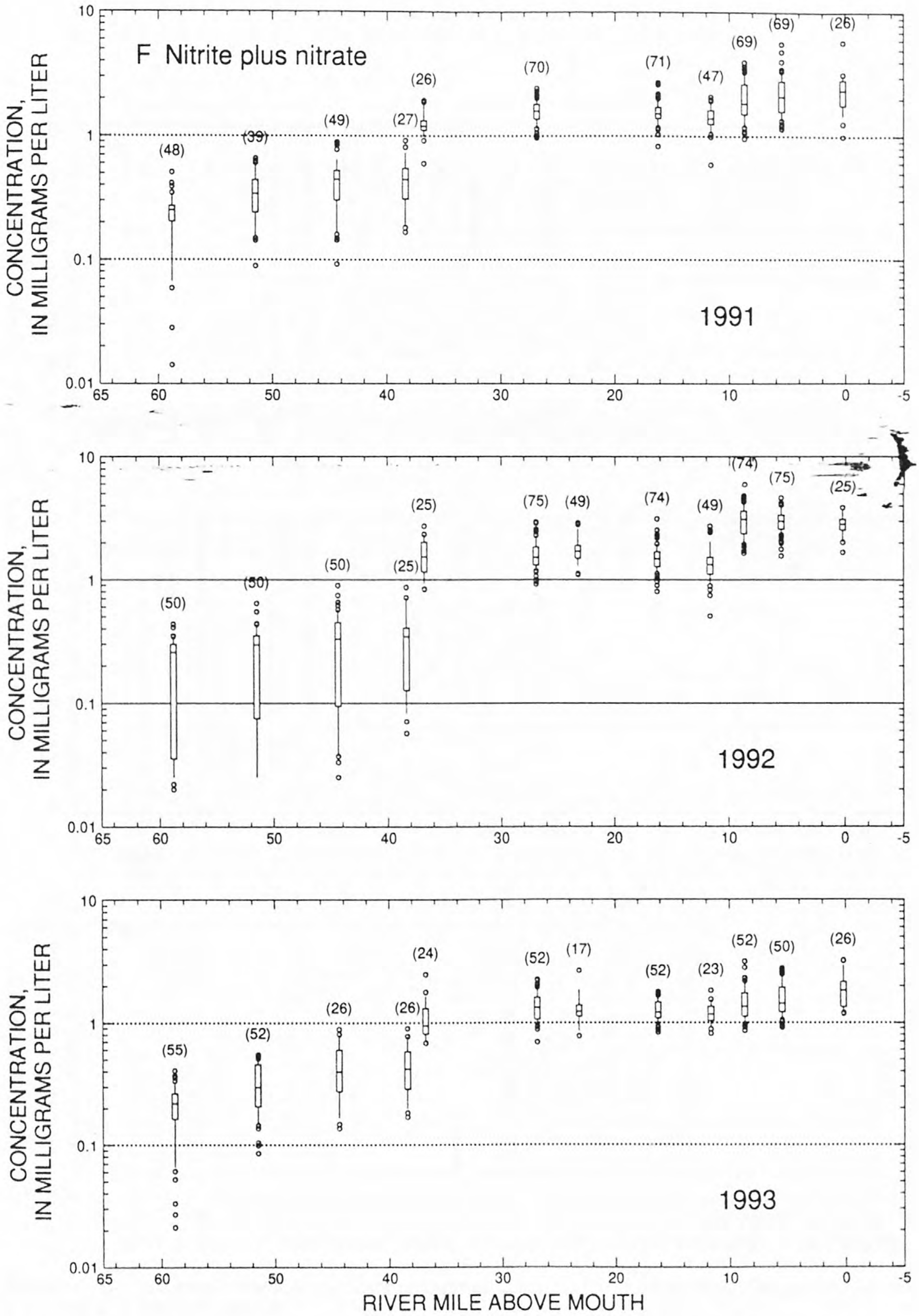



**Figure 20.** Concentrations of chloride and nutrients at selected sites in the main-stem Tualatin River, Oregon, during May through October 1991–93—Continued. Data are from the upper 10 feet—Continued. (TMDL, Total Maximum Daily Load) (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total Kjeldahl nitrogen, TKN (E) Ammonia (F) Nitrite plus nitrate

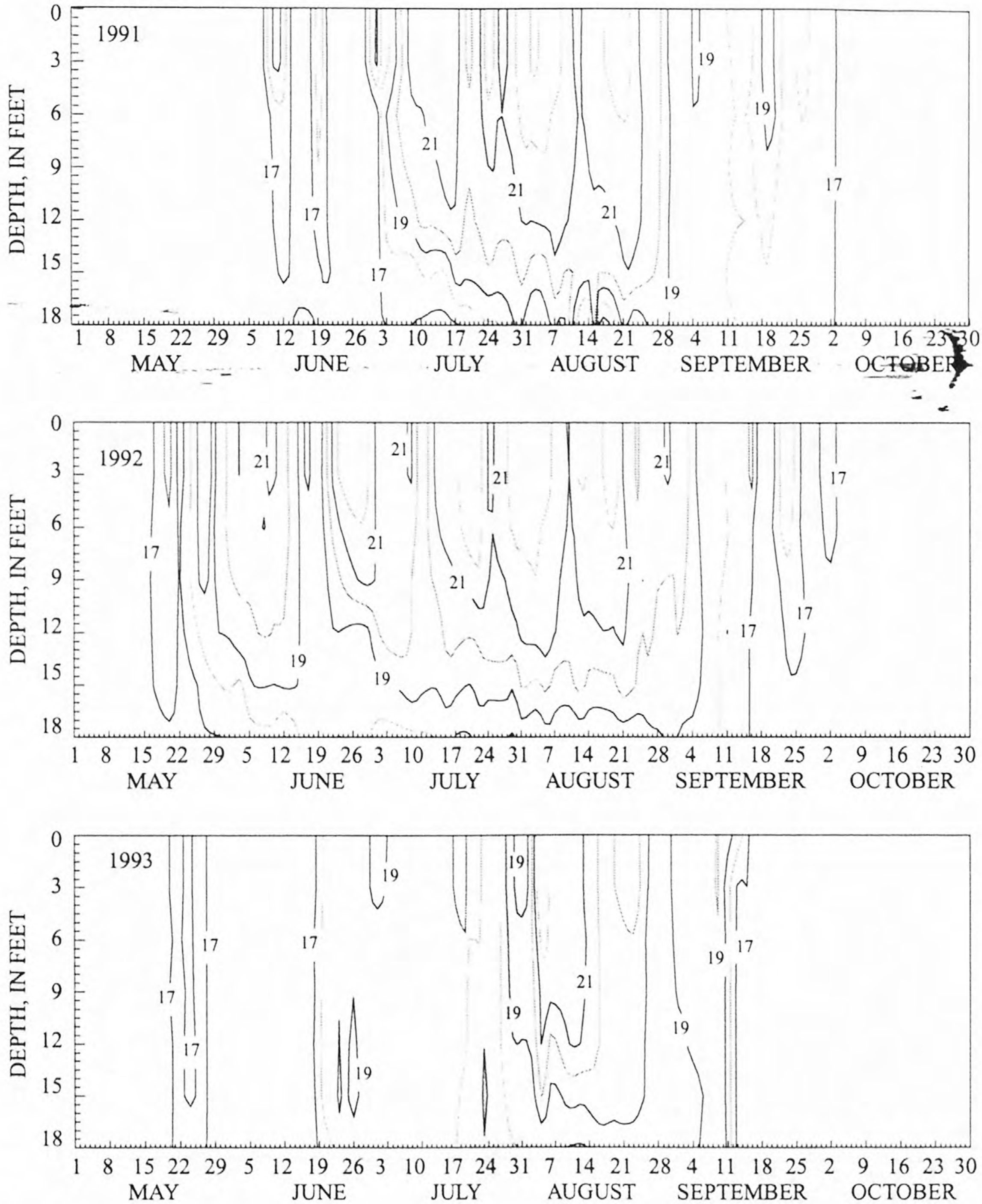



**Figure 21.** Contour map of water temperature (in degrees Celsius) in the Tualatin River, Oregon, at river mile 5.5 during May–October 1991–93.

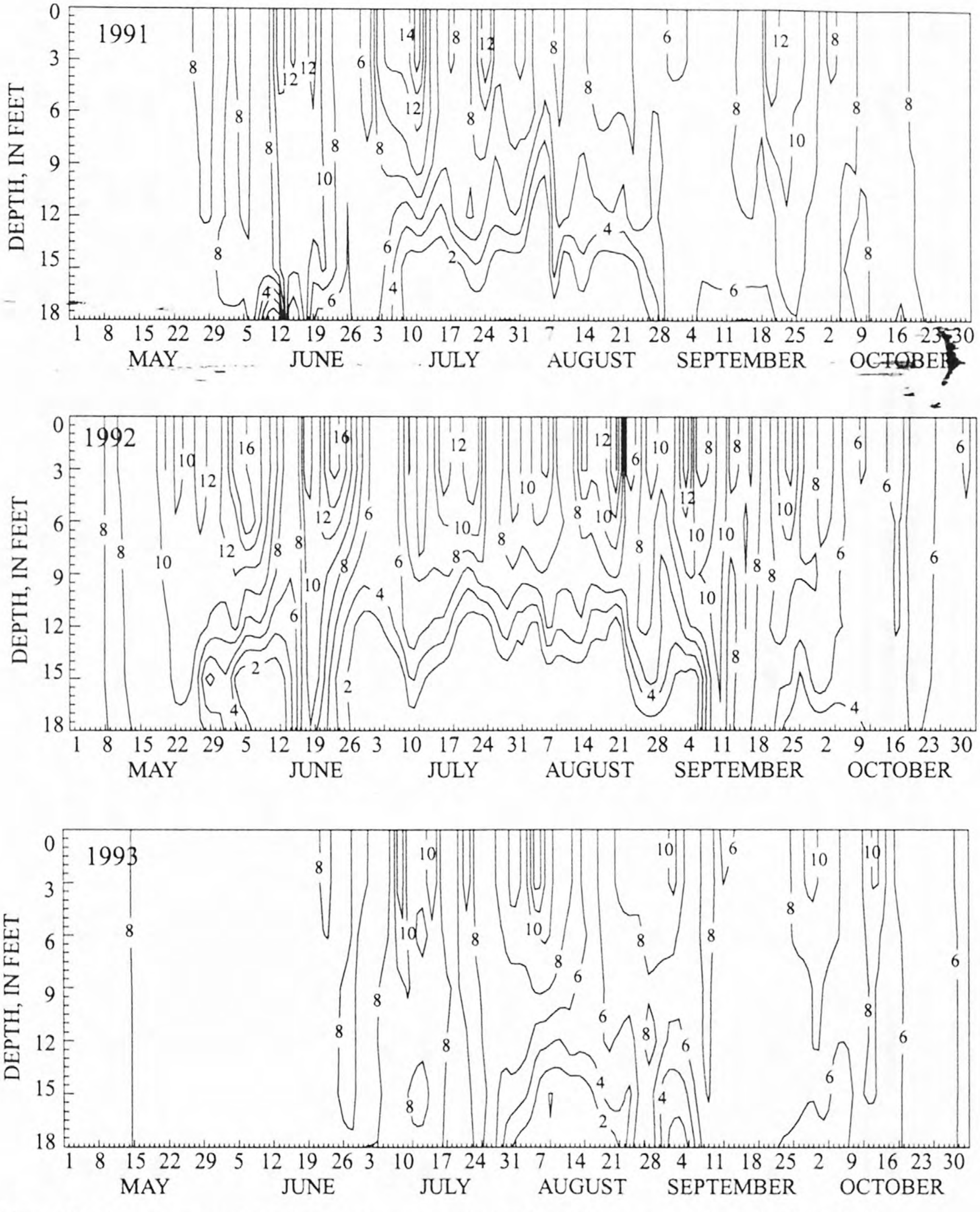



**Figure 22.** Contour map of dissolved oxygen concentration (in milligrams per liter) in the Tualatin River, Oregon, at river mile 5.5 during May–October 1991–93.

**Table 11.** Concentrations of nutrients and iron in the hypolimnion of the Tualatin River, Oregon, on July 20, 1992 (Doyle and Caldwell, 1996)

[Tributary river miles represent the river mile in the Tualatin River main stem at the confluence; depth, in feet; T, temperature, in degrees Celsius; specific conductance in microsiemens per centimeter at 25 degrees Celsius; orthophosphate as phosphorus; TKN, organic nitrogen plus ammonia as nitrogen; ammonia, ammonia as nitrogen; nitrate, nitrite plus nitrate as nitrogen; concentrations in milligrams per liter]

| Tualatin River mile | Depth | T | pH | Specific conductance | Dissolved oxygen | Total phosphorus | Ortho-phosphate | TKN | Ammonia | Nitrate | Total iron | Dissolved iron |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 11.6 | 16 | 19.7 | 7.0 | 240 | < 0.1 | 0.180 | 0.090 | 1.30 | 0.700 | 0.640 | 0.820 | 0.180 |
| 7.3 | 6 | 22.5 | 7.5 | 316 | 10.7 | .060 | .010 | .40 | .040 | 3.70 | .520 | .040 |
| 6.1 | 18 | 18.5 | 6.9 | 262 | < 0.1 | .070 | .060 | 1.30 | .930 | .960 | .620 | .100 |
| 5.5 | 14 | 19.5 | 6.9 | 260 | < 0.1 | .100 | .030 | 1.10 | .640 | 1.40 | .310 | .020 |
| 5.5 | 18 | 18.0 | 7.0 | 320 | < 0.1 | 1.90 | 1.80 | 5.00 | 3.50 | .050 | 13.0 | 11.0 |
| 4.6 | 18 | 17.0 | 6.9 | 300 | < 0.1 | .660 | .660 | 2.90 | 2.10 | .290 | 5.30 | .460 |
| 4.0 | 6 | 21.4 | 7.1 | 271 | 6.3 | .040 | .010 | .60 | .090 | 2.60 | .200 | .020 |
| 4.0 | 13 | 19.0 | 7.0 | 242 | < 0.1 | .030 | .010 | .80 | .510 | 1.50 | .170 | .010 |
| 4.0 | 17 | 17.5 | 7.1 | 280 | < 0.1 | .220 | .160 | 2.00 | 1.50 | .050 | .450 | .280 |
| 4.0 | 21 | 16.0 | 7.0 | 340 | < 0.1 | 1.60 | .300 | 4.20 | 3.20 | .050 | 7.90 | 6.70 |

These anoxic samples also contained elevated concentrations of ammonia (>3 mg/L) and iron (13.0 and 7.9 mg/L, respectively), most of which was in the dissolved or ferrous form. Nitrate concentrations were very low.

In samples taken higher in the water column, near the upper boundary of the oxygen-depleted water (about 12 feet depth), phosphorus concentrations were much lower (0.10 mg/L at RM 5.5). At RM 4.0, concentrations in the upper water were reduced still further, by more than an order of magnitude (0.22 mg/L at 17 feet and 0.03 mg/L at 13 feet). Similarly, concentrations of total iron were significantly less in the samples collected from more shallow depths at both sites; concentrations decreased by more than one order of magnitude in samples collected higher in the water column, with a larger proportion of particulate iron. Ammonia concentrations decreased in the same fashion, whereas nitrate concentrations increased considerably.

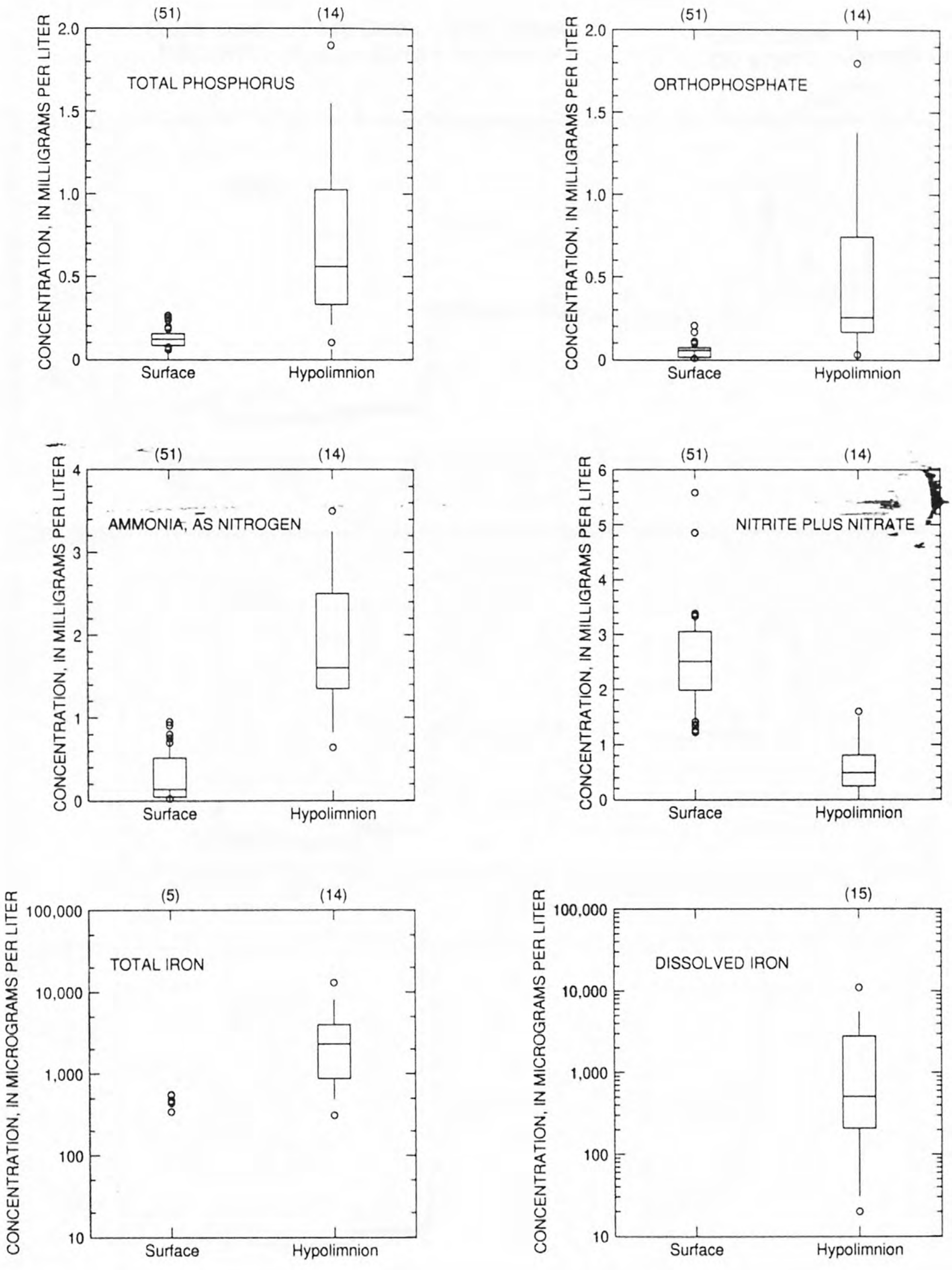
A comparison of concentration data from surface and hypolimnetic samples from RM 5.5 during the months of July and August in 1991 and 1992 confirms these results (fig. 23). Concentrations of total phosphorus were consistently on the order of 0.1 to 0.2 mg/L in the surface samples, whereas the median concentration in the hypolimnion samples was 0.5 mg/L and some values ranged up to 1.9 mg/L. A similar pattern was observed for iron. Ammonia concentrations were also much smaller in the surface waters, while nitrate showed the reverse pattern.

These results suggest that significant release of phosphorus and ammonia from the sediment into the Tualatin River does occur under reduced-oxygen conditions, although loading is apparently limited to water within a few feet of the river bottom when the water column is stratified. A clear concentration gradient is established in the hypolimnion, with higher concentrations of phosphorus and ammonia near the bottom sediments that progressively decline in the upper regions near the transition to the overlying epilimnetic waters. In the regions of the river that undergo stratification, therefore, loading of these constituents from the sediments is confined to a small volume of water in the bottom of deep pools, which are isolated from one another and do not circulate extensively with the overlying water. In addition, persistent stratification occurs in relatively limited reaches of the river, mostly within a few miles just above the Oswego diversion dam. The potential for nutrient loading from the sediments in other areas was not measured, although it is probably limited by the absence of persistent stratification.

## MASS BALANCE

Mass balances for chloride, total phosphorus, orthophosphate, total nitrogen, TKN, ammonia, and nitrate were generated for the main-stem Tualatin River based upon all the routinely measured surface-water sources to the river. The balances were determined using data only from the selected low-flow periods in order to minimize the effect of streamflow variability. For sites with measured streamflow data, the daily load associated with every sample was calculated by multiplying the measured concentration by the streamflow; these values were averaged over the low-flow period to determine the mean load for the site for each period. For main-stem sites with estimated streamflow, the measured concentration values were averaged for each low-flow period to produce a mean concentration, which was multiplied by the estimated streamflow to determine the estimated mean load. For the purpose of this analysis, concentrations values less than the minimum reporting limit (MRL) were assumed equal to one-half of the MRL.

Measured and estimated mean loads, described as observed loads, at the main-stem sampling sites were compared to the calculated sum of mean inputs and withdrawals (fig. 24). Error bars in the figures were defined for the observed loads ($\alpha$=0.05); errors in the calculated loads were based upon the standard error of the mean for the various sources, and propagated downstream using standard propagation of error techniques (Miller and Miller, 1988). From these figures, it is possible to ascertain whether significant ($\alpha$=0.05) sources or sinks are unaccounted for in the budget for each constituent and to estimate the range of missing loads.



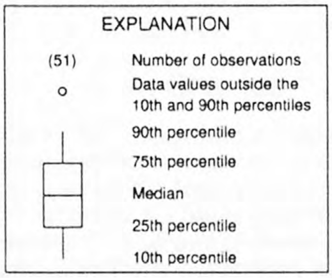
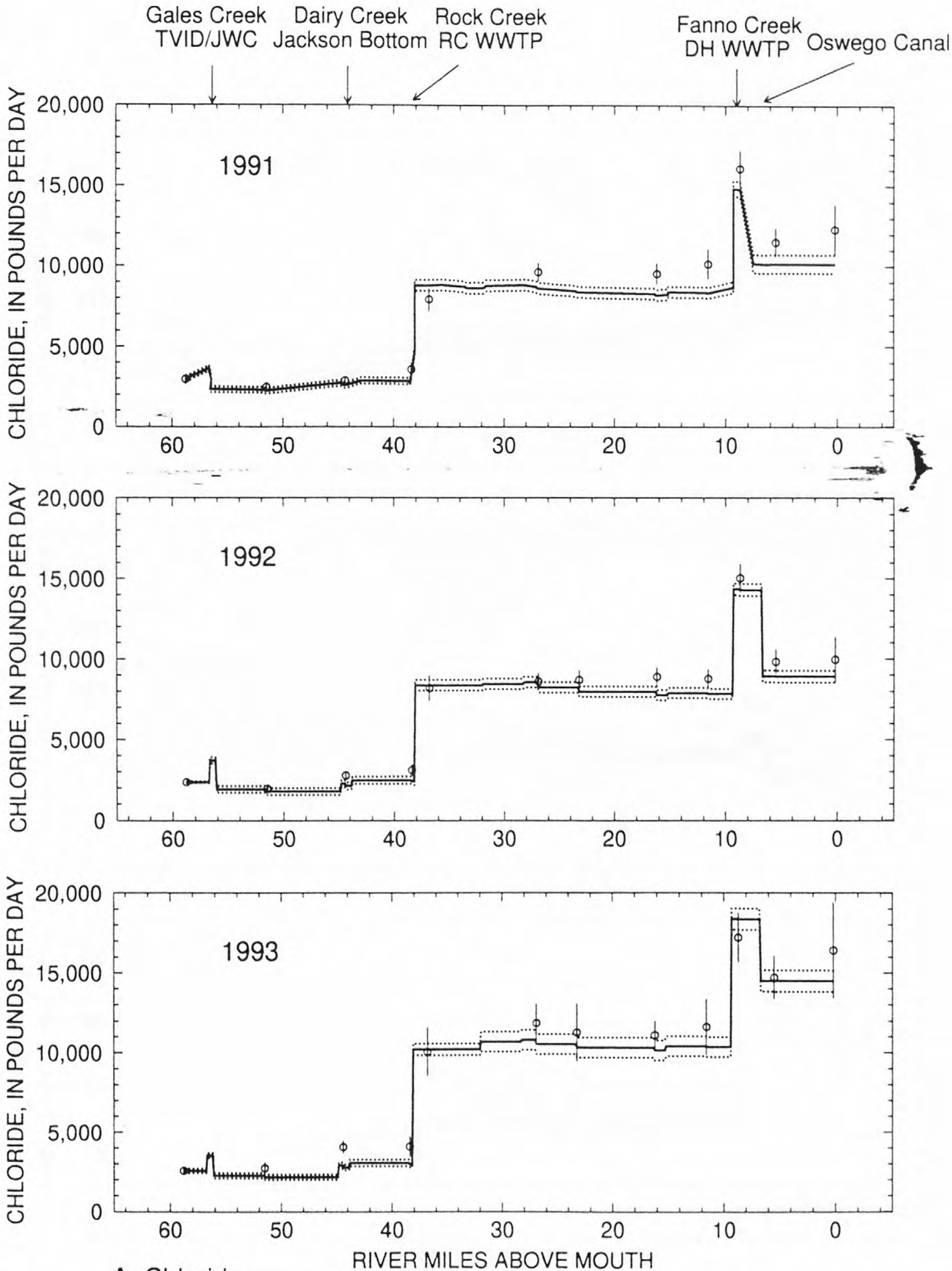




**Figure 23.** Comparison of total phosphorus, orthophosphate, ammonia, nitrite plus nitrate, and total and dissolved iron concentrations from surface (depth less than 10 feet) and hypolimnetic waters (depth greater than 10 feet) in the Tualatin River, Oregon, at river mile 5.5 during July–August 1991–92.




A. Chloride

**Figure 24.** Comparison of measured loads of selected constituents in the Tualatin River, Oregon, with loads calculated from measured inputs and withdrawals during selected low-flow periods in 1991, 1992, and 1993—(A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total nitrogen (E) Total Kjeldahl nitrogen (F) Ammonia (G) Nitrite plus nitrate EXPLANATION: Circles represent measured mean loads, error bars represent 95 percent confidence limits based upon the standard error of the mean; solid lines represent calculated loads; dotted lines represent errors in the calculated values propagated downstream.

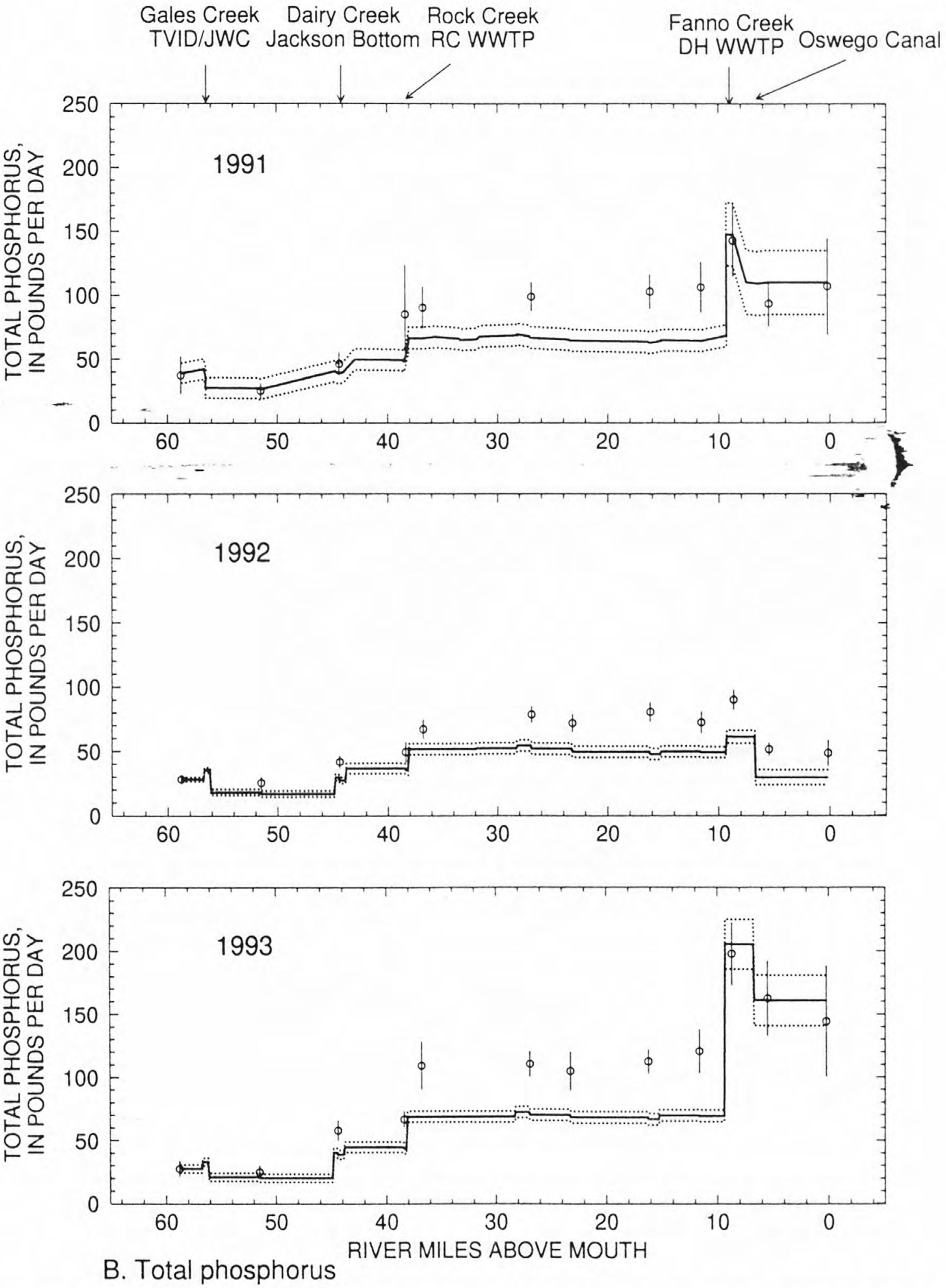



**Figure 24.** Comparison of measured loads of selected constituents in the Tualatin River, Oregon, with loads calculated from measured inputs and withdrawals during selected low-flow periods in 1991, 1992, and 1993—Continued. (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total nitrogen (E) Total Kjeldahl nitrogen (F) Ammonia (G) Nitrite plus nitrate EXPLANATION: Circles represent measured mean loads, error bars represent 95 percent confidence limits based upon the standard error of the mean; solid lines represent calculated loads; dotted lines represent errors in the calculated values propagated downstream.

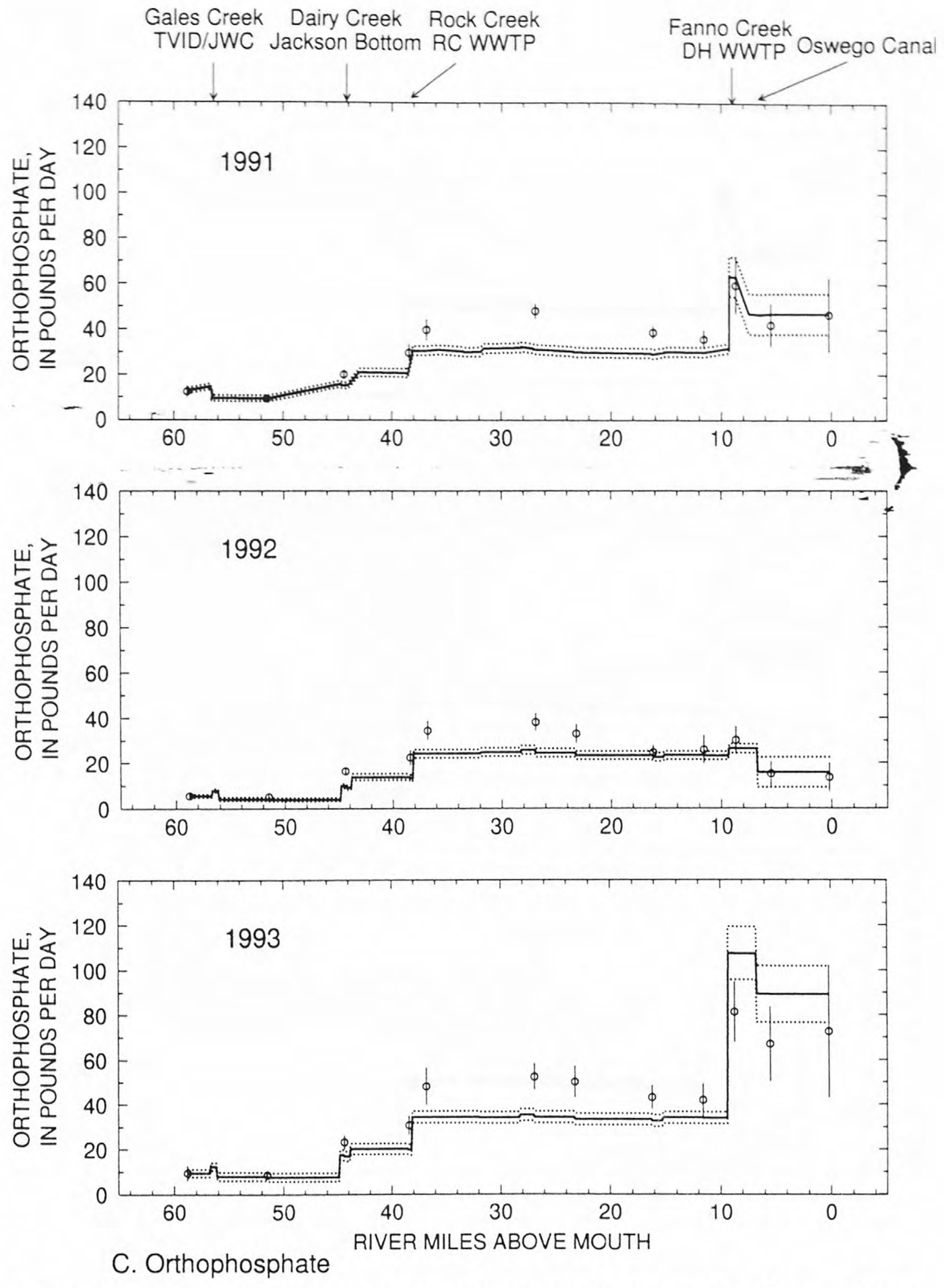
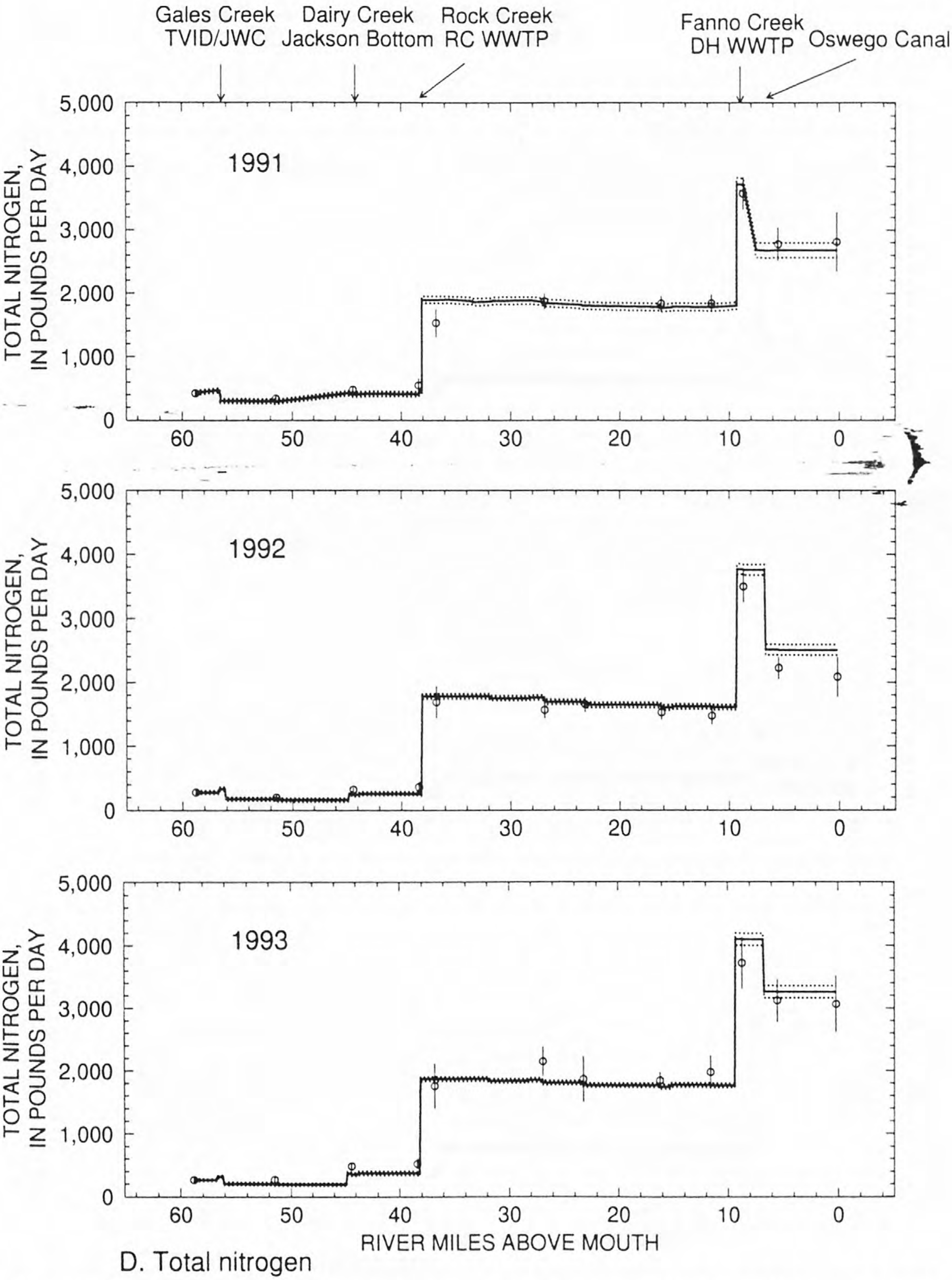
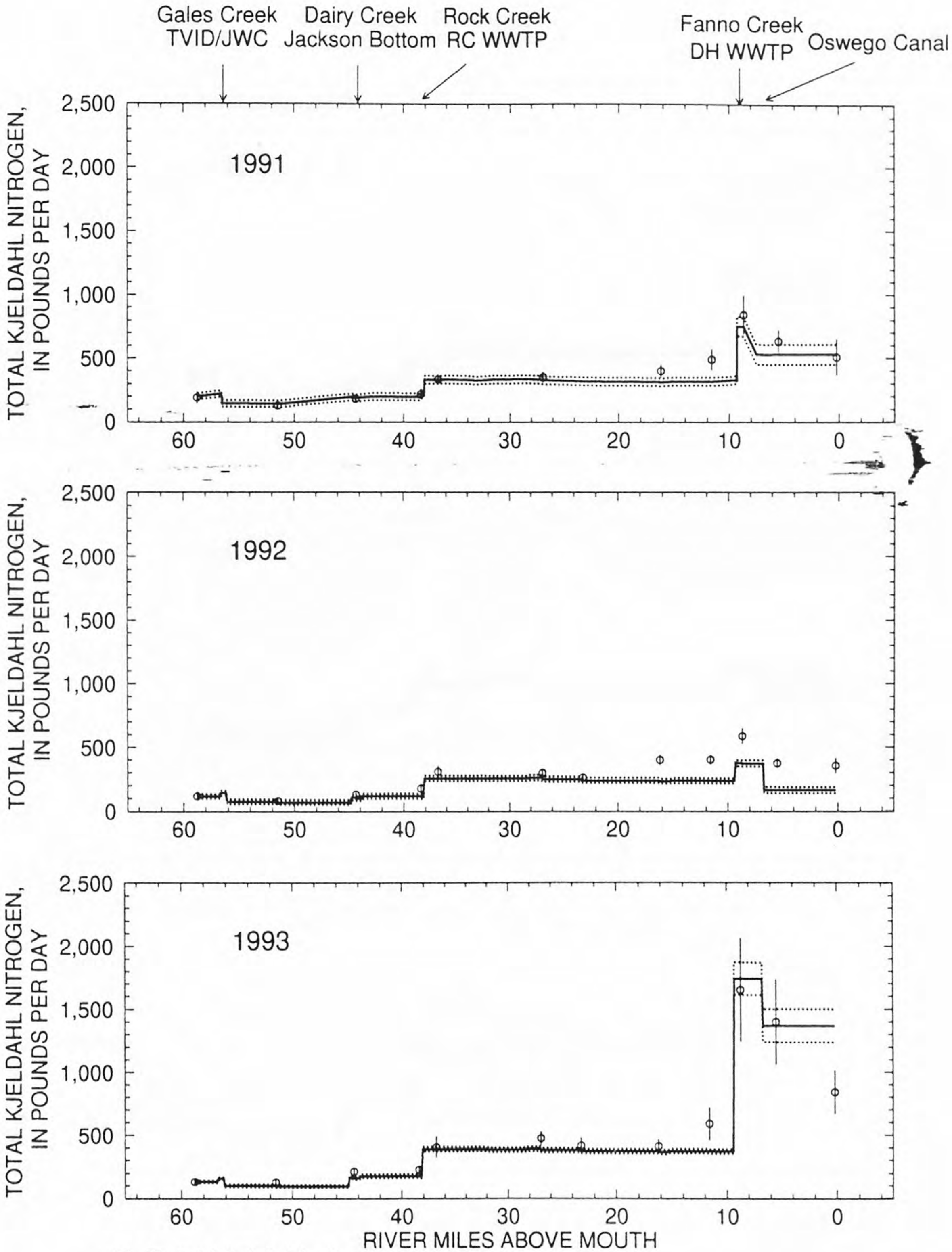



**Figure 24.** Comparison of measured loads of selected constituents in the Tualatin River, Oregon, with loads calculated from measured inputs and withdrawals during selected low-flow periods in 1991, 1992, and 1993—Continued. (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total nitrogen (E) Total Kjeldahl nitrogen (F) Ammonia (G) Nitrite plus nitrate EXPLANATION: Circles represent measured mean loads, error bars represent 95 percent confidence limits based upon the standard error of the mean; solid lines represent calculated loads; dotted lines represent errors in the calculated values propagated downstream.



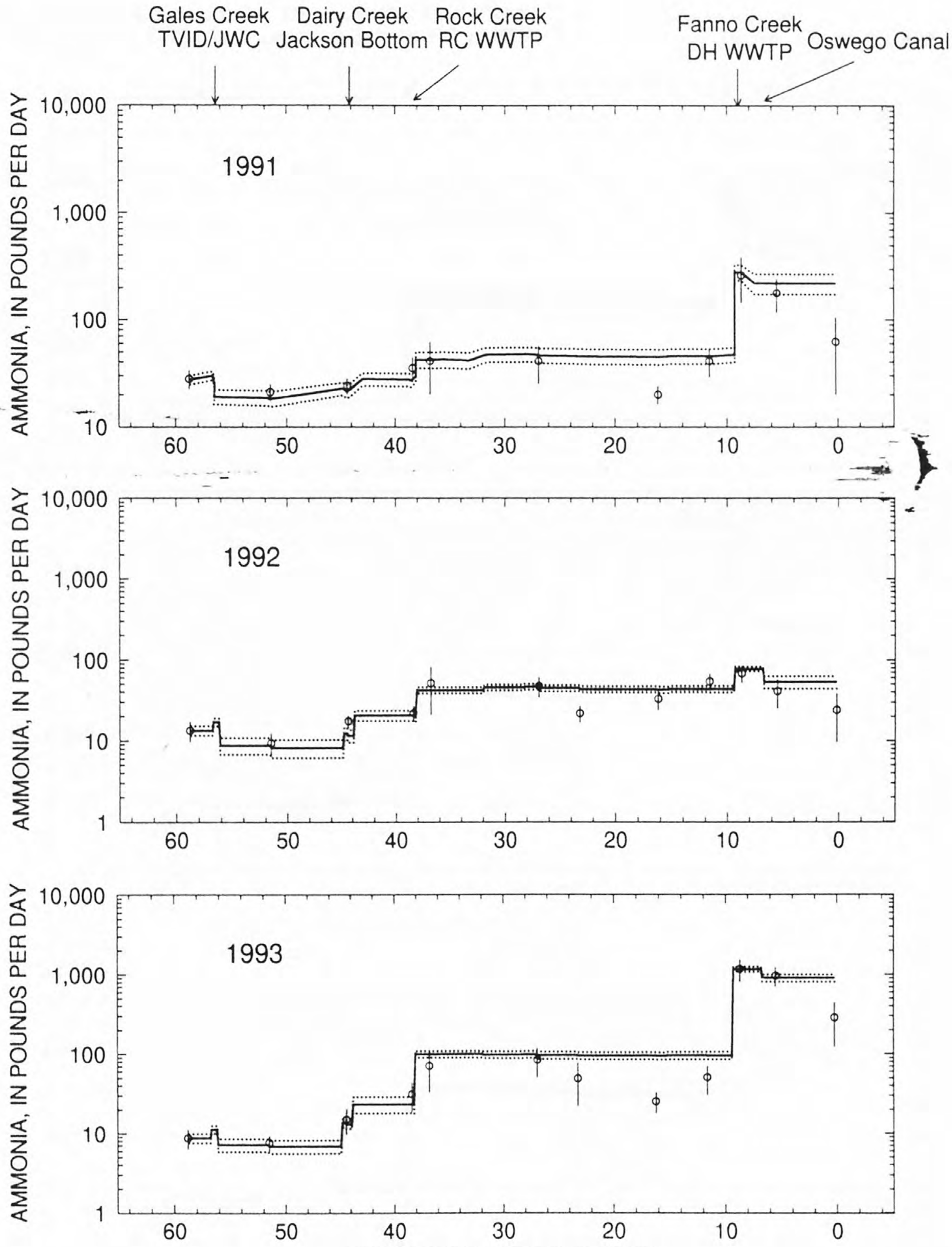

D. Total nitrogen

**Figure 24.** Comparison of measured loads of selected constituents in the Tualatin River, Oregon, with loads calculated from measured inputs and withdrawals during selected low-flow periods in 1991, 1992, and 1993—Continued. (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total nitrogen (E) Total Kjeldahl nitrogen (F) Ammonia (G) Nitrite plus nitrate EXPLANATION: Circles represent measured mean loads, error bars represent 95 percent confidence limits based upon the standard error of the mean; solid lines represent calculated loads; dotted lines represent errors in the calculated values propagated downstream.



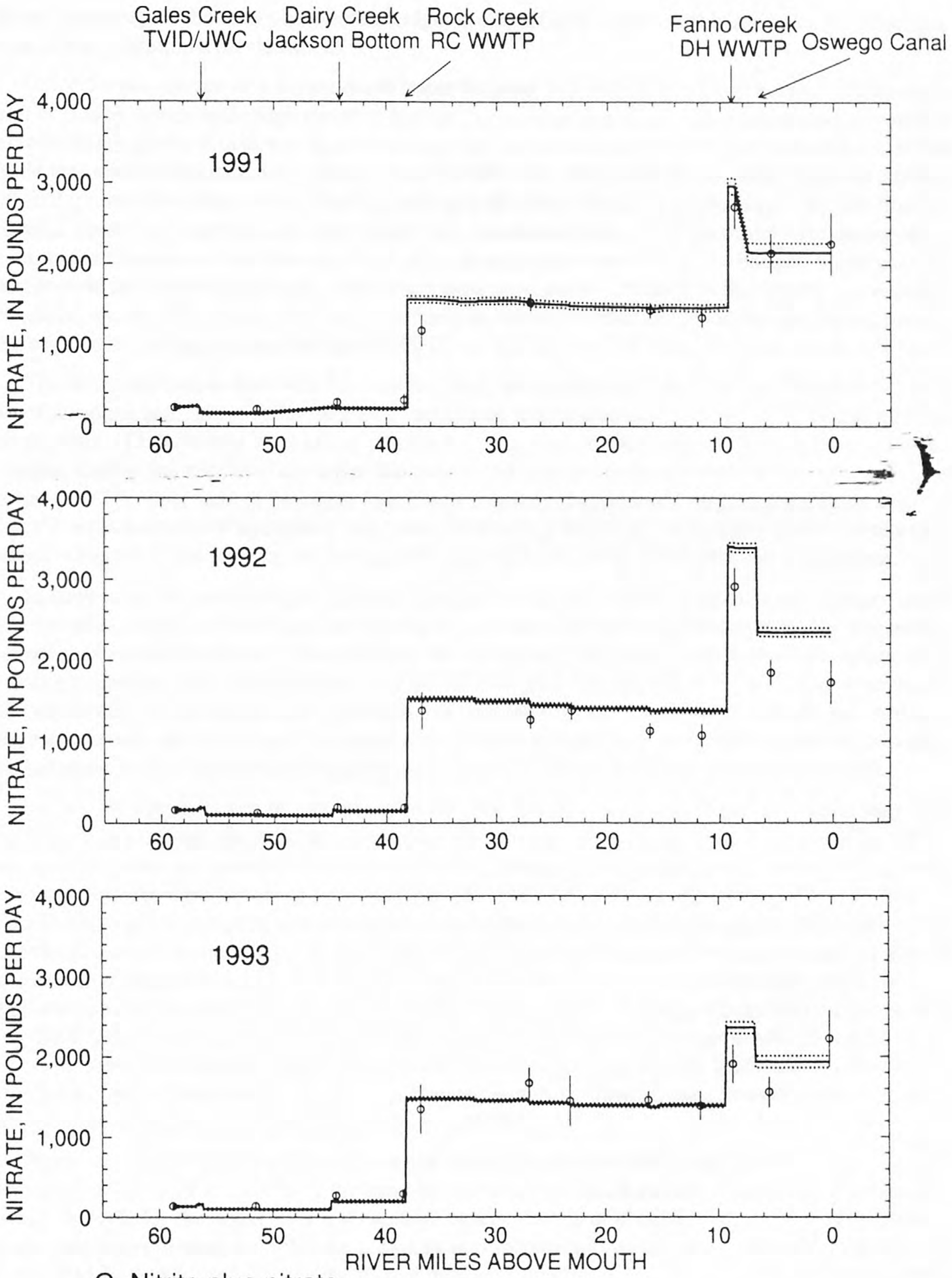

E. Total Kjeldahl nitrogen

**Figure 24.** Comparison of measured loads of selected constituents in the Tualatin River, Oregon, with loads calculated from measured inputs and withdrawals during selected low-flow periods in 1991, 1992, and 1993—Continued. (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total nitrogen (E) Total Kjeldahl nitrogen (F) Ammonia (G) Nitrite plus nitrate EXPLANATION: Circles represent measured mean loads, error bars represent 95 percent confidence limits based upon the standard error of the mean; solid lines represent calculated loads; dotted lines represent errors in the calculated values propagated downstream.




F. Ammonia

**Figure 24.** Comparison of measured loads of selected constituents in the Tualatin River, Oregon, with loads calculated from measured inputs and withdrawals during selected low-flow periods in 1991, 1992, and 1993—Continued. (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total nitrogen (E) Total Kjeldahl nitrogen (F) Ammonia (G) Nitrite plus nitrate EXPLANATION: Circles represent measured mean loads, error bars represent 95 percent confidence limits based upon the standard error of the mean; solid lines represent calculated loads; dotted lines represent errors in the calculated values propagated downstream.




G. Nitrite plus nitrate

**Figure 24.** Comparison of measured loads of selected constituents in the Tualatin River, Oregon, with loads calculated from measured inputs and withdrawals during selected low-flow periods in 1991, 1992, and 1993—Continued. (A) Chloride (B) Total phosphorus (C) Orthophosphate (D) Total nitrogen (E) Total Kjeldahl nitrogen (F) Ammonia (G) Nitrite plus nitrate EXPLANATION: Circles represent measured mean loads, error bars represent 95 percent confidence limits based upon the standard error of the mean; solid lines represent calculated loads; dotted lines represent errors in the calculated values propagated downstream.

A tabular summary of the total phosphorus budget is also included because it is a constituent of primary interest in the Tualatin River (table 12).

Chloride was chosen as a conservative tracer because it is not involved in processes of transformation or loss as it moves through the river system. As a consequence, the chloride balance provides a relatively unambiguous measure of how accurately the sources are accounted for in the budget. Loading of chloride was clearly dominated by effluent from the WWTPs, which discharged loads between 5,000 and 7,000 lb/d (pounds per day), while chloride loading from other sources was comparatively low (fig. 24A). In general, observed chloride loads were larger than calculated loads for much of the river during all 3 years, suggesting that not all the sources of chloride were accounted for by the budget. Significant differences between the observed and calculated loads were consistently detected in the upper river, especially pronounced during 1993. These differences, defined as surplus or observed loads that are not accounted for by the sources in the budget, equalled about 700 lb/d at RM 38.4 in 1991 and 1992, and 1,000 lb/d in 1993.

The observed load at RM 36.8 that was less than the calculated load in 1991 is almost certainly the result of sampling bias and the diel variability in effluent from the Rock Creek WWTP, located less than 2 miles upstream. This site was sampled only in the morning, thereby only capturing the influence of effluent discharged during the middle of the night. Because the calculated loads are based upon mean-daily data from the WWTPs, they tend to be larger. Significant surplus chloride loads ranging from about 1,000 to 2,000 lb/d were maintained throughout the lower river during 1991 only; although chloride surpluses remained apparent in the lower river during 1992 and 1993, they were not statistically significant.

In contrast to the conservative nature of chloride, the balances for phosphorus and nitrogen depend upon a complex variety of biological and chemical processes that occur as the water moves downstream. Observed loads represent the net effect of these various transformations. The balances for total phosphorus and total nitrogen provide a description of the overall transport characteristics for these constituents. Finer detail concerning the transformation processes that shift the forms of phosphorus and nitrogen during passage downriver, and which vary in importance in different regions of the river, is provided by analysis of the balances for the individual nutrient species (orthophosphate, TKN, ammonia, and nitrate).

Significant surplus loads of total phosphorus were observed for many of the main-stem sites during all 3 years, indicating that an important source for phosphorus was missing from the budget (fig. 24B). These surplus loads were generally well established in the upper river at RM 44.4 at around 10 to 20 lb/d; the largest surpluses were observed between RMs 16.2 and 11.6 and ranged between 24 and 51 lb/d (table 12). During 1992, significant phosphorus surpluses were maintained throughout the length of the river downstream to the mouth. It was not possible to statistically distinguish between observed and calculated loads downstream of RM 9.3 during 1991 and 1993, however, because of the large and highly variable phosphorus loads with their associated uncertainties that were discharged from the Durham WWTP during those years. The mass balance for orthophosphate in the upper river was similar to that for total phosphorus; significant surplus loads were detected at RM 44.4 and gradually increased to 13 to 18 lb/d at RM 26.9 (fig. 24C). These surpluses were not maintained farther downstream, however, but decreased until they were no longer detectable, generally by RM 11.6.

A primary source of phosphorus that is not included in the nutrient budgets is the input of phosphorus-enriched ground water directly to the main-stem river. The significant surpluses that were observed in the water budgets for the upper river and the high concentrations of phosphorus that were detected in ground water are consistent with the significant surplus loads of phosphorus that were generally well established by RM 38.4. Additionally, the fraction of total phosphorus load as soluble orthophosphate increased between RMs 58.8 and 26.9 from about 30 to 50 percent. Because phosphorus is transported in ground water predominantly as inorganic orthophosphate in the dissolved phase, these results are consistent with an input of phosphorus from ground water to the upper river. The surplus chloride loads that were observed at RM 38.4 also suggest the influence of ground water in the upper river; elevated chloride concentrations (greater than 300 mg/L) were observed in two domestic wells, indicating the presence of some saline ground water in the basin (fig. 17).

**Table 12.** Summary of total phosphorus loads in surface-water inputs and withdrawals in the Tualatin River Basin, Oregon, and comparison of measured or estimated cumulative mean loads calculated at main-stem sites during selected low-flow periods in 1991, 1992, and 1993

[Tributary river miles represent the river mile in the Tualatin River main stem at the confluence; * Loads estimated (see text for description); loads in pounds per day; cumulative, sum of all sources and sinks starting at river mile 58.8; WWTP, wastewater treatment plant; surplus, measured-cumulative; n.d., no data

| Site | Tualatin River mile | 1991 | | | 1992 | | | 1993 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Measured or estimated | Cumulative | Surplus | Measured or estimated | Cumulative | Surplus | Measured or estimated | Cumulative | Surplus |
| Tualatin River near Dilley | 58.8 | 37 | 37 | 0 | 28 | 28 | 0 | 28 | 28 | 0 |
| Gales Creek | 56.7 | 3.7 | | | 7.2 | | | 5.4 | | |
| Springhill Pumping Plant | 56.1 | -8.1 | | | -8.9 | | | -6.0 | | |
| Joint Water Commission | 56.1 | -6.6 | | | -8.0 | | | -6.1 | | |
| Irrigation withdrawals | 58.8 to 51.5 | -1.2 | | | -1.3 | | | -0.9 | | |
| Tualatin River at Golf Course Rd. | 51.5 | * 25 | 25 | 0 | 25 | 17 | +8 | 25 | 20 | +5 |
| Dairy Creek | 44.8 | 15 | | | 13 | | | 20 | | |
| Irrigation withdrawals | 51.5 to 44.4 | -2.0 | | | -2.4 | | | -1.8 | | |
| Tualatin River at Highway 219 | 44.4 | * 46 | 38 | +8 | * 42 | 27 | +15 | * 58 | 38 | +20 |
| Jackson Slough | 43.8 | 1.3 | | | 1.8 | | | 2.6 | | |
| Miller Swale | 43.5 | 9.9 | | | 7.4 | | | 3.4 | | |
| Irrigation withdrawals | 44.4 to 38.4 | -1.3 | | | -1.3 | | | -1.1 | | |
| Tualatin River at Rood Bridge | 38.4 | 85 | 48 | +37 | 49 | 35 | +14 | 67 | 43 | +24 |
| Rock Creek | 38.1 | 16 | | | 13 | | | 16 | | |
| Rock Creek WWTP | 38.1 | 3.2 | | | 3.7 | | | 8.8 | | |
| Tualatin River at Meriwether | 36.8 | * 90 | 67 | +23 | * 67 | 51 | +16 | * 109 | 68 | +41 |
| Butternut Creek | 35.7 | .5 | | | .3 | | | n.d. | | |
| Christensen Creek | 31.9 | .8 | | | .6 | | | .40 | | |
| Burris Creek | 31.6 | 2.2 | | | 1.9 | | | 1.5 | | |
| Baker Creek | 28.2 | .7 | | | .8 | | | 1.4 | | |
| McFee Creek | 28.2 | .8 | | | 1.3 | | | 2.1 | | |
| Irrigation withdrawals | 38.4 to 26.9 | -6.1 | | | -4.6 | | | -4.2 | | |

**Table 12.** Summary of total phosphorus loads in surface-water inputs and withdrawals in the Tualatin River Basin, Oregon, and comparison of measured or estimated cumulative mean loads calculated at main-stem sites during selected low-flow periods in 1991, 1992, and 1993—Continued

[Tributary river miles represent the river mile in the Tualatin River main stem at the confluence; * Loads estimated (see text for description); loads in pounds per day; cumulative, sum of all sources and sinks starting at river mile 58.8; WWTP, wastewater treatment plant; surplus, measured-cumulative; n.d., no data

| Site | Tualatin River mile | 1991 | | | 1992 | | | 1993 | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Measured or estimated | Cumulative | Surplus | Measured or estimated | Cumulative | Surplus | Measured or estimated | Cumulative | Surplus |
| Tualatin River at Scholls | 26.9 | * 99 | 66 | +33 | * 78 | 51 | +27 | * 110 | 69 | +41 |
| Irrigation withdrawals | 26.9 to 23.3 | -2.3 | | | -2.4 | | | -1.9 | | |
| Tualatin River at Neal's | 23.2 | n.d. | | | * 72 | 49 | -23 | * 104 | 68 | -36 |
| Irrigation withdrawals | 23.2 to 16.2 | -1.9 | | | -1.8 | | | -1.5 | | |
| Tualatin River at Elsner | 16.2 | * 102 | 62 | +40 | * 80 | 47 | +33 | * 112 | 66 | +46 |
| Chicken Creek | 15.2 | 1.9 | | | 1.7 | | | 1.5 | | |
| Rock Creek (South) | 15.2 | .5 | | | 0.3 | | | 1.6 | | |
| Irrigation withdrawals | 16.2 to 11.6 | -.5 | | | -.6 | | | -0.4 | | |
| Tualatin River at Highway 99W | 11.6 | * 106 | 64 | +42 | * 72 | 48 | +24 | * 120 | 69 | +51 |
| Fanno Creek | 9.3 | 4.1 | | | 5.6 | | | 7.6 | | |
| Durham WWTP | 9.3 | 58 | | | 6.3 | | | 129 | | |
| Irrigation withdrawals | 11.6 to 8.7 | -.4 | | | -.3 | | | -.2 | | |
| Tualatin River at Boones Ferry | 8.7 | * 143 | 126 | +17 | * 90 | 60 | +30 | * 198 | 205 | -7 |
| Nyberg Creek | 7.5 | 1 | | | 1.2 | | | n.d. | | |
| Oswego Canal | 6.7 | -41 | | | -33 | | | -44 | | |
| Irrigation withdrawals | 8.7 to 5.5 | -.06 | | | -.1 | | | -.2 | | |
| Tualatin River at Stafford Rd. | 5.5 | * 93 | 86 | +7 | * 51 | 28 | +23 | * 162 | 161 | +1 |
| Tualatin River at West Linn | 0.2 | 107 | 86 | +21 | 48 | 28 | +20 | 144 | 161 | -17 |

Downstream of RM 26.9, the decline of the surplus loads of orthophosphate is an effect of phytoplankton uptake, which is associated with the concomitant rise in chlorophyll-a concentrations that was consistently observed downstream of that site (fig. 5). The percentage of total phosphorus as orthophosphate typically decreased from about 50 percent to 30 percent by RM 11.6, reflecting the incorporation of soluble phosphorus into algal particulates. Surplus loads of total phosphorus in the downstream direction to RM 16.2 or 11.6 were generally stable, indicating that any losses of algae by settling were offset by phosphorus inputs from ground-water discharge or sediment release. Farther downstream of RM 11.6, the large loads of phosphorus that were discharged from the Durham WWTP (RM 9.3) in 1991 and 1993 obscured the clear algal signal that was observed in the surplus loads of total phosphorus upstream. Only in 1992 were these surplus loads preserved throughout the length of the lower river.

Significant surplus loads of total nitrogen generally did not occur, indicating that the major sources for nitrogen were included in the budget (fig. 24D). The major process influencing the transport of total nitrogen in the Tualatin River was the simple advection of inputs downstream. Observed nitrogen loads were significantly different from the calculated loads at only two sites, RMs 5.5 and 0.2 during 1992, suggesting an unaccounted sink for nitrogen in that region of the river during that period. The observed discrepancy for total nitrogen at RM 36.8 in 1991 was likely an artifact of diel loading variability from the Rock Creek WWTP, similar to the anomalous chloride load at that site previously discussed.

While total nitrogen acted essentially as a conservative constituent, significant differences were found between observed and calculated loads for the different forms of nitrogen. Significant surpluses of TKN occurred at one or more sites during all 3 years, and were especially pronounced in 1992 (fig. 24E). In contrast, observed ammonia loads were significantly less than calculated loads at a number of sites for every year (fig. 24F). Although only a few significant differences occurred between observed and calculated loads for nitrate, losses of nitrate were also observed in 1992 and 1993 (fig. 24G). A complex interplay of factors is associated with the distribution of nitrogen among these different forms. These include the dynamics of algal and bacterial processes in addition to the character of nitrogen loads in effluent from the WWTPs, clearly the dominant source for nitrogen.

The effect of the incorporation of inorganic nitrogen into algal populations is reflected in the surplus TKN loads that develop in the reaches where phytoplankton populations are large (fig. 24E). The effect of algal growth on ammonia, frequently the preferred form of nitrogen for algal uptake, is less straight-forward. The initial decline in ammonia loads that consistently developed in the region between RMs 23.3 and 16.2 is similar to the pattern observed for orthophosphate (fig. 24F). The subsequent increases in ammonia loads farther downstream at RM 11.6, however, suggests that uptake of ammonia by algae was being counterbalanced by another ammonia source. Although influx of ground water to the lower river cannot be discounted as a contributing factor, the water budgets indicate that little surplus water enters the river downstream of RM 33.3. Furthermore, a significant sediment oxygen demand has been observed throughout the lower river (Rounds and Doyle, 1997). These sediment decomposition processes may be a source for ammonia to this region of the river, although too small to be significant relative to the much larger loads of total nitrogen already present. Farther downstream, below the large loads of ammonia that were discharged from the Durham WWTP in 1991 and 1993, the observed losses of TKN and ammonia were probably the result of nitrification in the shallow reach below RM 3.4.

The balances for nitrate (fig. 24G), typically the primary nitrogen constituent in WWTP effluent, are generally similar to those for total nitrogen. The nitrate losses that were observed may be attributed to some combination of algal uptake and denitrification in the anoxic regions of the sediment. Significant nitrate losses persisted as far upstream as RM 16.2 in 1992, concomitant with the low streamflow and generally warm and sunny conditions that occurred during that year. In 1993, significant nitrate losses were observed only at RM 8.7 and 5.5, and the pattern was reversed by RM 0.2. This increase in nitrate load may be associated with nitrification of the large ammonia load from the Durham WWTP in 1993, when ammonia comprised about 45 percent of the total nitrogen load.

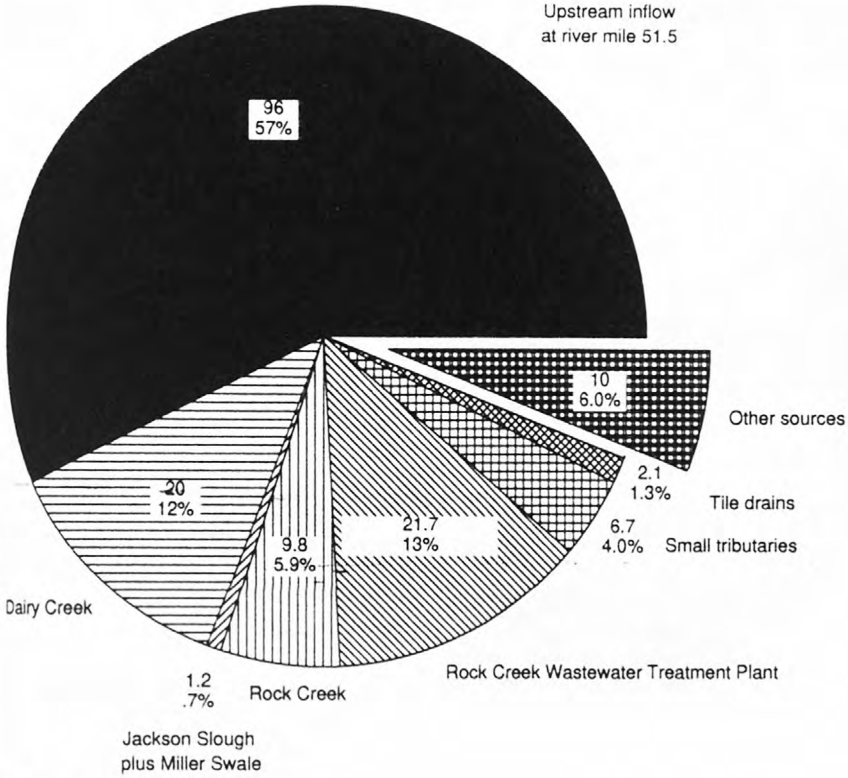
## Comparison of Sources

Perspective on the relative importance of the various measured and unmeasured nutrient sources to the river is necessary for effective water-quality management within the basin. This perspective is provided by pie charts that represent the sources of water, phosphorus, total nitrogen, and ammonia in proportion to one another. Pie charts were generated for the reach extending from RMs 51.5 to 16.2 during the low-flow period in 1992, including data from the synoptic survey (fig. 25). The synoptic reach was extended from RM 26.9 to RM 16.2 assuming conditions were comparable to those observed upstream. The entire "pie" in the charts represents the values for streamflow and loads of total phosphorus, nitrogen, and ammonia observed at RM 16.2, plus the addition of estimates for water and loads that were withdrawn for irrigation within the specified reach.

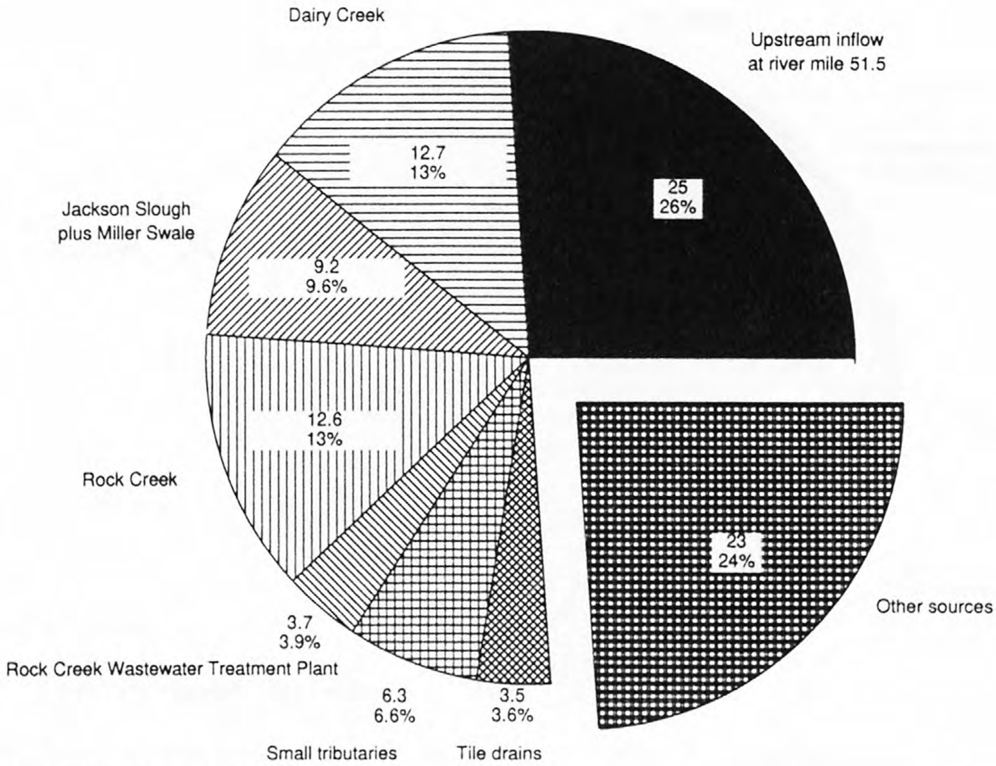
The volume of missing streamflow input to the main-stem channel between RM 51.5 and RM 16.2 was determined to be 10 $ft^3/s$, a relatively small fraction (6 percent) of the total volume of streamflow input to the reach (fig. 25A). In contrast, the load of missing phosphorus was approximately 23 lb/d, accounting for nearly 25 percent of the total phosphorus load (fig. 25B). The load contributed from the Rock Creek WWTP, the source which is most amenable to management control, was among the smallest fractions of the total load (about 4 percent). Inputs from the Hillsboro WWTP via Jackson Bottom represented nearly 10 percent, reflecting the relatively high loads in Miller Swale during 1992. Loadings from the two major tributaries (Dairy and Rock Creeks) were slightly larger, 13 percent of the total each. Although no single source dominated the phosphorus budget during this period, the unaccounted load, presumably from ground water, was nearly the largest component in the budget, comparable to the incoming loads from the upstream reach. In contrast, loading of nitrogen was overwhelmingly dominated by effluent from the Rock Creek WWTP (fig. 25C). About 75 percent of the total nitrogen in the river was contributed from this one source, which was predominantly in the form of nitrate. Loading of ammonia, less than 3 percent of the total nitrogen load during this period, was roughly equivalent between point and nonpoint sources (fig. 25D). A small fraction, about 1 percent, of the Rock Creek nitrogen load was in the form of ammonia during this period, reflecting the efficiency of the WWTP nitrification process.

These results highlight a critical difference between managing the sources of phosphorus and of nitrogen by enforcement of TMDLs in the Tualatin River. Reduction in nutrient loads depends upon identification of the important sources; furthermore, these sources must be subject to influences that can be remedied. The results of this study demonstrate that the most significant source of phosphorus to the main-stem river may be direct input of a relatively small volume of ground water, naturally enriched with phosphorus by the geologic characteristics of the basin. Additionally, the close correspondence that was observed between the tributaries and ground water suggests naturally enriched "background" conditions for phosphorus in the streams throughout the basin that are not amenable to management control. As a consequence, while application of Best Management Practices have been appropriate and effective in reducing phosphorus loads that exceed background levels, they are not likely to result in significant future reductions in phosphorus loads during low-flow conditions. Similarly, additional measures to restrict loading of phosphorus from the WWTPs is likely to have a negligible effect since the WWTP contribution is already small.

In contrast, the influence of the WWTPs is clearly the most important factor determining the loading of ammonia to the Tualatin River. Ground water is not a significant source of nitrogen in general, and other surface-water sources contribute relatively small proportions of the total nitrogen load. Consequently, implementation of TMDLs that limit the discharge of nitrogen as ammonia from the WWTPs to the river is the most effective means to control ammonia within the main-stem river.

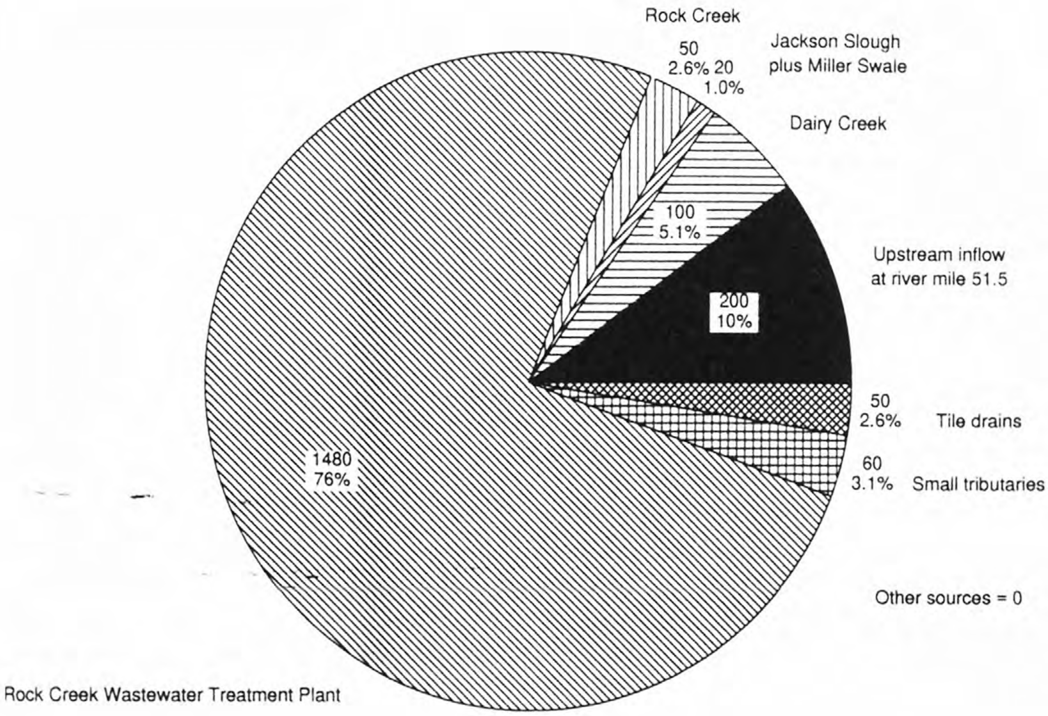



A. Streamflow

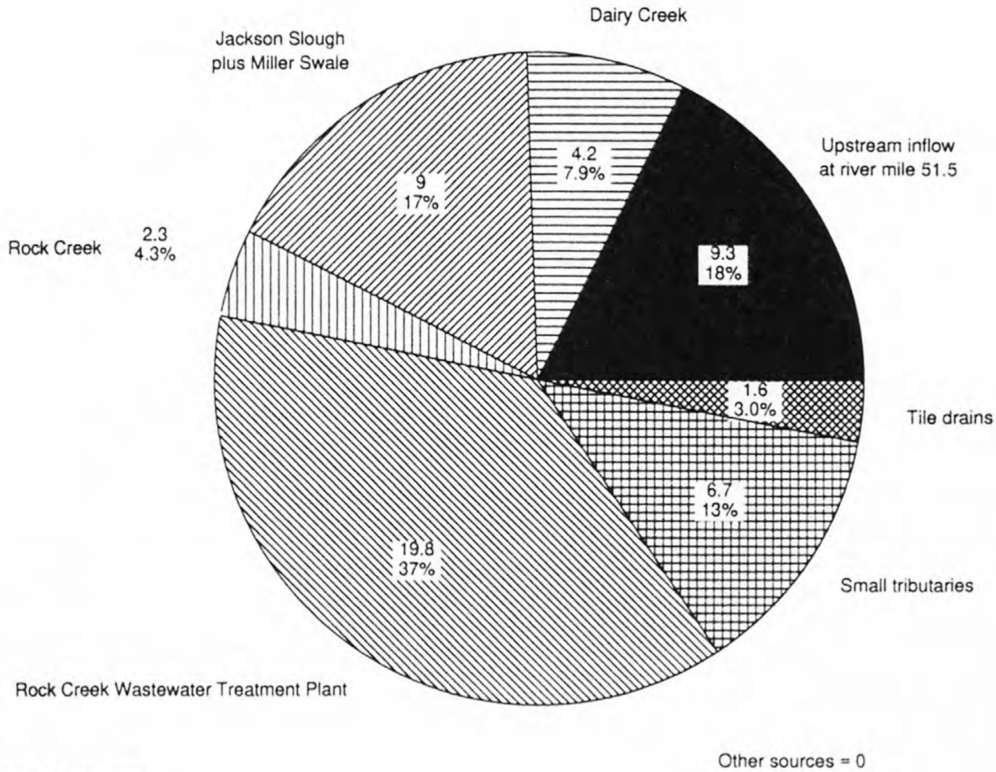



B. Total phosphorus

**Figure 25.** Budgets for streamflow, phosphorus, total nitrogen, and ammonia nitrogen in the Tualatin River, Oregon, between river miles 51.5 and 16.2 during the summer low-flow period 1992. The entire pie represents the estimated value at river mile 16.2 plus withdrawals for irrigation. (A) Streamflow, in cubic feet per second; (B) Total phosphorus, in pounds per day; (C) Total nitrogen, in pounds per day; (D) Ammonia nitrogen, in pounds per day.




C. Total nitrogen




D. Ammonia

**Figure 25.** Budgets for streamflow, phosphorus, total nitrogen, and ammonia nitrogen in the Tualatin River, Oregon, between river miles 51.5 and 16.2 during the summer low-flow period 1992—Continued. The entire pie represents the estimated value at river mile 16.2 plus withdrawals for irrigation. (A) Streamflow, in cubic feet per second; (B) Total phosphorus, in pounds per day; (C) Total nitrogen, in pounds per day; (D) Ammonia nitrogen, in pounds per day.

## SUMMARY

In the late 1980s, the Tualatin River, a major tributary to the Willamette River in northwest Oregon, experienced significant water-quality problems that impacted the designated beneficial uses during May through October. Unsightly algal blooms resulted in fluctuations in oxygen concentrations and pH conditions; reduction of phosphorus concentrations was determined to the most effective control mechanism for these conditions. Elevated ammonia concentrations also contributed to low oxygen concentrations. Because designated beneficial uses were not being met, the Oregon Department of Environmental Quality (ODEQ) established Total Maximum Daily Loads (TMDLs) for phosphorus and ammonia in the Tualatin Basin, as required by the Clean Water Act. As a consequence, the U.S. Geological Survey and the Unified Sewerage Agency cooperated in a study during 1991–93 to evaluate sources and loading of phosphorus and ammonia to the main-stem river during the summer. The maximum TMDL criterion concentrations established for total phosphorus and ammonia were used to determine the significanee of the various sources to the river.

Detailed mass balances for water during summer low-flow conditions showed that significant ($\alpha$=0.05) surpluses of water occurred when observed conditions in the main-stem river were compared to measured sources and sinks. More water was consistently delivered to the main-stem river than could be accounted for by surface-water sources in the basin. The potential for ground-water discharge directly to the main-stem river channel was demonstrated by positive upward pressure, which was widely observed in ground water adjacent to and underneath the river. Although the high silt and clay content of the channel bottom tends to retard ground-water influx, direct seepage of ground water in the main-stem river was observed. Measured seepage rates ranged from 0.1 L/m$^2$/d (liters per square meter per day) to as high as 200 L/m$^2$/d. Results from wells located within the river channel suggest a complex interaction exists between deep (regional) and shallow (local) ground-water systems beneath the streambed.

Concentrations of phosphorus in ground water throughout the basin were very high relative to 0.07 mg/L, the TMDL criterion for total phosphorus in the lower main-stem river. Concentrations generally ranged between 0.1 and 0.3 mg/L in shallow ground water, to nearly 1.0 mg/L in deep ground water, with a maximum concentration of greater than 2 mg/L. Ammonia concentrations were generally less than the lower main-stem TMDL of 0.85 to 1.0 mg/L, with median values of 0.22 and 0.55 mg/L for shallow and deep ground water, respectively. The highest concentrations were found near the interface between the two major geologic strata in the basin: the upper catastrophic flood deposits and the deeper Sandy River Mudstone equivalent. Decomposition of the large amounts of organic material buried at the interface between these strata and the presence of minerals rich in phosphorus below the flood deposits probably contribute to the elevated concentrations of phosphorus and ammonia in deep ground water.

Concentrations of total phosphorus in Tualatin River tributaries were generally between 0.1 and 0.3 mg/L, consistently greater than the TMDL criterion concentration for the lower river. The similarity between phosphorus concentrations in tributaries and shallow ground water indicates a direct link between shallow ground water and tributaries during summer low-flow conditions. This relationship is corroborated by the relatively large proportion, from 25 to more than 60 percent, of total phosphorus in the tributaries that was in the dissolved form as orthophosphate. In contrast, concentrations of ammonia in the tributaries were fairly consistent and low, generally less than the TMDL criteria. Most of the nitrogen in the streams was in the form of nitrate or organic nitrogen. The forms of nitrogen in various sources to the river are apparently governed primarily by environmental factors, especially the availability of dissolved oxygen.

Improvement of land management practices was observed to have a measurable effect on nutrient concentrations in some of the smaller tributary basins. Elevated concentrations of phosphorus and ammonia (1.0 mg/L and higher) that were observed in two streams in 1991 and 1992 were reduced in 1993 as a result of the application of Best Management Practices. In general, however, the influence of land use on phosphorus concentrations was determined to be less important than the effect of geology.

Increased streamflow during the early summer resulted in little increase in nutrient concentrations during the study period. A shift in phosphorus to a higher particulate fraction was measured, indicating that increased surface runoff may deliver more particulate phosphorus eroded from soils to the streams in the basin. Under baseflow conditions later in the summer, dissolved phosphate was the predominant form of phosphorus, indicating that input from ground water was the primary influence in the tributaries.

Total phosphorus concentrations in effluent from the two large wastewater treatment plants (WWTPs) that discharge to the Tualatin River during the summer were highly variable, depending upon the extent of treatment. Full implementation of advanced nutrient removal produced phosphorus concentrations that were less than the TMDL limits, although construction activity at the WWTPs reduced the efficiency of treatment for extended periods during the study. Concentrations ranged as high as 1 to 3 mg/L under these conditions. Ammonia concentrations also fluctuated widely depending upon treatment efficiency; typical values were less than 1 mg/L with complete treatment, although maximum values reached 10 mg/L otherwise.

In the main-stem Tualatin River downstream from about river mile (RM) 40, concentrations of total phosphorus consistently exceeded the TMDL criterion concentration (median value approximately 0.1 mg/L). Ammonia concentrations, in contrast, were generally very low relative to the TMDL criteria, except for a few occasions when wastewater treatment plant efficiencies had been compromised. Elevated concentrations of phosphorus (greater than 1.5 mg/L) and ammonia (greater than 3 mg/L) were observed on occasion in deep waters of the lower river, associated with thermal stratification and anoxic conditions that occur periodically in isolated pools. Little evidence was found for extensive loading of nutrients from sediments into the overlying water under stratified conditions, although the potential for release of nutrients from the sediments in other areas was not measured.

Mass balances of total phosphorus indicated significant ($\alpha$=0.05) inputs of phosphorus were occurring that were not accounted for by the measured surface-water sources. Surplus loads of phosphorus were generally well defined by RM 44.4, and increased downstream to about RM 16.2. A similar situation for total nitrogen was not observed. Balances for the individual phosphorus and nitrogen species (orthophosphate, total Kjeldahl nitrogen [TKN], ammonia, and nitrate) indicate that biological processes of algal growth and bacterial transformation are important factors in altering the forms of phosphorus and nitrogen during transit through the river.

The relative proportion of the phosphorus input unaccounted for by surface-water sources was determined to be nearly one-fourth of the total input to the river between RMs 51.5 and 16.2 in 1992. No single source was larger, although the combined input from several tributaries was roughly equivalent. The contribution from WWTP effluent was among the smallest components. Conversely, the most important source for total nitrogen was the Rock Creek WWTP, contributing nearly 75 percent of the total nitrogen load for the same reach. Most of this load was in the form of nitrate, indicating the efficiency of WWTP treatment for nitrogen. Ammonia represented a small proportion, less than 3 percent, of the total nitrogen load in the river during this period.

A large fraction of the surplus phosphorus load in the Tualatin River can be attributed to a ground-water source. The observed surpluses of water and phosphorus are consistent with the occurrence of measurable rates of ground-water seepage directly into the main-stem channel, and the elevated phosphorus concentrations in ground water throughout the basin. Because ground water naturally enriched with phosphorus is also a primary influence on the tributaries during the summer, options for further reduction of phosphorus loading to the river are limited by the lack of an effective remediation method for this important source. In contrast, the dominance of the WWTPs in loading of nitrogen highlights the effectiveness of efficient wastewater treatment in controlling ammonia in the main-stem river.

## REFERENCES CITED


Abrams, M., and Jarrel, W., 1995, Soil phosphorus as a potential nonpoint source for elevated stream phosphorus levels: Journal of Environmental Quality, v. 24, no. 1, p. 132–138.

Doyle, M.C., and Caldwell, J.M., 1996, Water-quality, streamflow, and meteorological data for the Tualatin River Basin, Oregon, 1991–93, U.S. Geological Survey Open-File Report 96–173, 49 p., 1 CD-ROM.

Carr, M.R., and Winter, T.C., 1980, An annotated bibliography of devices developed for direct measurement of seepage: U.S. Geological Survey Open-File Report 80–344, 37 p.

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

Hart, D.H., and Newcomb, R.C., 1965, Geology and ground water of the Tualatin Valley Oregon: U.S. Geological Survey Water-Supply Paper 1697, 172 p.

Heath, R.C., 1983, Basic ground-water hydrology: U.S. Geological Survey Water-Supply Paper 2220, 84 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier Science Publishing Company Inc., 522 p.

Lee, K.K., 1995, Stream velocity and dispersion characteristics determined by dye-tracer studies on selected stream reaches in the Willamette River Basin, Oregon: U.S. Geological Survey Water-Resources Investigations Report 95–4078, 39 p.

Madin, I.P., 1990, Earthquake-hazard geology maps of the Portland metropolitan area, Oregon—Text and map explanation: Oregon Department of Geology and Mineral Industries, 21 p.

Mayer, T.D., and Jarrell, W.M., 1995, Assessing colloidal forms of phosphorus and iron in the Tualatin River Basin: Journal of Environmental Quality, v. 24, p. 1117–1124.

Miller, J.C., and Miller, J.N., 1988, Statistics for analytical chemistry, 2d ed.: Chichester, England, Ellis Horwood Limited, 227 p.

Oregon Department of Environmental Quality, 1997, Oregon Administrative Rules: Dissolved oxygen in Tualatin River, OAR 340–041–0445(2aE); pH in Tualatin River, OAR 340–041–0445(2dB); nuisance phytoplankton growth, OAR 340–041–0150(1b); TMDLs for Tualatin River, OAR 340–041–0470(9).

Risley, J.C., 1997, Relations of Tualatin River water temperatures to natural and human-caused factors: U.S. Geological Survey Water-Resources Investigations Report 97–4071.

Risley, J.C., and Doyle, M.C., 1997, Water-temperature, specific-conductance, and meteorological data for the Tualatin River Basin, Oregon, 1994–95: U.S. Geological Survey Open-File Report 96–315.

Rounds, S.A., and Doyle, M.C., 1997, Sediment oxygen demand in the Tualatin River Basin, Oregon, 1992–1996: U.S. Geological Survey Water-Resources Investigations Report 97–4103, 19 p.

Rounds, S.A., Wood, T.M., and Lynch, D.D., 1998, Modeling discharge, temperature, and water quality in the Tualatin River, Oregon: U.S. Geological Survey Open File Report 98–186, 122 p.

Trimble, D.E., 1963, Geology of Portland, Oregon and adjacent areas: U.S. Geological Survey Bulletin 1119, 119 p.

Unified Sewerage Agency, 1990, Wastewater facilities plan, v. 1, Technical report: Hillsboro, Oregon [Available from Unified Sewerage Agency, 155 North First Ave., Hillsboro, Oregon, 97124].

U.S. Environmental Protection Agency, 1986, Quality criteria for water 1986: EPA 440/5-86-001

Washington County, 1982, Soil survey of Washington County, Oregon: Washington County, Oregon, Soil and Water Conservation District, 138 p.

Wilson, D.C., 1997, Post-middle Miocene geologic history of the Tualatin Basin, Oregon with hydrogeologic implications: Portland, Oregon, Portland State University, Ph.D. thesis.

Woessner, W.W. and Sullivan, K.E., 1984, Results of seepage meter and mini-piezometer study, Lake Mead, Nevada: Ground Water, v. 22 no. 5, p. 561–568.

# APPENDIXES

# APPENDIXES

# Appendix A

# Appendix A

# APPENDIX A

## Laboratory Quality Assurance

The laboratory quality assurance (QA) program was designed to quantify bias and variability in the sampling and analytical processes. The QA program was administered by U.S. Geological Survey (USGS) Oregon District personnel and consisted of weekly quality-control (QC) samples submitted to the three Unified Sewerage Agency (USA) laboratories responsible for generating chemical analyses. A mix of laboratory and field QC samples were included to test both the laboratory sample analysis and the field sample collection.

### Bias

Bias results from a systematic error within an analytical process and may be either positive or negative. Positive bias occurs as a result of contamination of the sample, whereas negative bias is frequently associated with some kind of interference from the sample matrix or loss of analyte through sorption or precipitation. The potential for contamination was evaluated by blank samples; loss of analyte due to interference from the sample matrix was evaluated by field-spiked samples. The degree of accuracy, or agreement between the measured value and the "true" value was assessed with standard reference samples.

#### Blank samples

Blanks were prepared from glass-distilled deionized water (DI). The blank data were evaluated with reference to minimum reporting levels (MRLs) established by the USA laboratory to reflect the limits of their instruments (table A1). Blank values were assumed to be significant if they were greater than twice the MRL. Results demonstrate that contamination was not significant for any constituent, although considerable analytical "noise" was present for analysis of total Kjeldahl nitrogen (TKN), or organic nitrogen plus ammonia nitrogen. The MRL for this constituent decreased during the period of this study, ranging from 0.25 mg/L during the first months of the summer in 1992 to 0.1 mg/L for most of the rest of the study period. Only one sample showed a detection for TKN of greater than twice the MRL, however, representing 2 percent of the measured concentrations in blank samples (N=48).

#### Field-spiked samples

Systematic error due to matrix interference was evaluated with field-spiked samples, which were submitted from a main-stem river site (river mile [RM] 16.2) once per week during 1993. Percent recovery of nutrient spikes was calculated as the difference in concentration between the spiked and unspiked samples, divided by the concentration of the spike and expressed in percent (fig. A1). No evidence of significant ($\alpha$=0.05) bias due to matrix effects was observed for any constituent except TKN; median recoveries for ammonia, nitrate, and the phosphorus species were greater than 90 percent. Analyses of TKN, however, indicate a positive bias (median recovery equal to 143 percent of the spike concentration). This bias is consistent with the same contamination problem found with the blank samples, because 43 percent of the concentration range of the added spike solution is approximately 0.05–0.07 mg/L, within the range of the concentrations observed in the blank samples.

#### Standard reference samples

Standard reference samples were prepared using DI and reagent-grade nutrient salts. Three ranges of nutrient levels: low, medium, and high were included to test the full analytical range of each laboratory, and so that the standard reference data could be evaluated in context with the concentration ranges of the ambient data.

**Table A1.** Data from blank samples analyzed by the Unified Sewerage Agency Water Quality Laboratory for May–October 1992–93
[Minimum Reporting Level (MRL) concentrations in milligrams per liter]

| Constituent | Minimum reporting level (MRL) | Percent of values greater than twice the MRL |
|---|---|---|
| Ammonia, as nitrogen | 0.025 | 0 |
| Ammonia plus organic nitrogen, as nitrogen (TKN) | .05-.25 | 2 |
| Nitrite-plus-nitrate, as nitrogen | .010 | 0 |
| Total phosphorus, as phosphorus | .025 | 0 |
| Orthophosphate, as phosphorus | .010 | 0 |

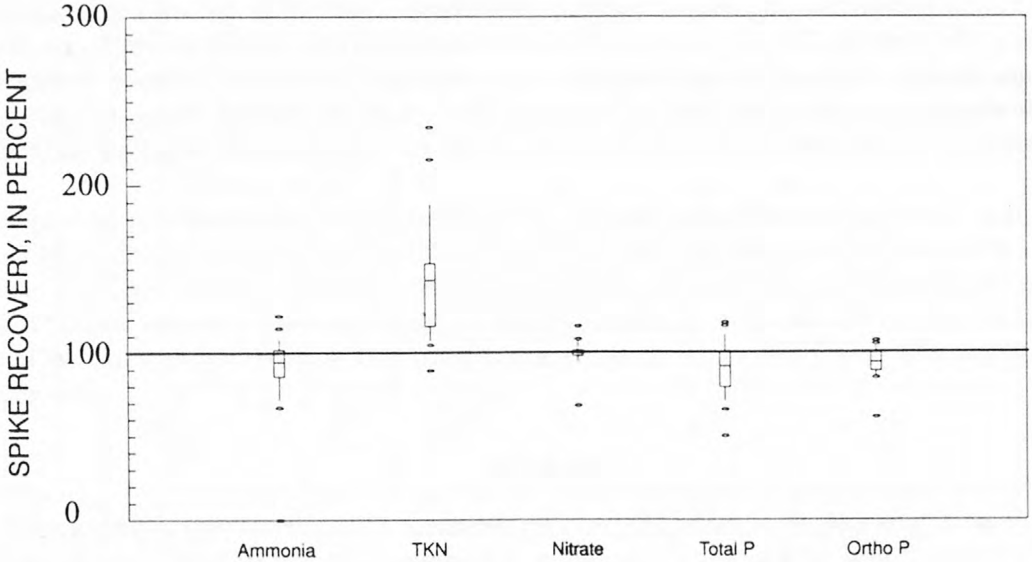



**Figure A1.** Spike recovery data from the Tualatin River at river mile 16.2 during May–October in 1993. (Percent recovery was calculated as the difference between spiked and unspiked concentrations, divided by the spike concentration, and expressed as percent.)

Paired groups of true and measured concentrations of the reference samples were compared with the sign test (Helsel and Hirsch, 1992) for each constituent and concentration range. Systematic error or bias was identified when one group was significantly different from the other ($\alpha$=0.05). Because the distribution of the results was not always normal, the central tendency of this error was estimated as the median difference between the two groups (table A2). Estimates of systematic error, when observed, were not used to adjust the ambient data, but were used in the calculation of confidence intervals around the appropriate mean loads for the main-stem river sites.

In general, no significant biases were detected, although there were a few exceptions. While slight negative biases were observed on occasion for nitrate, orthophosphate, and total phosphorus (generally 5 percent or less), more significant positive biases were observed for low-level analyses of ammonia, total phosphorus, and TKN. A positive bias was estimated for low-level ammonia analyses in 1991 at about 35 percent, and for low-level total phosphorus at about 25 percent. The largest bias was observed in the analysis of low-level TKN in 1991 and 1992, estimated between 130 and 260 percent of the true value. These results are consistent with the TKN contamination previously mentioned.

Despite its magnitude, the observed bias for low-level TKN is not significant in the context of the ambient data. Concentrations of TKN in the main-stem river and tributaries are larger by at least an order of magnitude than concentrations in the low-level QC samples submitted during 1991 and 1992. The biases for low-level ammonia and total phosphorus merit more concern because some ambient concentrations are observed in the low-level range. These data were considered to be acceptable for the purpose of this study, however, because the errors were small and any sources with concentrations of total phosphorus or ammonia in this range generally do not contribute significant loads. Uncertainty in the low-level analyses, therefore, had only a small effect on the calculation of the nutrient budget.

Data from the standard reference samples were also used to determine the limits of accuracy of the laboratory results. For each constituent, the relative error (observed concentration minus true concentration, as a fraction of the true concentration, expressed in percent) was plotted against the true concentration. Data are plotted with a separate symbol for each year (fig. A2). During 1991 and 1992, some standard reference samples for TKN contained concentrations less than the minimum reporting limit (MRL); these values are included in the analysis. Points on the plots that are beyond the scale of the y-axis are plotted on the top or bottom edge of the figure, with the actual relative error shown adjacent to the point.

Figure A2 provides a visual estimate of accuracy for each constituent for each year relative to the true concentration of the reference samples. The positive biases previously discussed for low-level ammonia, TKN, and total phosphorus are evident. In general, for the constituents that require digestion (that is, TKN and total phosphorus), accuracy is approximately +/- 20 percent within the concentration ranges of the ambient data. For the other constituents, greater accuracy was attained, generally within +/-10 percent.

### Variability

The variability (or precision) of a measurement generally refers to the degree of difference between two (or more) measurements which are assumed to be identical. The precision of individual measurements was measured by the relative difference of field duplicate samples (difference between duplicate concentrations, divided by the mean concentration), expressed as percent. The relative difference was plotted against the mean concentration to evaluate the effect of concentration (fig. A3). For the concentration ranges of these data, there was no apparent effect of concentration on precision, with the exception of a loss in precision for ammonia concentrations less than 0.05 mg/L. In general, except for low-level ammonia, levels of precision were similar to the accuracy limits previously discussed. Precision of duplicate values for digested constituents (total phosphorus and TKN) was generally better than 20 percent; for orthophosphate and nitrate, precision was generally better than 10 percent. Precision for low-concentration ammonia values, on the other hand, ranged up to about 50 percent, which is more typical for analyses near the MRL.

**Table A2.** Summary statistics for standard reference sample data during May–October in 1991, 1992, and 1993
[Concentrations in milligrams per liter; N, number of observations; difference, observed-true; %, percent; IQR, range between 75% and 25%]

| Year | Concentration range | N | Bias | Median difference | 75% | 25% | IQR |
|---|---|---|---|---|---|---|---|
| | | | | **Ammonia, as nitrogen** | | | |
| 1991 | .019–.043 | 22 | + | .010 | .014 | .006 | .008 |
| 1991 | .226–.594 | 22 | 0 | -.002 | .007 | -.026 | .033 |
| 1991 | 2.68–6.10 | 22 | 0 | .035 | .270 | -.120 | .390 |
| 1992 | .022–.078 | 23 | 0 | .002 | .012 | -.001 | .013 |
| 1992 | .142–1.14 | 23 | 0 | -.004 | .007 | -.016 | .023 |
| 1992 | 1.42–8.21 | 23 | 0 | -.060 | .110 | -.280 | .390 |
| 1993 | .174–.500 | 25 | 0 | .001 | .009 | -.003 | .012 |
| 1993 | .349–.872 | 25 | 0 | .005 | .017 | -.010 | .027 |
| 1993 | .700–4.36 | 25 | 0 | .011 | .060 | -.010 | .070 |
| | | | | **Ammonia plus organic nitrogen, as nitrogen (TKN)** | | | |
| 1991 | .02–.04 | 22 | + | .03 | .18 | .02 | .16 |
| 1991 | .23–.59 | 22 | 0 | .03 | .07 | -.04 | .12 |
| 1991 | 2.7–6.1 | 22 | 0 | -.21 | .09 | -.61 | .70 |
| 1992 | .02–.08 | 15 | + | .12 | .20 | .06 | .14 |
| 1992 | .14–1.1 | 23 | 0 | -.02 | .04 | -.05 | .08 |
| 1992 | 2.3–8.2 | 23 | 0 | .03 | .39 | -.43 | .82 |
| 1993 | .17–.50 | 25 | 0 | 0 | .03 | -.01 | .04 |
| 1993 | .35–.87 | 25 | 0 | 0 | .01 | -.03 | .04 |
| 1993 | .70–4.4 | 25 | 0 | 0 | .01 | -.06 | .07 |
| | | | | **Nitrite-plus-nitrate nitrogen, as nitrogen** | | | |
| 1991 | .065–.130 | 22 | 0 | -.004 | .002 | -.015 | .017 |
| 1991 | .546–1.17 | 22 | 0 | -.024 | .039 | -.105 | .144 |
| 1991 | 3.64–8.76 | 22 | 0 | -.158 | .225 | -.850 | 1.075 |

**Table A2.** Summary statistics for standard reference sample data during May–October in 1991, 1992, and 1993—Continued
[Concentrations in milligrams per liter; N, number of observations; difference, observed-true; %, percent; IQR, range between 75% and 25%]

| Year | Concentration range | N | Bias | Median difference | 75% | 25% | IQR |
|---|---|---|---|---|---|---|---|
| | | | Nitrite-plus-nitrate nitrogen, as nitrogen—Continued | | | | |
| 1992 | .077–.151 | 23 | 0 | -.003 | .001 | -.007 | .008 |
| 1992 | .540–1.51 | 23 | - | -.013 | .000 | -.030 | .030 |
| 1992 | 3.07–6.47 | 24 | 0 | -.040 | .040 | -.136 | .176 |
| 1993 | .433–.748 | 25 | - | -.013 | -.006 | -.020 | .014 |
| 1993 | 1.15–2.89 | 25 | - | -.020 | -.010 | -.050 | .040 |
| 1993 | 2.89–7.23 | 25 | 0 | -.010 | .040 | -.070 | .110 |
| | | | Total phosphorus, as phosphorus | | | | |
| 1991 | .015–.050 | 22 | 0 | -.006 | .013 | -.017 | .029 |
| 1991 | .109–.241 | 22 | 0 | .001 | .035 | -.010 | .045 |
| 1991 | .547–2.47 | 22 | 0 | .080 | .265 | -.160 | .425 |
| 1992 | .024–.051 | 24 | + | .008 | .016 | .002 | .014 |
| 1992 | .103–.331 | 23 | 0 | .006 | .004 | .037 | .041 |
| 1992 | .820–3.40 | 23 | 0 | 0 | .080 | -.210 | .290 |
| 1993 | .044–.070 | 25 | 0 | -.003 | .001 | -.007 | .008 |
| 1993 | .069–.779 | 25 | - | -.005 | -.002 | -.009 | .007 |
| 1993 | .664–1.52 | 25 | - | -.027 | -.016 | -.060 | .044 |
| | | | Orthophosphate, as phosphorus | | | | |
| 1991 | .015–.050 | 22 | 0 | .001 | .004 | -0.002 | .006 |
| 1991 | .109–.241 | 22 | - | -.015 | -.005 | -.026 | .021 |
| 1991 | .547–2.47 | 22 | - | -.070 | -.015 | -.098 | .083 |
| 1992 | .015–.043 | 23 | 0 | .002 | .004 | -.001 | .005 |
| 1992 | .103–.331 | 23 | 0 | -.001 | .003 | -.009 | .012 |
| 1992 | .820–2.14 | 24 | - | -.025 | 0 | -.045 | .045 |
| 1993 | .021–.050 | 25 | 0 | 0 | .002 | -.002 | .004 |
| 1993 | .048–.123 | 25 | 0 | 0 | .001 | -.002 | .003 |
| 1993 | .477–1.23 | 25 | 0 | .005 | .014 | -.002 | .016 |

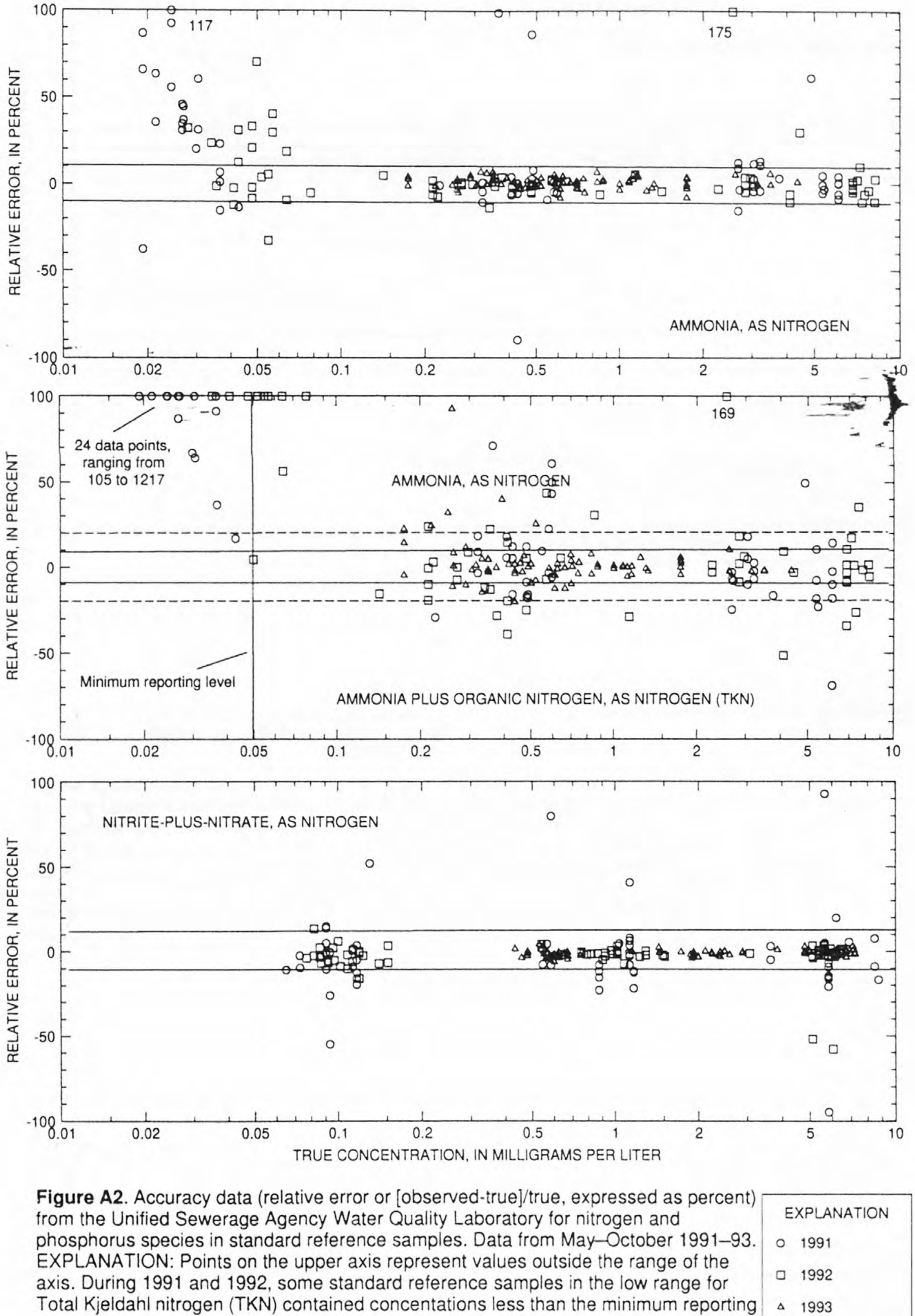



**Figure A2.** Accuracy data (relative error or [observed-true]/true, expressed as percent) from the Unified Sewerage Agency Water Quality Laboratory for nitrogen and phosphorus species in standard reference samples. Data from May–October 1991–93. EXPLANATION: Points on the upper axis represent values outside the range of the axis. During 1991 and 1992, some standard reference samples in the low range for Total Kjeldahl nitrogen (TKN) contained concentations less than the minimum reporting level. Dashed lines represent +/-20 percent; solid lines represent +/- 10 percent.

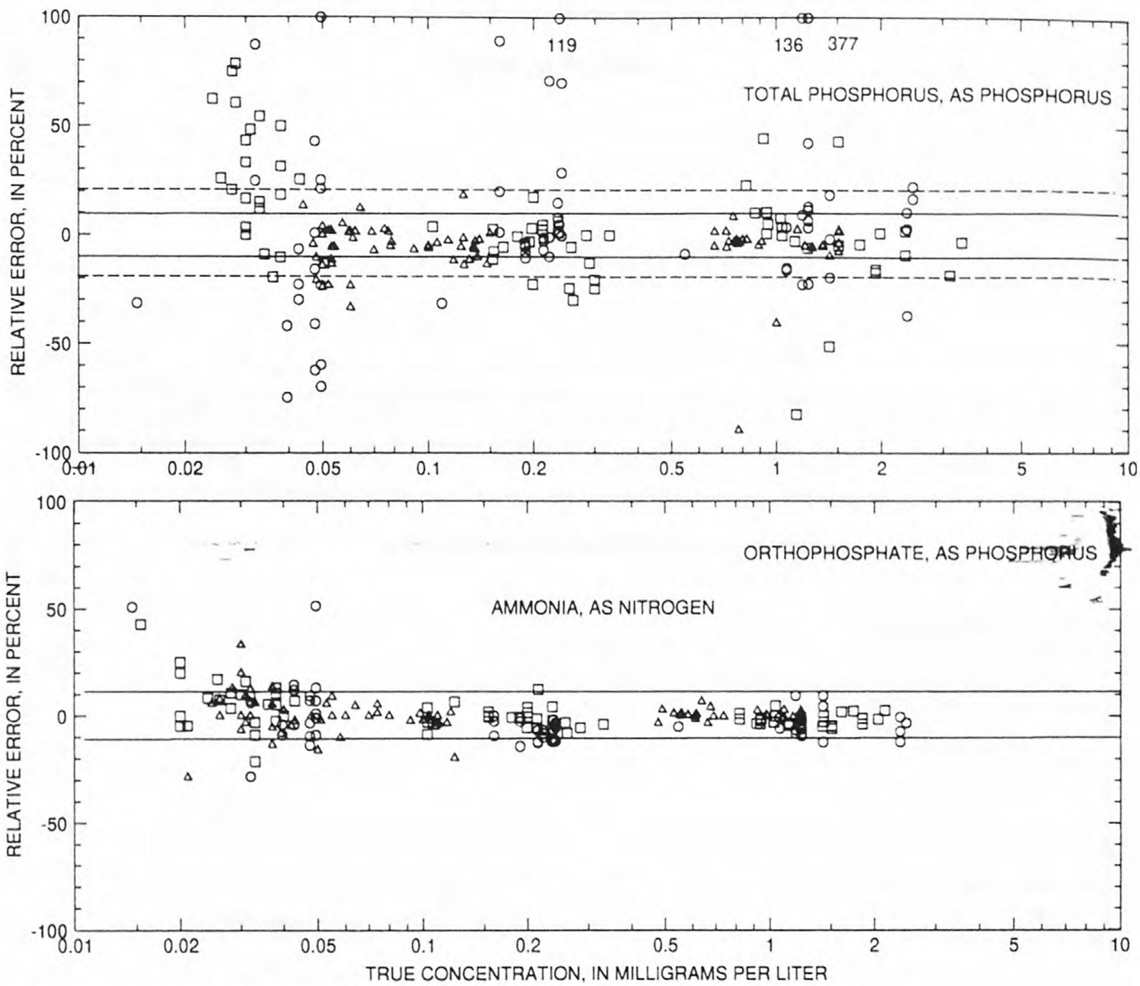



**Figure A2.** Accuracy data (relative error or [observed-true]/true, expressed as percent) from the Unified Sewerage Agency Water Quality Laboratory for nitrogen and phosphorus species in standard reference samples—Continued. Data from May–October 1991–93. EXPLANATION: Points on the upper axis represent values outside the range of the axis. During 1991 and 1992, some standard reference samples in the low range for Total Kjeldahl nitrogen (TKN) contained concentations less than the minimum reporting level. Dashed lines represent +/-20 percent; solid lines represent +/- 10 percent.

EXPLANATION

○ 1991

□ 1992

△ 1993

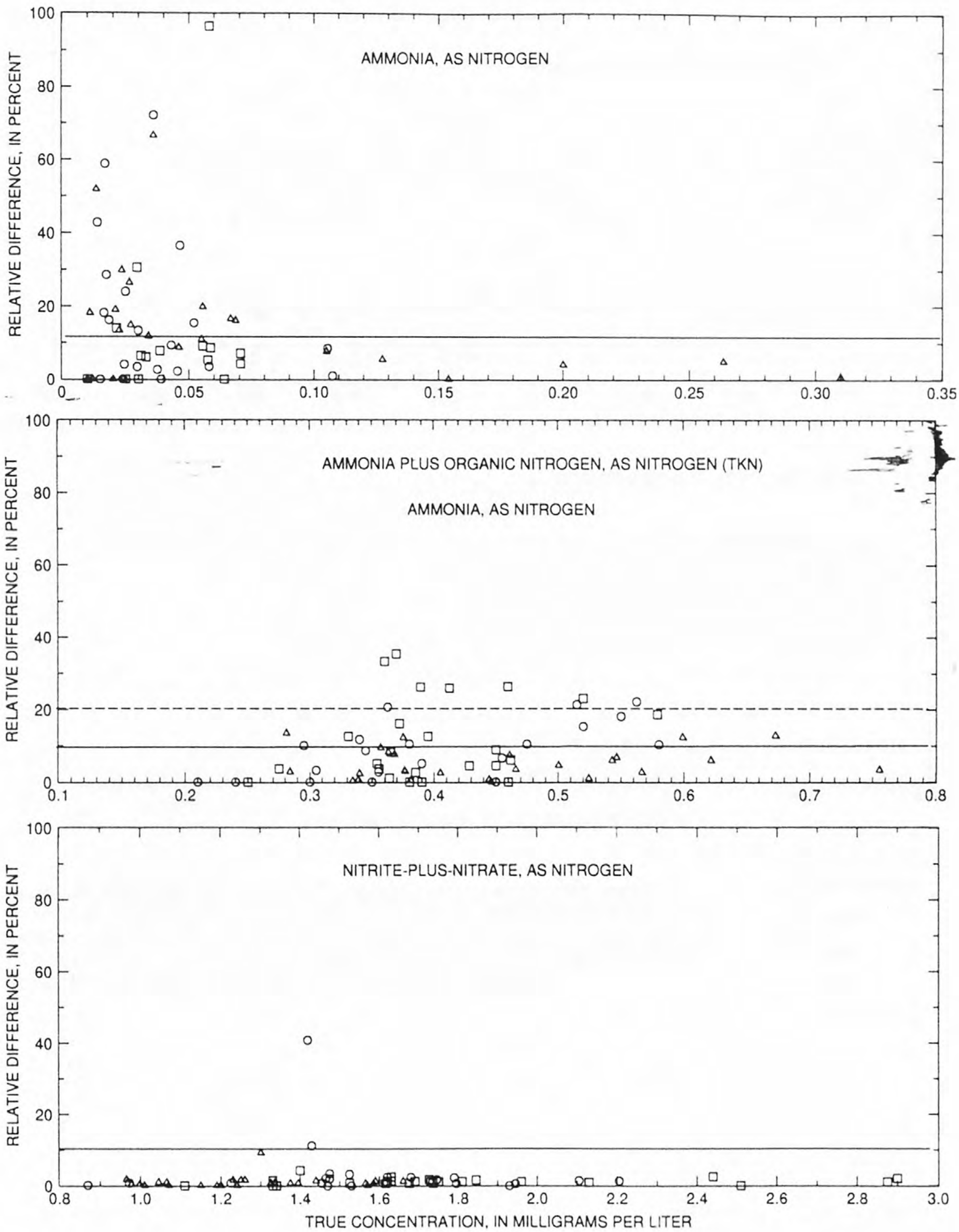
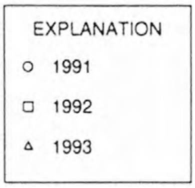
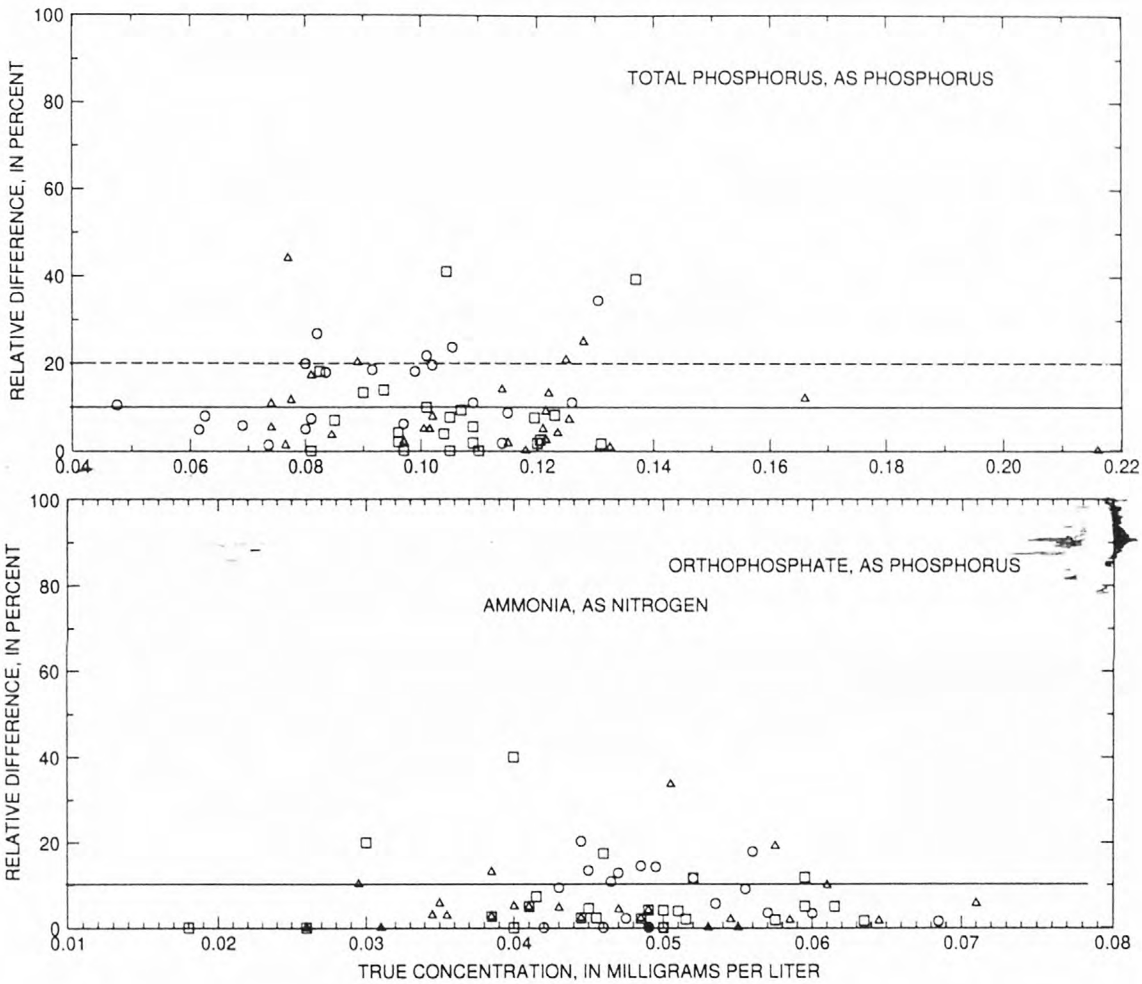



**Figure A3.** Precision data (difference/mean, expressed as percent) from the Unified Sewerage Agency Water Quality Laboratory for nitrogen and phosphorus species in field duplicate samples. Data from May–October 1991–93. EXPLANATION: The dashed line represents 20 percent difference; solid lines represent 10 percent difference. (TKN, Total Kjeldahl nitrogen)





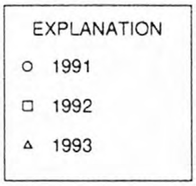




**Figure A3.** Precision data (difference/mean, expressed as percent) from the Unified Sewerage Agency Water Quality Laboratory for nitrogen and phosphorus species in field duplicate samples—Continued. Data from May–October 1991–93. EXPLANATION: The dashed line represents 20 percent difference; solid lines represent 10 percent difference. (TKN, Total Kjeldahl nitrogen)

# Appendix B

# Appendix B

## APPENDIX B

### Time Series Plots for Wastewater Treatment Plant Nutrient Concentrations

The Rock Creek and Durham Wastewater Treatment Plants (WWTPs) are important influences on the quality of the Tualatin River below river mile (RM) 38.1. This influence can be attributed to both the quality of the effluent and its volume.

During the low-flow summer period between May 1 and October 31, WWTP effluent accounts for a significant fraction of the streamflow in the Tualatin River below RM 38.1. This fraction can be as high as 20 to 40 percent, depending on the amount of flow from other sources and whether the site of interest is downstream of one or both WWTPs. The fact that effluent volume is significant relative to the total streamflow means that the effluent will affect, and in many cases be the major influence on, the instream concentrations of many constituents.

The concentrations of some constituents, such as chloride, in WWTP effluent are typically higher than the instream concentrations upstream of the WWTP outfalls. The effluent, therefore, will cause the instream concentration of these constituents to increase downstream of the outfall. For chloride and nitrate, the increase will be large. For other constituents, such as total phosphorus when the removal efficiency of this constituent is high, the concentrations in effluent are small relative to instream concentrations. In this situation, the effluent acts as dilution water, decreasing the instream concentrations. Even when the effluent concentrations are low relative to instream concentrations, therefore, the WWTPs are important influences on the water quality of the river.

This appendix contains time series plots of chloride, total phosphorus, orthophosphate, total nitrogen, organic nitrogen plus ammonia (total Kjeldahl nitrogen), ammonia, and nitrite plus nitrate concentrations in figures B1 through B7, respectively, for both the Rock Creek and Durham WWTPs during the May through October periods of 1991, 1992, and 1993.

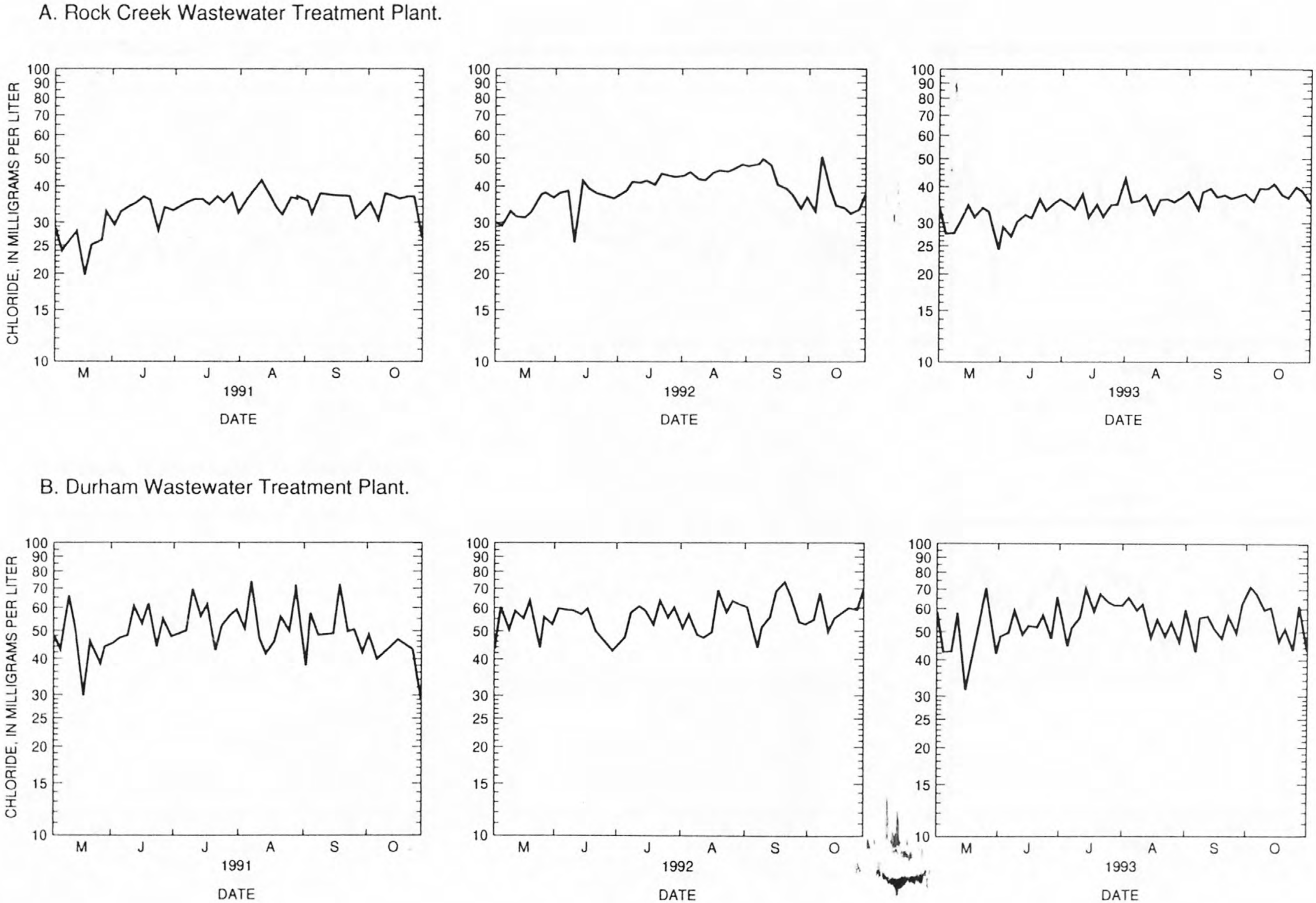



**Figure B1.** Concentrations of chloride in effluent from the Rock Creek and Durham Wastewater Treatment Plants during the summer season (May–October) in 1991, 1992 and 1993.

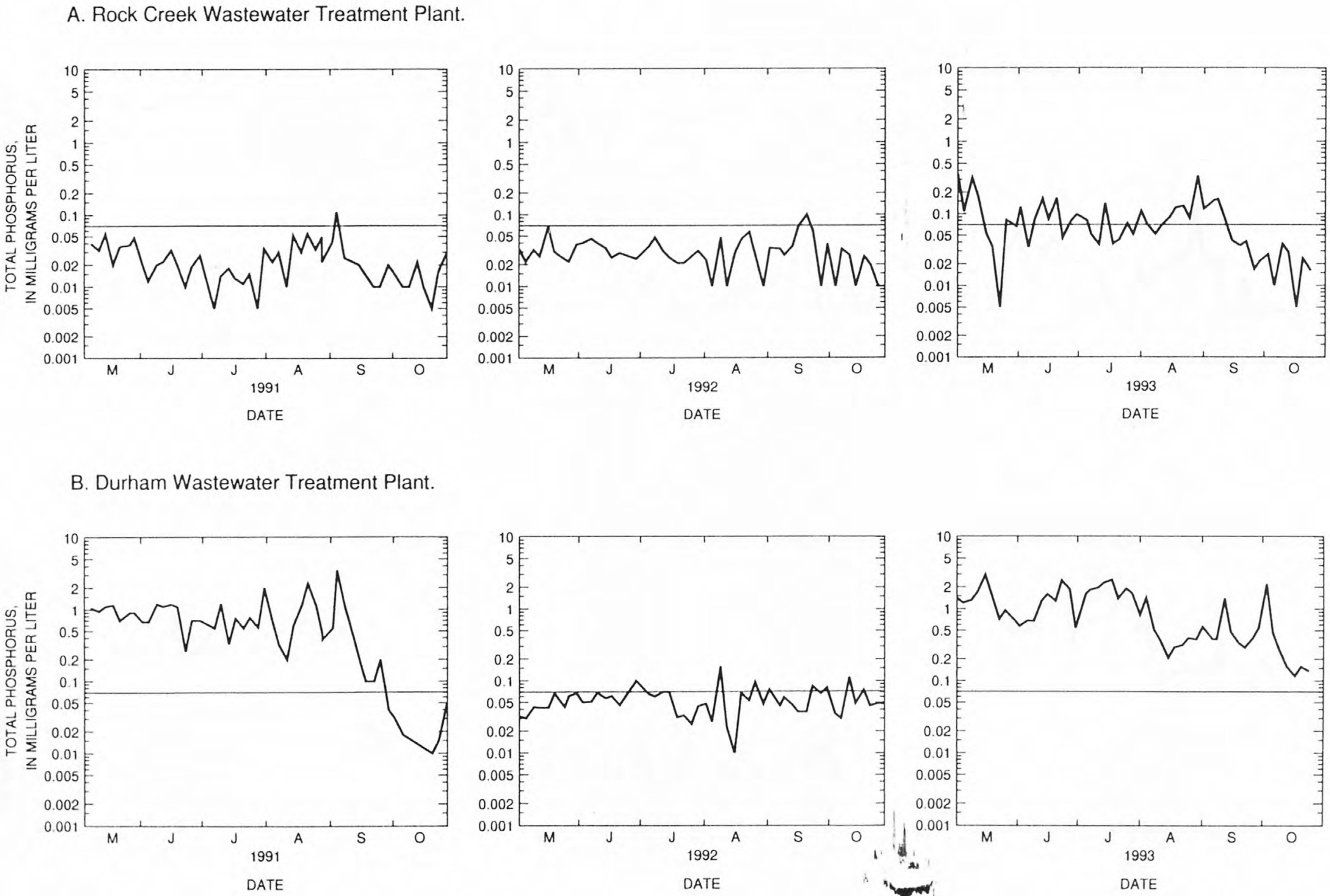



**Figure B2.** Concentrations of total phosphorus in effluent from the Rock Creek and Durham Wastewater Treatment Plants during the summer season (May–October) in 1991, 1992 and 1993. (Reference line represents the Total Maximum Daily Load [TMDL] criterion concentration for the lower main-stem river.

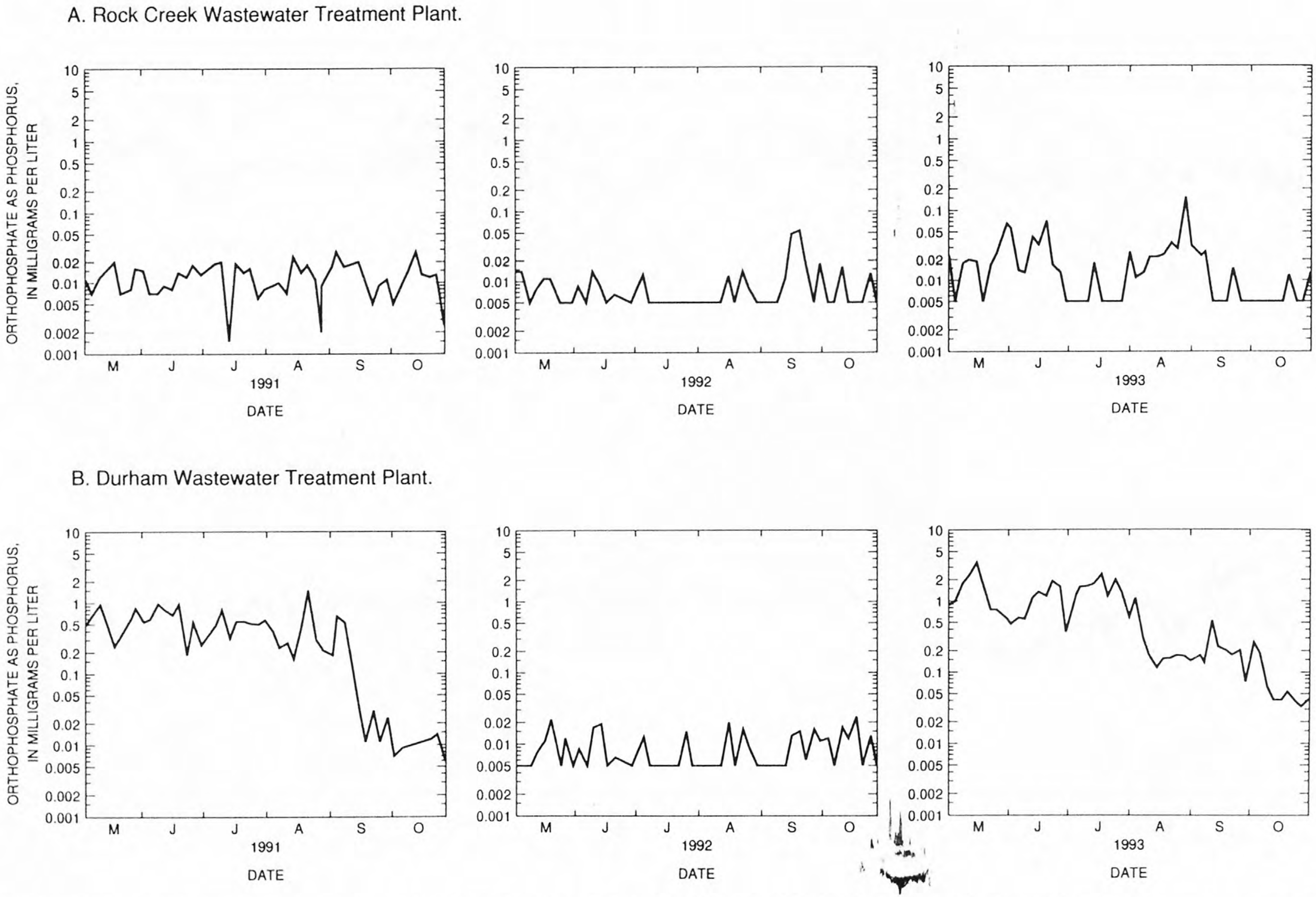
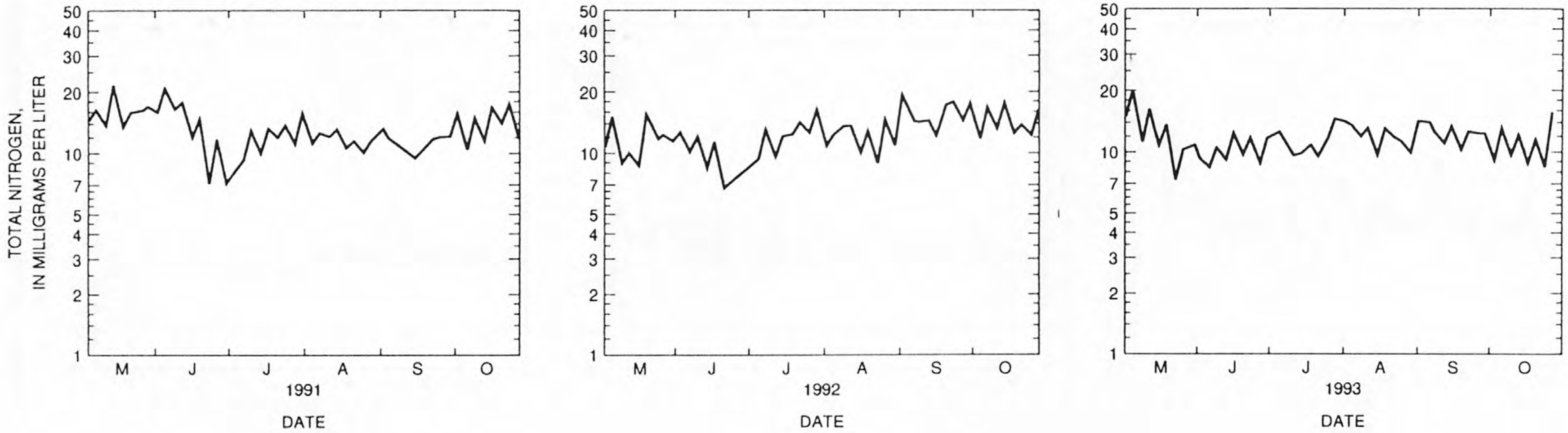



**Figure B3.** Concentrations of orthophosphate, as phosphorus, in effluent from the Rock Creek and Durham Wastewater Treatment Plants during the summer season (May–October) in 1991, 1992 and 1993.

A. Rock Creek Wastewater Treatment Plant.




B. Durham Wastewater Treatment Plant.

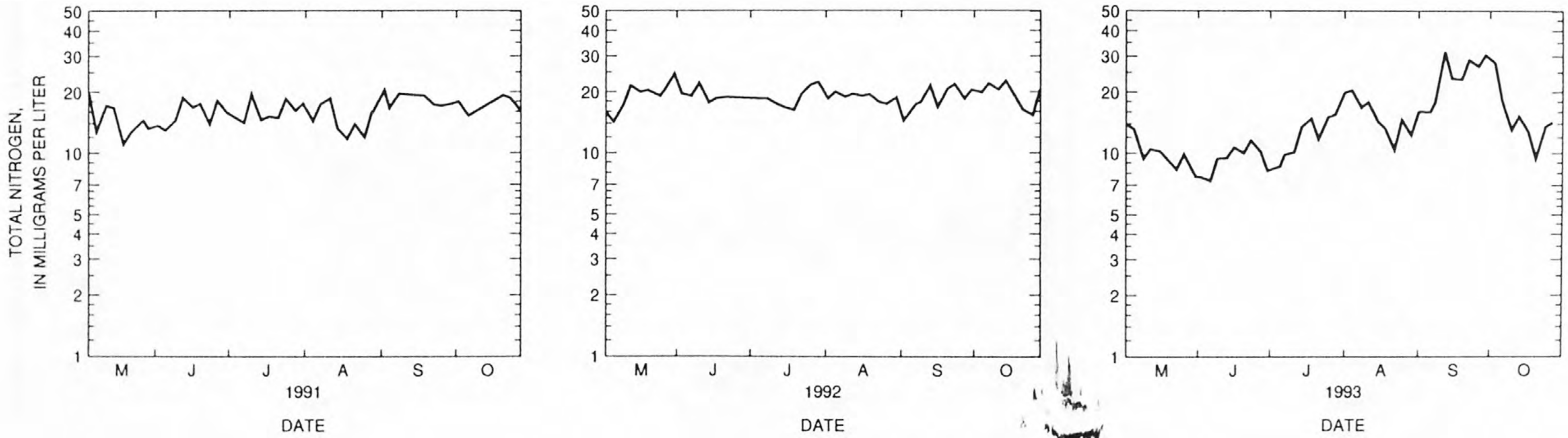



**Figure B4.** Concentrations of total nitrogen in effluent from the Rock Creek and Durham Wastewater Treatment Plants during the summer season (May–October) in 1991, 1992 and 1993.

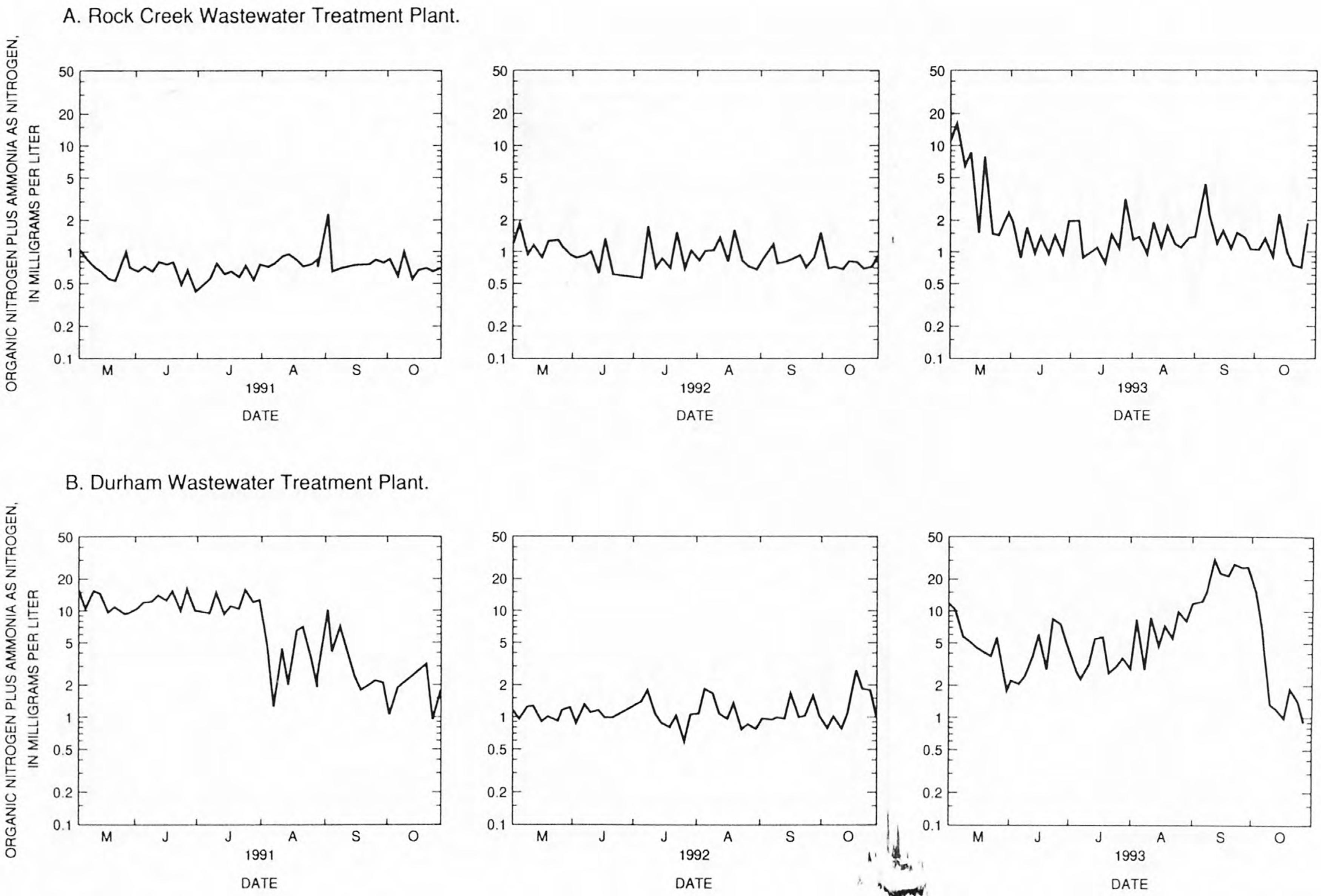
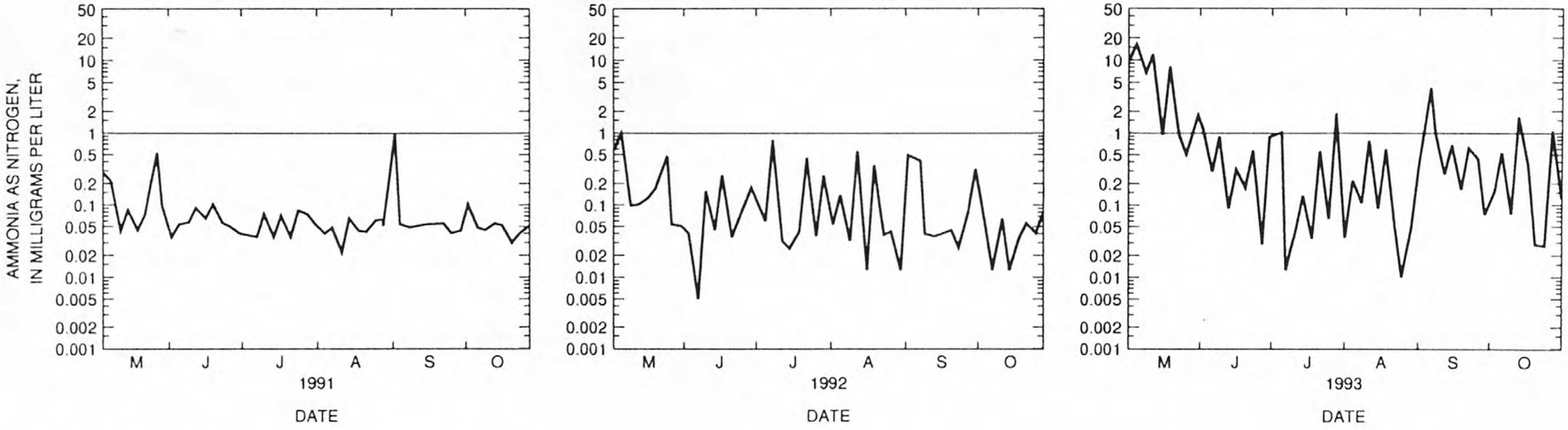



**Figure B5.** Concentrations of organic nitrogen plus ammonia as nitrogen (TKN [Total Kjeldahl nitrogen]) in effluent from the Rock Creek and Durham Wastewater Treatment Plants during the summer season (May–October) in 1991, 1992 and 1993.

A. Rock Creek Wastewater Treatment Plant.




B. Durham Wastewater Treatment Plant.

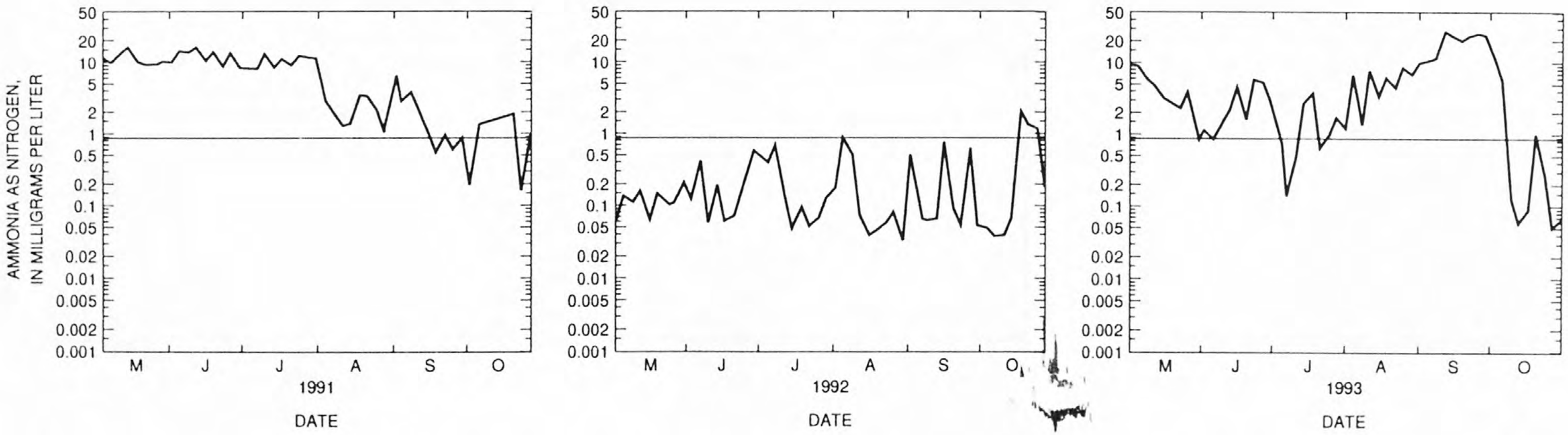



**Figure B6.** Concentrations of ammonia as nitrogen in effluent from the Rock Creek and Durham Wastewater Treatment Plants (WWTP) during the summer season (May–October) in 1991, 1992 and 1993. (Reference lines represent the Total Maximum Daily Load [TMDL] criterion concentration for ammonia in the river at each treatment plant outfall [1.0 mg/L at Rock Creek WWTP, 0.85 mg/L at Durham WWTP].)

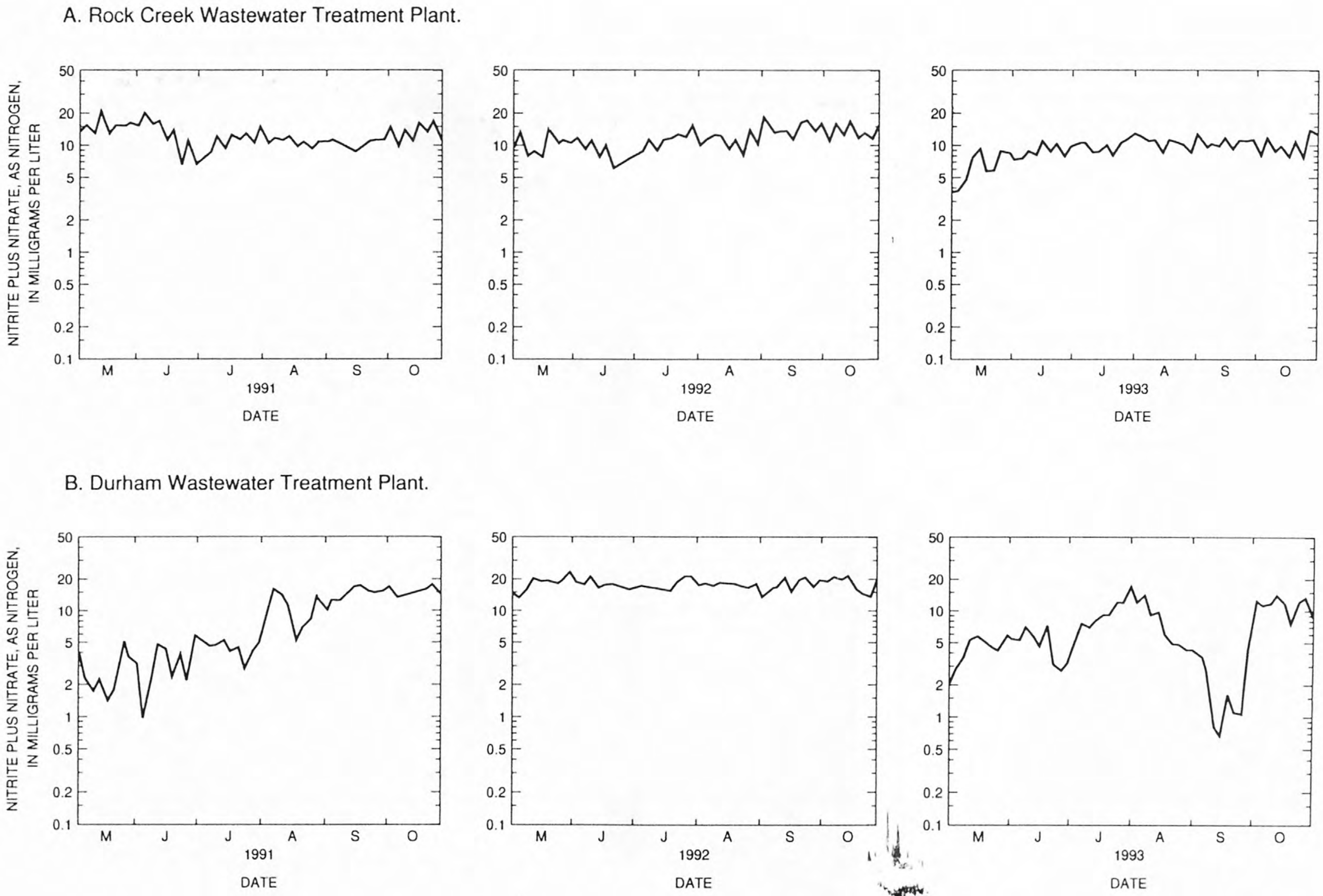



**Figure B7.** Concentrations of nitrite plus nitrate as nitrogen in effluent from the Rock Creek and Durham Wastewater Treatment Plants (WWTP) during the summer season (May–October) in 1991, 1992 and 1993.