Relations Among Floodplain Water Levels, Instream Dissolved-Oxygen Conditions, and Streamflow in the Lower Roanoke River, North Carolina, 1997–2001

By Jerad D. Bales and Douglas A. Walters

Prepared in cooperation with

U.S. Fish and Wildlife Service,
North Carolina Division of Water Resources,
North Carolina Division of Water Quality, and
The Nature Conservancy

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Conversion Factors, Datums, and Acronyms and Abbreviations

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	1.057	quart (qt)
	Flow rate	
centimeter per second (cm/s)	0.394	inch per second (in/s)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
meter per second (m/s)	3.281	foot per second (ft/s)
	Volume per unit of time	
centimeter per day (cm/d)	0.394	inch per day (in/d)
kilometer per hour (km/h)	0.6214	mile per hour (mi/hr)
	Mass	
kilogram (kg)	2.205	pound avoirdupois (lb)

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

°F = (1.8 x °C) + 32

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD29).

Horizontal (latitude and longitude) coordinate information is referenced to the North American Datum of 1983 (NAD83).

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

Acronyms and abbreviations:

BOD	biochemical oxygen demand
DO	dissolved oxygen
GPS	global positioning system
hr	hour
mg/L	milligram per liter, a water-quality unit of measure
N	nitrogen
NCDWQ	North Carolina Division of Water Quality
NWS	National Weather Service
ppt	parts per thousand, a water-quality unit of measure
TOC	total organic carbon
USGS	U.S. Geological Survey

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Abstract

The lower Roanoke River corridor in North Carolina contains a floodplain of national significance. Data from a network of 1 streamflow-measurement site, 13 river-stage sites, 13 floodplain water-level sites located along 4 transects, and 5 in situ water-quality monitoring sites were used to characterize temporal and spatial variations of floodplain and river water levels during 1997–2000 and to describe dissolved-oxygen conditions in the lower Roanoke River for the period 1998–2001.

Major differences in the relation of floodplain inundation to flow occurred both among sites at a given transect and among transects. Several floodplain sites were inundated for the full range of flow conditions measured during the study. These included one site on the Big Swash transect (at about river kilometer 119); one site on the Broadneck Swamp transect (river kilometer 97), which was inundated 91 percent of the time during the study; one site on the Devils Gut transect (river kilometer 44), which was inundated throughout the study; and three sites on the Cow Swamp transect (near river kilometer 10).

The relation of floodplain inundation depth to Roanoke River flow was highly variable among sites. There was no relation between flow and inundation depth at one of the Big Swash sites or at any of the four Cow Swamp sites. At two of the Big Swash transect sites, there was some relation between inundation depth and 10-day mean flow for flows greater than 700 cubic meters per second. A relatively strong relation between inundation depth and 10-day mean flow occurred at two of the Broadneck Swamp sites and, to a lesser degree, at two of the Devils Gut transect sites.

There was much greater interannual variability in floodplain water levels, as represented by the difference between the maximum and minimum daily water level for a given calendar date during January–May and September–October than during the summer and late fall months. If data from this study are representative of long-term conditions, then this means that there is less uncertainty about what future floodplain water levels will be during June–August and November–December than during other months.

Rates of ground-water decline, primarily due to evapotranspiration, were fairly similar at all sites, ranging from about 3 to 4 centimeters per day. For a 10-day mean flow of 300 cubic meters per second, an evaporative loss of 2 centimeters per day is equal to about 56 cubic meters per second. Evapotranspiration rates are much lower during the fall and winter months, so losses of river flow to floodplain processes likely are much lower during those months.

The ground-water gradient at most sites was from the floodplain to the river, indicating a potential for ground-water movement into the river from the floodplain. At two of the Devils Gut sites, however, the water level often was higher in the river than in the floodplain when floodplain sites were not inundated. This indicates that there is a potential for river water to move as ground water from the river into the floodplain. It seems likely that this feature observed at the Devils Gut transect occurs elsewhere in the lower Roanoke River corridor.

Dissolved-oxygen concentrations typically decrease with increasing distance from Roanoke Rapids Dam. During the 1998–2001 study period, the median dissolved-oxygen concentration at Halifax (river kilometer 187), the upstream-most station, was 8.4 milligrams per liter, and the median concentration at the downstream-most station (NC-45, bottom sensor; river kilometer 2.6) was 6.6 milligrams per liter. Several synoptic measurements of dissolved-oxygen concentration down the river identified the presence of a dissolved-oxygen sag in the vicinity of Halifax, with some recovery of concentrations between Halifax and about Scotland Neck at river kilometer 156. Data from the synoptic measurements also indicated that the greatest rate of dissolved-oxygen change with distance along the river was downstream from Hamilton (river kilometer 97).

The frequency with which the North Carolina water-quality standards for dissolved oxygen were exceeded also increased with distance from Roanoke Rapids Dam, and many of the low dissolved-oxygen events were concurrent with backswamp drainage. The number of days during the study period for which the daily mean dissolved-oxygen concentration was less than 5 milligrams per liter was: Halifax—2 days; Oak City—18 days; Grabtown—45 days; Jamesville—136 days; and NC-45 bottom—235 days. Most of these occurrences were during the months of May–October, with the most in

September. If the low dissolved-oxygen concentrations associated with Hurricane Floyd flooding were not considered, the month during which daily mean dissolved oxygen was most likely to be less than 5 milligrams per liter was June—typically the month during which the higher spawning-enhancement flows are stepped down to the lower, summer load-following flows. It is likely that this change in flow regime and the associated draining of the backswamps is at least partially responsible for the relatively large number of occurrences of low dissolved oxygen in June. It also is worth noting that during the study period, monthly point-source biochemical oxygen demand loads in the summer were typically one-third of the loads during the winter.

Dissolved-oxygen concentrations are qualitatively related to flow conditions. Daily mean dissolved-oxygen concentrations less than 5 milligrams per liter occurred only at 10-day mean flows (measured at Roanoke River at Roanoke Rapids) of 180–280 cubic meters per second at Oak City, only at 10-day mean flows less than 240 cubic meters per second at Grabtown, and primarily at 10-day mean flows less than 300 cubic meters per second at Jamesville. At the NC-45 site, under current loading conditions, it is unlikely that the bottom daily mean dissolved-oxygen concentration would be less than 5 milligrams per liter for 10-day mean flows greater than about 290 cubic meters per second. Likewise, at a 10-day mean flow of 200 cubic meters per second, bottom daily mean dissolved-oxygen concentrations could be as low as, but probably no lower than, 3 milligrams per liter. The difference between mid-depth and bottom dissolved-oxygen concentrations at the NC-45 site also are related to flow in somewhat the same manner as daily mean dissolved-oxygen concentrations. At 10-day mean flows less than 200 cubic meters per second, the difference between mid-depth and bottom dissolved-oxygen concentrations is likely to be greater than 1 milligram per liter; at 10-day mean flows less than 100 cubic meters per second, the difference is likely to be 2 milligrams per liter. For both flows, the difference is as likely to be positive (mid-depth greater than bottom) as negative (mid-depth less than bottom).

During May 11, 2000–December 31, 2001, when data from both the mid-depth and bottom sensors were available at the NC-45 site, the median bottom dissolved-oxygen concentration was 6.1 milligrams per liter, and the median mid-depth concentration was 6.1 milligrams per liter. Hourly dissolved-oxygen concentrations less than 4 milligrams per liter occurred about four times more often at the bottom sensor than at the top, but hourly dissolved-oxygen concentrations greater than 8 milligrams per liter occurred about 50 percent more frequently at the bottom than at mid-depth. Dissolved-oxygen concentrations were about as likely to be higher at the bottom sensor as at the mid-depth sensor.

Introduction

The Roanoke River (fig. 1) is an important resource for North Carolina, Virginia, and the Nation. Floodplains of the lower Roanoke River, which extends from Roanoke Rapids Dam to the mouth of the river, have been described as nationally significant (U.S. Fish and Wildlife Service, 1988). The lower Roanoke River and floodplain, or lower Roanoke River corridor, support a large and diverse population of nesting birds, waterfowl, freshwater and anadromous fish, and wildlife, including threatened and endangered species. Important species dependent on resources of the lower Roanoke River corridor include a "highly significant population of striped bass" (U.S. Fish and Wildlife Service, 1988), largemouth bass, bald eagle, a remnant population of black bear, and possibly the endangered shortnose sturgeon. In addition to providing critical habitat for wildlife, the Roanoke River is used for a variety of other purposes, including water supply, hydropower production, wastewater assimilation, and recreation.

The interstate drainage basin and the many competing uses of the Roanoke River often have led to a lack of consensus on appropriate uses of the resource. The Lake Gaston pipeline, which now provides the City of Virginia Beach, Virginia, with raw water from Lake Gaston, was the source of numerous court actions and a major controversy between the State of North Carolina and the City of Virginia Beach from the late 1980's until the mid-1990's. The City of Raleigh is currently evaluating the use of Kerr Lake as a water supply, and this proposal could be as controversial as the Lake Gaston pipeline. Proposals to construct large new industrial facilities on the banks of the lower Roanoke River have been met with strong opposition from environmental, fisheries, and wildlife interests because of the unknown but potentially harmful effects of increased wastewater loadings to the river. The process of relicensing the Roanoke Rapids and Gaston hydropower projects with the Federal Energy Regulatory Commission has been underway by Dominion Generation since 1993. Difficult issues regarding fisheries, flow regimes (for example, spring spawning flows, minimum flows, and flood and drought response), water quality, effects on floodplain plant and wildlife resources, and recreation have been (and continue to be in 2003) negotiated among resource agencies, stakeholders' groups, and Dominion Generation.

The relations among Roanoke River flow, floodplain water level, and instream dissolved-oxygen (DO) concentrations are important but poorly understood. Flooding and floodplain inundation no longer follow a natural seasonal pattern of large floods in the late winter, occasional floods in the fall, and lower flows throughout the remainder of the year (Konrad, 1998) but are governed primarily by upstream reservoir releases. The timing, duration, and extent of floodplain inundation can have either positive or negative effects

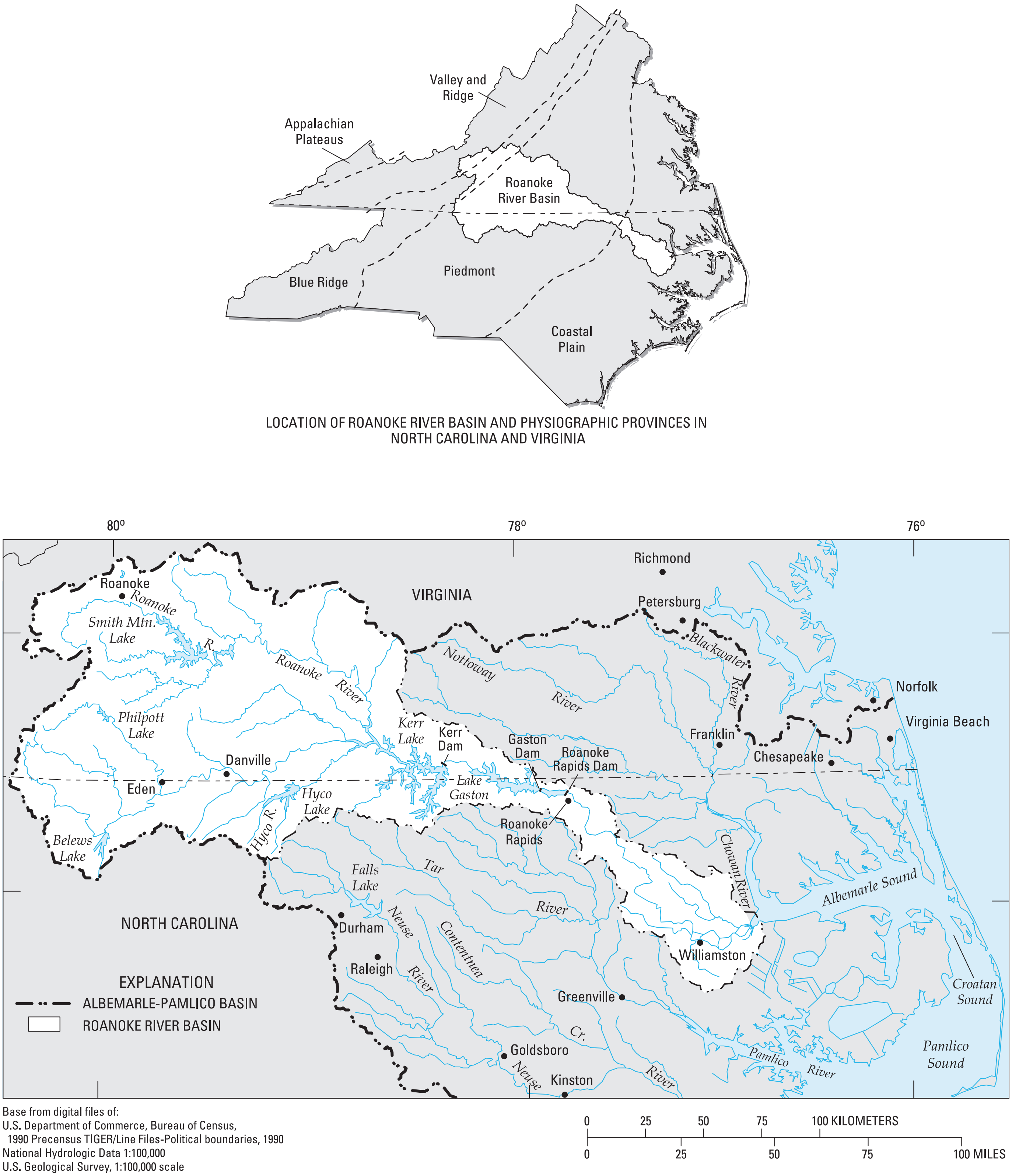


Figure 1. The Roanoke River basin in Virginia and North Carolina.

on vegetation, wildlife, and fisheries in the lower Roanoke River corridor, depending on the inundation characteristics (Rulifson and Manooch, 1993). A numerical hydraulic model for continuous simulation of instream flows and floodplain inundation throughout the entire lower Roanoke River corridor for the full range of flow conditions is not available, although recent work by Townsend and Foster (2002) provides information on inundated areas for selected flow conditions.

> The North Carolina water-quality standard for DO is as follows: *"Dissolved oxygen: not less than 6.0 mg/L* [milligrams per liter] *for trout waters; for non-trout waters, not less than a daily average of 5.0 mg/L with a minimum instantaneous value of not less than 4.0 mg/L; swamp water, lake coves or backwaters, and lake bottom waters may have lower values if caused by natural conditions."* (North Carolina Department of Environment and Natural Resources, 2002).

The downstream-most 29 km (kilometers) of the Roanoke River between about Jamesville and Albemarle Sound are classified as swamp waters, as are all tributaries in that reach (fig. 2; North Carolina Department of Environment and Natural Resources, 2003).

Largemouth bass are an important recreational fish species in the lower Roanoke River; growth of this species is impaired at DO concentrations less than 8 mg/L, and is substantially inhibited at concentrations less than 4 mg/L (Stuber and others, 1982). Survival of striped bass egg and larvae also are reduced at DO concentrations less than 5 mg/L (Bain and Bain, 1982). Exceedances of the North Carolina DO standards have been observed in the Roanoke River, most often in the late spring, summer, and early fall (Rulifson and Manooch, 1991). One of the most notable cases of low DO occurred during July 28–August 2, 1995, when a rapid decline in river flow allowed flooded backswamps to discharge DO-depleted waters to the river, resulting in the death of more than 25,000 fish (North Carolina Department of Environment and Natural Resources, 2000). There is, however, uncertainty regarding the relative contributions of point-source discharges and floodplain drainage to instream DO concentrations, as well as whether floodplain drainage constitutes "natural conditions" for a system in which the natural hydroperiod has been altered and natural levees have been breached by canals and ditches. A numerical water-quality model capable of simulating the effects of both point-source discharges and floodplain drainage on river DO conditions has not been developed for the Roanoke River (North Carolina Department of Environment, Health, and Natural Resources, 1996), so decisions about new or increased point-source discharges and floodplain water management currently (2003) must be made with inadequate information.

Environmental decisionmaking for the lower Roanoke River is complicated by the nature of the corridor—flow regulated by hydropower operations, expansive floodplains with numerous inlets and outlets, tidal effects that extend more than halfway up the river (Bales and others, 1993), saltwater intrusion, and a complex distributary system at the mouth of the river. Moreover, the absence of long-term hydrologic data, including river flows in the middle and lower portion of the river, and the lack of good modeling tools for understanding the system and simulating the effects of change further hinder informed environmental management of the system. In response to the need for a better understanding of the hydrology and water-quality conditions of the lower Roanoke River corridor, the U.S. Geological Survey (USGS) conducted simultaneous, complementary studies of floodplain water-level characteristics and instream water quality in the lower Roanoke River during 1997–2001. The water-level study was conducted in cooperation with the North Carolina Division of Water Resources and The Nature Conservancy; the instream water-quality study was conducted in cooperation with the U.S. Fish and Wildlife Service and the North Carolina Division of Water Quality. The objectives of the studies were to (1) characterize relations between river flow and floodplain water levels, (2) document the frequency and duration of low (less than 5 mg/L) DO concentrations, and (3) identify possible factors resulting in low DO concentrations in the river.

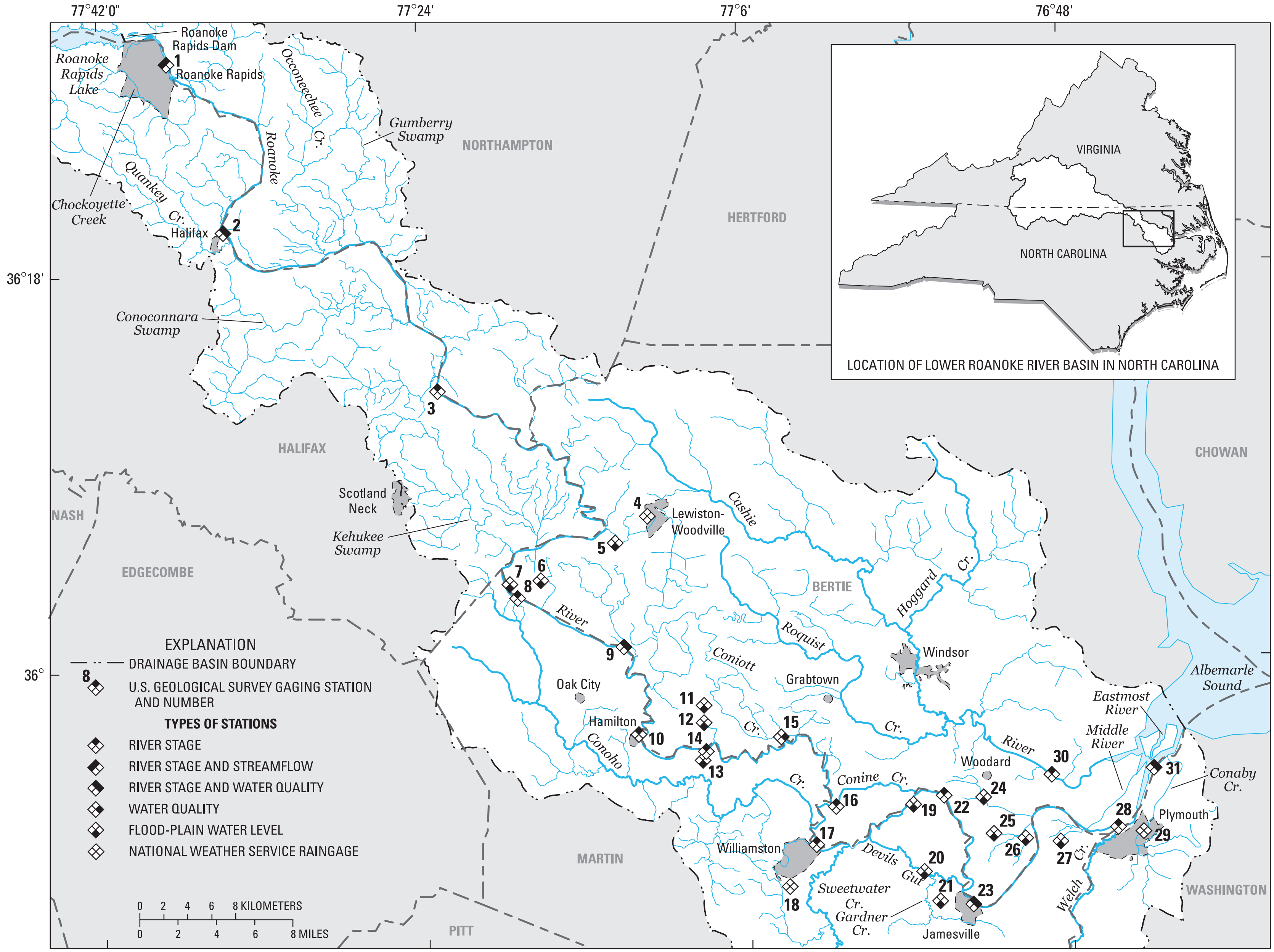
Purpose and Scope

This report describes temporal and spatial variations of floodplain and river water levels at four locations in the lower Roanoke River corridor and characterizes DO conditions in the river at five sites. Both water levels and DO concentrations are characterized with regard to temporal variations at a site and variations among sites. The relations of streamflow and river stage to floodplain water levels are described, and results are placed in the context of previous studies. Instream DO concentrations are characterized with regard to river flow and floodplain water levels, and results from this study are compared with previous monitoring information.

Analyses in the report are based primarily on data collected by the USGS at 1 streamflow measurement site, 13 river stage sites, 13 floodplain water-level sites, and 5 in situ water-quality monitoring sites. Precipitation data from three National Weather Service raingages and previously collected flow and water-quality data also are used in the analyses. River stage and floodplain water-level data for this study were collected during 1997–2000, and in situ water-quality data were collected during 1998–2001. Streamflow and rainfall data were available for the entire 1997–2001 study period.

Study Area

The study area is in the Roanoke River basin from Roanoke Rapids Dam to the mouth of the river, a distance of about 220 river km (fig. 2). The Roanoke River drainage area at Roanoke Rapids Dam is 21,810 km^2 (square kilometers), and the drainage area at the mouth of the river is 25,430 km^2. Major tributaries to the river in this reach include the following, in downstream order: Chockoyette Creek (56 km^2), Quankey



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1990
National Hydrologic Data 1:100,000
U.S. Geological Survey, 1:100,000 scale

Figure 2. U.S. Geological Survey and National Weather Service data-collection sites in the Roanoke River basin downstream from Roanoke Rapids Dam.

Creek (90 km^2), Occoneechee Creek (73 km^2), Gumberry Swamp (89 km^2), Conoconnara Swamp (127 km^2), Kehukee Swamp (84 km^2), Conoho Creek (322 km^2), Welch Creek (117 km^2), and the Cashie River (793 km^2), which joins the Roanoke River in a distributary near study site 31 (fig. 2). Together, these nine tributaries drain about half of the 3,620-km^2 catchment between Roanoke Rapids Dam and Albemarle Sound.

No impoundments or major diversions are in the lower Roanoke River. Total surface-water withdrawals in the lower Roanoke River basin, excluding the Cashie River basin, averaged 4.8 m^3/s (cubic meters per second) in 2000; an additional 0.2 m^3/s of water was withdrawn from the Cashie River, and about 0.2 m^3/s was withdrawn from the ground-water system in the basin (North Carolina Department of Environment and Natural Resources, 2001). The largest surface-water withdrawals in the basin were made by Champion International at Roanoke Rapids (1.1 m^3/s) and Weyerhaeuser (2.9 m^3/s; North Carolina Department of Environment and Natural Resources, 2001), together accounting for about 80 percent of the surface-water withdrawals in 2000. Wastewater discharges in the Roanoke River basin downstream from Roanoke Rapids Dam averaged 3.6 m^3/s in 2000 (J. Phillips, North Carolina Division of Water Quality, written commun., October 29, 2001); total permitted discharge was about 5 m^3/s (North Carolina Department of Environment and Natural Resources, 2001). At low flows, surface-water withdrawals from the river can equal nearly 20 percent of the total flow, although most of the withdrawals are returned to the river as wastewater. For example, during the 1997–2001 study period, the lowest observed instantaneous flow at the Roanoke Rapids gage (site 1, fig. 2) was 26.9 m^3/s; the highest flow at this site was 1,017 m^3/s, and the median flow was 88.2 m^3/s.

In 1997, forests composed 63.4 percent of the basin, which includes 470 km^2 of drainage area between Gaston Dam and Roanoke Rapids Dam (North Carolina Department of Environment and Natural Resources, 2001). The other major land use in the basin was cultivated cropland, which accounted for 24.4 percent of the land use. Urban or developed areas accounted for 4.2 percent of the land use. As in much of the Coastal Plain of North Carolina, land in the lower Roanoke River basin has been ditched and drained to accommodate agriculture and silviculture. These hydromodifications, including some ditches and canals that breach the natural levee along the Roanoke River, result in lower water tables and more rapid drainage of land than would occur under natural conditions. Moreover, the breaches in the natural river levee allow more rapid and extensive inundation of the floodplain than would occur naturally because water can enter the floodplain at lower river stages than if the levee were intact.

The 1990 population in the area was 119,578, which was an increase of less than 2 percent from 1980. Population density was about 38 persons per km^2 (North Carolina Department of Environment and Natural Resources, 2001), compared to a 1990 statewide average of 48 persons per km^2 (North Carolina Department of Environment and Natural Resources, 1999).

In 2000, there were 4 registered cattle, 1 poultry, and 22 swine operations in the Roanoke River basin downstream from Gaston Dam (North Carolina Department of Environment and Natural Resources, 2001). Most of these operations were located between Roanoke Rapids Dam and Hamilton (fig. 2). Swine populations in the basin increased about 70 percent between 1994 and 1998; poultry populations increased about 7 percent, and the cattle population was unchanged.

The lower Roanoke River flows through a floodplain of "national significance" (Manooch and Rulifson, 1989). The floodplain, which covers an area of about 610 km^2 (Rice and Peet, 1997), "contains the largest intact and least disturbed bottomland hardwood and cypress-tupelo ecosystems on the Atlantic Coast of North America" (North Carolina Department of Environment and Natural Resources, 2001). The highest density of nesting birds in North Carolina is located in the floodplain, and American bald eagles winter along the river. The river serves as a spawning and nursery area for several anadromous fish species, including striped bass, American shad, hickory shad, blueback herring, alewife, and possibly the endangered shortnose sturgeon. About 210 km^2 of land in the floodplain is in public ownership or under conservation easement (The Nature Conservancy, 2002).

The climate of the study area is classified as humid subtropical, with mild winters and generally abundant moisture throughout the year. At Lewiston (site 4, fig. 2), the monthly mean temperature ranges from 4.7 °C (degrees Celsius) in January to 25.8 °C in July; farther east at Plymouth (site 29, fig. 2), temperatures are slightly warmer with an annual mean temperature of 16.7 °C compared to an annual mean temperature of 15.3 °C at Lewiston (National Oceanic and Atmospheric Administration, 2002). Annual average precipitation at Lewiston is 1,201 mm (millimeters) and 1,321 mm at Plymouth (National Oceanic and Atmospheric Administration, 2002). The lowest mean monthly precipitation is in November (69 mm and 81 mm at Lewiston and Plymouth, respectively). Mean monthly precipitation is highest in the summer—137 mm in July at Lewiston and 142 mm in August at Plymouth. Nine of the 13 largest rainfall events from 1930 to 1993 occurred during the months of August–September (Konrad, 1998).

In an analysis of climate data for the period 1949−98, Boyles (2000) reported that minimum daily temperatures generally increased statewide during the period, with an increase of about 1.3 °C at Plymouth. Boyles also reported increasingly drier springs (April−June) and wetter winters (January−March), in slight contrast to earlier findings of wetter springs and drier summers during the 20th century (Stahle and Cleaveland, 1992). Boyles (2000) estimated that average annual rainfall increased between about 1 and 3 percent in the lower Roanoke River basin during 1949−98.

Acknowledgments

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Data

Hydrologic data were collected in the lower Roanoke River corridor from a USGS network of sites that included 1 streamflow-measurement site, where stage also was measured; 13 river-stage sites; 5 water-quality monitoring sites; and 13 floodplain water-surface-elevation sites (fig. 2; table 1). Installation and operation of the gages were in accordance with USGS standards described in Buchanan and Somers (1969, 1982); Rantz and others (1982); Kennedy (1983, 1984, 1990); and Wagner and others (2000).

Streamflow

Continuous streamflow data were collected at Roanoke Rapids on the Roanoke River (site 1) about 3 km downstream from the Roanoke Rapids Dam (fig. 2; table 1). Stage was recorded at 15-minute intervals. Streamflow routinely was measured, and a stage-discharge rating curve was developed for computation of streamflow from measured stage. Hourly and daily mean streamflow from the Roanoke Rapids gage were used in the analyses described in this report. The Roanoke Rapids gage is the only streamflow measurement station in the lower Roanoke River.

River Stage and Floodplain Water Level

In addition to the streamgage at Roanoke Rapids, river stage was measured at 15-minute intervals at 11 sites on the Roanoke River, 1 site on Conine Creek, and 1 site on the Cashie River (fig. 2; table 1). Stage was measured in meters above sea level relative to National Geodetic Vertical Datum of 1929 (NGVD29). Hourly and daily mean river stages are used in this report.

Water level was measured at gages located along four floodplain transects oriented approximately perpendicular to the main stem of the Roanoke River (fig. 2; table 1). Each transect had three or four water-level gages, and at least one river-stage gage was associated with each transect. Water level at each floodplain gage, whether above or below the land surface, was recorded at 15-minute intervals; hourly and daily mean water levels are used in this report. Data collected at these sites are reported relative to sea level (NGVD29) and to the land surface at the gage.

A static global positioning system (GPS) was used to determine the land-surface elevation at locations where no elevation marks were available. The GPS incorporates satellite technology to determine vertical position from known benchmarks or reference points. The accuracy of the calculated elevation is plus or minus 10 cm (centimeters) of the actual elevation and is based on NGVD29. Horizontal coordinate information is referenced to North American Datum of 1983 (NAD83).

Water Quality

<u>In situ monitoring</u>—Water-quality data were collected at five sites along the Roanoke River (fig. 2; table 1). Specific conductance, pH, water temperature, and DO concentration were measured at 15-minute intervals using an in situ multiparameter water-quality sensor connected to a datalogger. Sensors were located at approximately mid-depth for low-flow conditions at the four upstream-most sites. At the downstream-most site (NC-45 bridge, site 31), a sensor was installed about 0.6 m (meter) above the river bottom at the beginning of the study. In May 2000, a second sensor was installed about 4.2 m above the bottom. The sensors were serviced and replaced with a cleaned and calibrated unit approximately every 4 weeks. Maintenance, operation, calibration, and record computation were conducted using the methods described by Wagner and others (2000).

<u>Synoptic sampling</u>—On three separate occasions, physical characteristics (DO concentration, water temperature, specific conductance, and pH) were measured more or less synoptically at multiple locations along the Roanoke River, and water samples were collected for subsequent analysis of biochemical oxygen demand (BOD) concentration. Measurements were made and samples were collected on June 3 and September 3, 1998, and May 8–9, 2000.

Measurements were made at 29 locations on the Roanoke River and at 22 sites in tributaries that drain to the river (table 2). Tributary measurements were made within 100 m of the mouths of the respective tributaries. Measurements typically were made at mid-depth; at several sites, however, measurements were made near the surface, near the bottom, and

Table 1. U.S. Geological Survey streamflow, water level, and continuous water-quality monitoring gages, and National Weather Service raingages in the lower Roanoke River basin, North Carolina, 1996–2001.

[Floodplain transect and associated river gages are shaded. USGS, U.S. Geological Survey; river kilometer, the distance from the mouth of the Roanoke River to the station; km^2, square kilometer; NAD83, North American Datum of 1983; m, meter; ---, not applicable; Q, streamflow; Present, December 2002; WL, water level; WQ, continuous water quality, including pH, water temperature, specific conductance, and dissolved-oxygen concentration; RF, rainfall]

Station name (site number, shown in fig. 2)	USGS station number	Station type	River kilo-meter	Drainage area (km^2)	Latitude (NAD83)	Longitude (NAD83)	Land-surface elevation (m above mean sea level)	Vegetation type[a]	Data	Period of record
Roanoke River at Roanoke Rapids (site 1)	02080500	River	208	21,816	36°27'38"	77°38'03"	---	---	Q WL	Dec. 1911–Present Dec. 1911–Present
Roanoke River at Halifax (site 2)	0208062765	River	187	22,001	36°19'59"	77°34'58"	---	---	WQ WL	Mar. 1998–Present Nov. 1996–Present
Roanoke River at Scotland Neck (site 3)	02081000	River	156	22,557	36°12'35"	77°23'02"	---	---	WL	Mar. 1974–Present
Lewiston (site 4)	---	Raingage	---	---	36°08'	77°10'	15	---	RF	---
Big Swash 1 (site 5)	360533077131601	Floodplain transect	---	---	36°05'34"	77°13'15"	7.53	Pine	WL	May 1997–Jan. 2001
Big Swash 2 (site 6)	360356077172601	Floodplain transect	---	---	36°03'56"	77°17'26"	5.36	Tupelo-cypress	WL	May 1997–Jan. 2001
Big Swash 3 (site 7)	360347077191401	Floodplain transect	---	---	36°03'48"	77°19'13"	6.40	High-levee bottom-lands	WL	May 1997–Jan. 2001
Roanoke River near Hills Ferry (site 8)	0208102115	River	119	22,851	36°03'11"	77°18'45"	---	---	WL	Nov. 1996–Jan. 2001
Roanoke River near Oak City (site 9)	02081022	River	106	22,927	36°00'51"	77°12'54"	---	---	WQ WL	Mar. 1998–Present Jan. 1997–Present
Roanoke River at Hamilton (site 10)	02081028	River	97	23,117	35°56'51"	77°12'09"	---	---	WL	Aug. 1986–Present
Broadneck 1 (site 11)	355812077082301	Floodplain transect	---	---	35°58'10"	77°08'27"	3.60	Tupelo-cypress	WL	Apr. 1997–Jan. 2001
Broadneck 2 (site 12)	355722077082801	Floodplain transect	---	---	35°57'21"	77°08'29"	4.18	Mixed swamp forest flats	WL	Nov. 1996–Jan. 2001
Broadneck 3 (site 13)	355540077083401	Floodplain transect	---	23,127	35°55'41"	77°08'35"	3.75	High-levee bottom-lands	WL	Aug. 1996–Jan. 2001

Table 1. U.S. Geological Survey streamflow, water level, and continuous water-quality monitoring gages, and National Weather Service raingages in the lower Roanoke River basin, North Carolina, 1996–2001.—Continued

[Floodplain transect and associated river gages are shaded. USGS, U.S. Geological Survey; river kilometer, the distance from the mouth of the Roanoke River to the station; km^2, square kilometer; NAD83, North American Datum of 1983; m, meter; ---, not applicable; Q, streamflow; Present, December 2002; WL, water level; WQ, continuous water quality, including pH, water temperature, specific conductance, and dissolved-oxygen concentration; RF, rainfall]

Station name (site number, shown in fig. 2)	USGS station number	Station type	River kilo-meter	Drainage area (km^2)	Latitude (NAD83)	Longitude (NAD83)	Land-surface elevation (m above mean sea level)	Vegetation type[a]	Data	Period of record
Roanoke River near Hamilton (site 14)	0208102925	River	95	23,132	35°56'03"	77°08'23"	---	---	WL	Apr. 1996–Oct. 1999
Roanoke River near Grabtown (site 15)	0208102855	River	74	23,213	35°56'40"	77°04'10"	---	---	WQ	Jan. 1998–Present
Roanoke River at Williamston (site 16)	02081054	River	58	23,595	35°51'41"	77°02'19"	---	---	WL	Dec. 1985–Present
Conine Creek at US 13/17 (site 17)	0208108600	River	---	---	35°53'25"	77°01'10"	---	---	WL	Aug. 1996–Jan. 2001
Williamston (site 18)	---	Raingage	---	---	35°51'	77°02'	6	---	RF	---
Devils Gut 1 (site 19)	355326076565301	Floodplain transect	---	---	35°53'27"	76°56'52"	0.87	Maple, green ash bottom-lands	WL	Aug. 1996–Jan. 2001
Devils Gut 2 (site 20)	355024076562301	Floodplain transect	---	---	35°50'25"	76°56'18"	0.51	Tupelo-cypress	WL	Aug. 1996–Jan. 2001
Devils Gut 3 (site 21)	354900076554101	Floodplain transect	---	---	35°49'04"	76°55'28"	0.53	Tupelo-cypress	WL	Aug. 1996–Jan. 2001
Roanoke River near Woodard (site 22)	0208108650	River	44	23,905	35°53'51"	76°55'12"	---	---	WL	Aug. 1996–Jan. 2001
Roanoke River at Jamesville (site 23)	02081094	River	31	24,056	35°48'49"	76°53'37"	---	---	WQ	Mar. 1998–Present
									WL	Oct. 1990–Sept. 1993; Aug. 1996–Present

Table 1. U.S. Geological Survey streamflow, water level, and continuous water-quality monitoring gages, and National Weather Service raingages in the lower Roanoke River basin, North Carolina, 1996–2001.—Continued

[Floodplain transect and associated river gages are shaded. USGS, U.S. Geological Survey; river kilometer, the distance from the mouth of the Roanoke River to the station; km^2, square kilometer; NAD83, North American Datum of 1983; m, meter; ---, not applicable; Q, streamflow; Present, December 2002; WL, water level; WQ, continuous water quality, including pH, water temperature, specific conductance, and dissolved-oxygen concentration; RF, rainfall]

Station name (site number, shown in fig. 2)	USGS station number	Station type	River kilometer	Drainage area (km^2)	Latitude (NAD83)	Longitude (NAD83)	Land-surface elevation (m above mean sea level)	Vegetation type[a]	Data	Period of record
Cow Swamp 1 (site 24)	355312076533601	Floodplain transect	---	---	35°53'44"	76°52'57"	2.49	Young forest	WL	May 1997–Sept. 2000
Cow Swamp 2 (site 25)	355205076522501	Floodplain transect	---	---	35°52'04"	76°52'24"	0.44	Swamp blackgum	WL	Aug. 1996–Jan. 2001
Cow Swamp 3 (site 26)	355149076504001	Floodplain transect	---	---	35°51'50"	76°50'39"	0.44	Swamp blackgum	WL	Aug. 1996–Jan. 2001
Cow Swamp 4 (site 27)	355140076484201	Floodplain transect	---	---	35°51'41"	76°48'40"	0.44	---	WL	Aug. 1996–Jan. 2001
Roanoke River at Plymouth (site 28)	0208114055	River	13	24,269	35°52'00"	76°45'18"	---	---	WL	Aug. 1996–Sept. 2001
Plymouth (site 29)	---	Raingage	---	---	35°52'	76°39'	6	---	RF	---
Cashie River at San Souci Ferry (site 30)	0208113400	River	---	---	35°54'43"	76°49'03"	---	---	WL	Oct. 1990–Sept. 1993; Aug. 1996–Jan. 2001
Roanoke River at NC-45 Bridge (site 31)	0208114150	River	2.6	25,143	35°54'54"	76°43'22"	---	---	WQ	Mid-depth, Nov. 1997–Present Top, May 2000–Present
									WL	Oct. 1990–Sept. 1993; Aug. 1996–Present

[a] Vegetation information is from Townsend and Walsh (1997a, b).

Table 2. Locations for synoptic measurements of dissolved-oxygen concentration and water sampling for analysis of biochemical oxygen demand on June 3 and September 3, 1998, and May 8–9, 2000, in the Roanoke River basin, North Carolina.

[USGS, U.S. Geological Survey; NAD83, North American Datum of 1983; NC, State road; WWTP, wastewater-treatment plant]

Location	USGS station number	River kilometer[a]	Latitude (NAD83)	Longitude (NAD83)
Roanoke River main-stem measuring stations				
At NC-48 in Roanoke Rapids	362854077384400	210.0	36°28'54"	77°38'44"
At Highway 158 near Weldon	362551077352700	205.2	36°25'51"	77°35'27"
Downstream from Trouble Field Creek and upstream from Mush Island Gut	362400077324700	195.2	36°24'00"	77°32'47"
At Halifax	0208062765	186.9	36°19'59"	77°34'58"
Upstream from Caledonia Prison WWTP	361930077264000	175.0	36°19'30"	77°26'40"
At Caledonia Prison	361755077251500	171.0	37°17'55"	77°25'15"
Downstream from Caledonia Prison WWTP	361559077243900	165.6	36°15'59"	77°24'39"
At Highway 258 near Scotland Neck	02081000	156.0	36°12'35"	77°23'02"
Near Kelford at railroad bridge	360934077164200	143.9	36°09'34"	77°16'42"
Near Buzzards Point (downstream from outfall and upstream from Flag Run Gut)	360703077144000	135.5	36°07'03"	77°14'40"
Downstream from Flag Run Gut	360608077140000	132.2	36°06'08"	77°14'00"
Downstream from Buzzard Point and upstream from Cypress Swamp	360555077161000	125.8	36°05'55"	77°16'10"
Near Hills Ferry (at gage)	0208102115	118.5	36°03'10"	77°18'46"
At Highways 42-11 bridge near Oak City (at gage)	02081022	106.0	36°00'51"	77°12'54"
Oxbow above Hamilton	35573007112400	102.7	35°57'30"	77°11'24"
At Hamilton boat ramp (at gage)	02081028	97.0	35°56'51"	77°12'09"
Near Hamilton (at gage)	0208102925	95.0	35°56'03"	77°08'23"
At powerline crossing upstream from Coniott Creek	355541077055200	81.3	35°55'41"	77°05'52"
Near Grabtown (at gage)	0208102855	74.0	35°56'40"	77°04'10"
Upstream from Conine Creek	355450077013900	68.5	35°54'50"	77°01'39"
At Williamston (at gage)	02081054	58.0	35°51'41"	77°02'19"
Downstream from Sweetwater Creek and upstream from Devils Gut	355136077001200	55.5	35°51'36"	77°00'12"
Near Woodard (at gage)	0208108650	44.2	35°53'51"	76°55'12"
At Jamesville (at gage)	02081094	31.0	35°48'49"	76°53'37"
At powerline crossing downstream from Jamesville	355308076500100	21.1	35°53'08"	76°50'01"
Downstream from Middle River and upstream from Huff Island	355202076470300	14.2	35°52'02"	76°47'03"
At Plymouth (at gage)	0208114055	13.0	35°52'00"	76°45'18"
Upstream from Highway 45 bridge	355404076432300	5.2	35°54'04"	76°43'23"
At Highway 45 bridge (at gage)	0208114150	2.6	34°54'54"	76°43'22"

Table 2. Locations for synoptic measurements of dissolved-oxygen concentration and water sampling for analysis of biochemical oxygen demand on June 3 and September 3, 1998, and May 8–9, 2000, in the Roanoke River basin, North Carolina.—Continued

[USGS, U.S. Geological Survey; NAD83, North American Datum of 1983; NC, State road; WWTP, wastewater-treatment plant]

Location	USGS station number	River kilometer[a]	Latitude (NAD83)	Longitude (NAD83)
Tributary measuring stations				
Mush Island Gut near mouth	362246077325000	196.6	36°22'46"	77°32'50"
Quankey Creek near mouth	361931077343300	186.1	36°19'31"	77°34'33"
Occoneechee Creek near mouth	361856077291700	178.9	36°18'56"	77°29'17"
Gumberry Swamp near mouth	361915077281700	177.3	36°19'15"	77°28'17"
Conoconnara Swamp near mouth	361548077243600	165.2	36°15'48"	77°24'36"
Cypress Swamp (upstream from Sandy Run)	361055077184100	155.6	36°10'55"	77°18'41"
Sandy Run near mouth	361007077153300	146.0	36°10'07"	77°15'33"
Cypress Swamp (downstream from Buzzards Point)	360526077174300	125.6	36°05'26"	77°17'43"
Kehukee Swamp near mouth	360511077185800	123.7	36°05'11"	77°18'58"
Kiahs Gut near mouth	360212077172900	116.1	36°02'12"	77°17'29"
Unnamed tributary upstream from Highways 42-11 bridge near mouth	360057077130400	110.2	36°00'57"	77°13'04"
Unnamed tributary downstream from Highways 42-11 bridge near mouth	360024077122100	108.5	36°00'24"	77°12'21"
Indian Creek near mouth upstream from Hamilton	355904077313100	106.5	35°59'04"	77°31'31"
Black Gut Creek near mouth (drains Broadneck Swamp)	355627077075900	97.1	35°56'27"	77°07'59"
Coniott Creek near mouth	355638077041400	76.1	35°56'38"	77°04'21"
Conoho Creek near mouth	355232077024200	61.3	35°52'32"	77°02'42"
Sweetwater Creek near mouth	355138077003100	56.5	35°51'38"	77°00'31"
Conine Creek near mouth (downstream from Devils Gut)	355259076580400	51.5	35°52'59"	76°58'04"
Devils Gut near mouth	354942076541400	34.4	35°49'42"	76°54'14"
Broad Creek near mouth	355222076503200	22.3	35°52'22"	76°50'32"
Warren Neck Creek near mouth	355209076473000	14.8	35°52'09"	76°47'30"
Welch Creek at bridge	355149076455000	12.6	35°51'49"	76°45'50"

[a]River kilometer for tributary stations identifies location of confluence of tributary with the main stem of the Roanoke River.

at mid-depth. Water samples for subsequent analysis of BOD were collected just below the water surface at a subset of the measurement sites. Samples were analyzed at the North Carolina Division of Water Quality laboratory using standard techniques.

Precipitation

Daily precipitation data were obtained from three National Weather Service (NWS) climatic index stations located in the general vicinity of the study area (fig. 2; National Oceanic and Atmospheric Administration, 1997–2001). These stations were located at Lewiston (site 4; NWS station ID 314962), Williamston (site 18; NWS station ID 319440), and Plymouth (site 29; NWS station ID 316853). Rainfall values were reported as daily totals.

Point-Source Wastewater Discharges

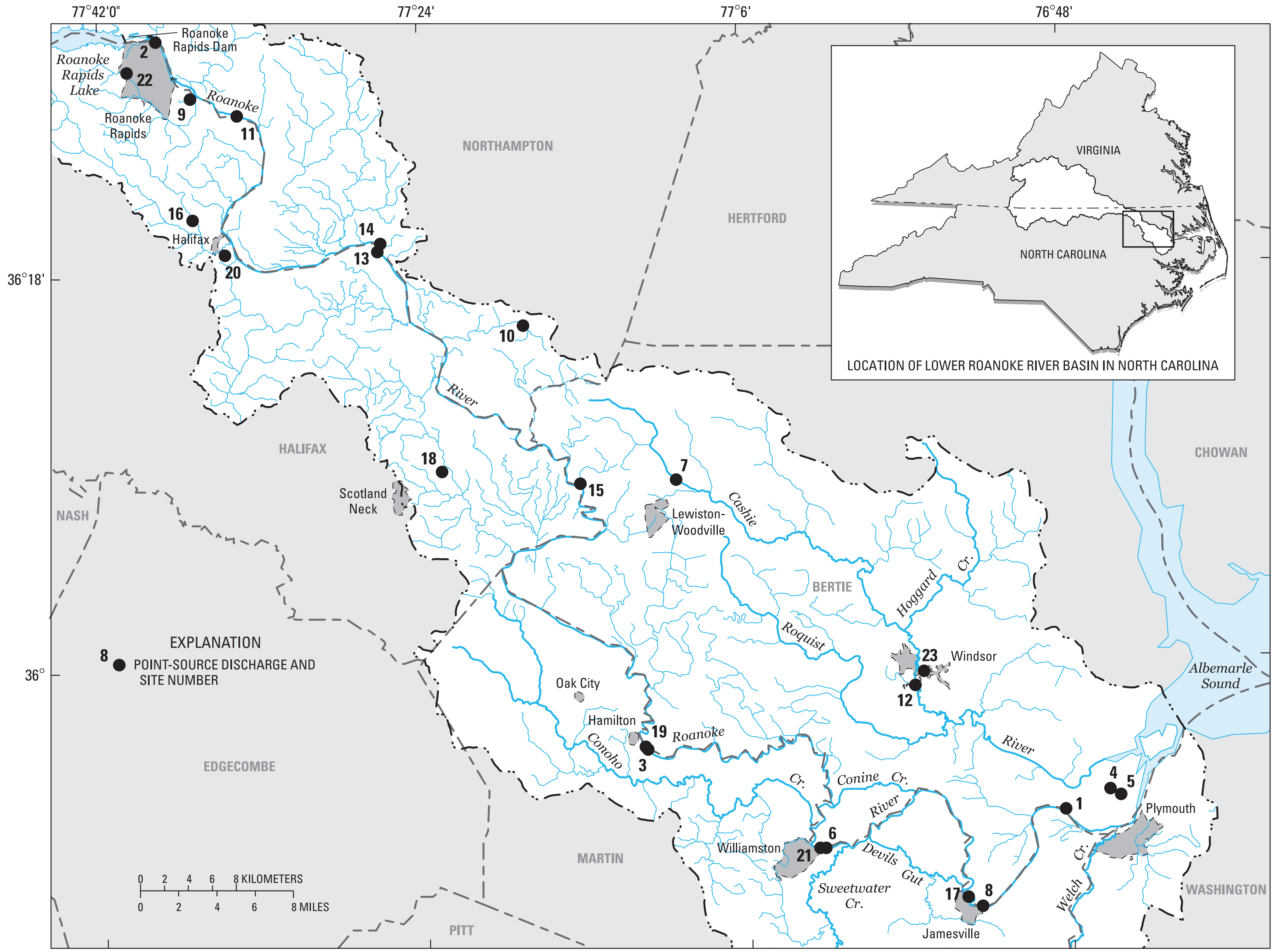
Monthly compliance monitoring records for 23 individual wastewater dischargers (table 3; fig. 3) in the Roanoke River basin downstream from Roanoke Rapids Dam were provided by the North Carolina Division of Water Quality (J. Phillips, North Carolina Division of Water Quality, written commun., October 29, 2001). Monthly mean flows were available for all dischargers; monthly mean BOD concentrations were available for 19 of the 23 dischargers, including all of the large dischargers; and DO, total nitrogen (N), ammonia-N, and total phosphorus concentrations were available for selected dischargers (table 3).

Most of the point-source flow to the Roanoke River is from two dischargers (fig. 4A). During 1996–2000, 85 percent of the reported point-source discharge to the Roanoke River was from two paper mills. These two mills delivered 91 percent of the point-source BOD load to the river during the same period (fig. 4B). During 1996–2000, the minimum monthly BOD load always occurred during August, and the August load increased from 3,008 kg (kilograms) in 1996 to 4,042 kg in 2000.

Table 3. Flow and reported constituents measured by permitted point-source dischargers in the Roanoke River downstream from Roanoke Rapids Dam, North Carolina.

[DO, dissolved oxygen; BOD, biochemical oxygen demand; N, nitrogen; NH_3-N, ammonium reported as nitrogen; TP, total phosphorus; ---, not measured; WTP, water-treatment plant; WWTP, wastewater-treatment plant; NCDOC, North Carolina Department of Correction; BOE, Board of Education]

Facility	Site no. (fig. 3)	Flow	Reported constituents				
			DO	BOD	Total-N	NH_3-N	TP
Weyerhaeuser, Plymouth Mill (pipe 1)	1	X	X	X	X	X	X
Weyerhaeuser, Plymouth Mill (pipe 2)	1	X	---	---	---	---	---
Weyerhaeuser, Plymouth Mill (pipe 5)	1	X	---	---	---	---	---
International Paper, Halifax (pipe 1)	2	X	X	X	X	---	X
International Paper, Halifax (pipe 2)	2	X	---	---	---	---	---
International Paper, Halifax (pipe 3)	2	X	---	---	---	---	---
International Paper, Halifax (pipe 4)	2	X	---	---	---	---	---
Alamac Knit Fabrics, Hamilton	3	X	---	X	X	---	X
Plymouth WTP	4	X	---	---	---	---	---
Plymouth WWTP	5	X	---	X	X	X	X
Williamston WWTP	6	X	---	X	X	X	X
Lewiston Woodville WWTP	7	X	X	X	X	X	X
Liberty Fabrics	8	X	---	X	X	---	X
Roanoke Rapids WWTP	9	X	X	X	X	X	X
Rich Square WWTP	10	X	X	X	X	X	X
Weldon WWTP	11	X	---	X	X	X	X
Windsor WWTP	12	X	X	X	X	X	X
NCDOC, Caledonia	13	X	---	X	X	X	X
NCDOC, Odom Correctional Institution	14	X	X	X	X	X	X
Perdue Farms, Lewiston	15	X	---	X	X	X	X
NCDOC, Halifax Correctional Center	16	X	X	X	---	X	---
Jamesville WWTP	17	X	---	X	X	X	X
Halifax County BOE, Bakers Elementary	18	X	X	X	---	X	---
Hamilton WWTP	19	X	X	X	X	X	X
Halifax WWTP	20	X	X	X	X	X	X
United Organics Corporation	21	X	---	---	---	---	---
Panda Rosemary	22	X	---	---	---	---	---
Williford Logging	23	X	---	---	---	---	---



Base from digital files of:
U.S. Department of Commerce, Bureau of Census,
1990 Precensus TIGER/Line Files-Political boundaries, 1990
National Hydrologic Data 1:100,000
U.S. Geological Survey, 1:100,000 scale

Figure 3. Permitted point-source dischargers in the Roanoke River basin downstream from Roanoke Rapids Dam.

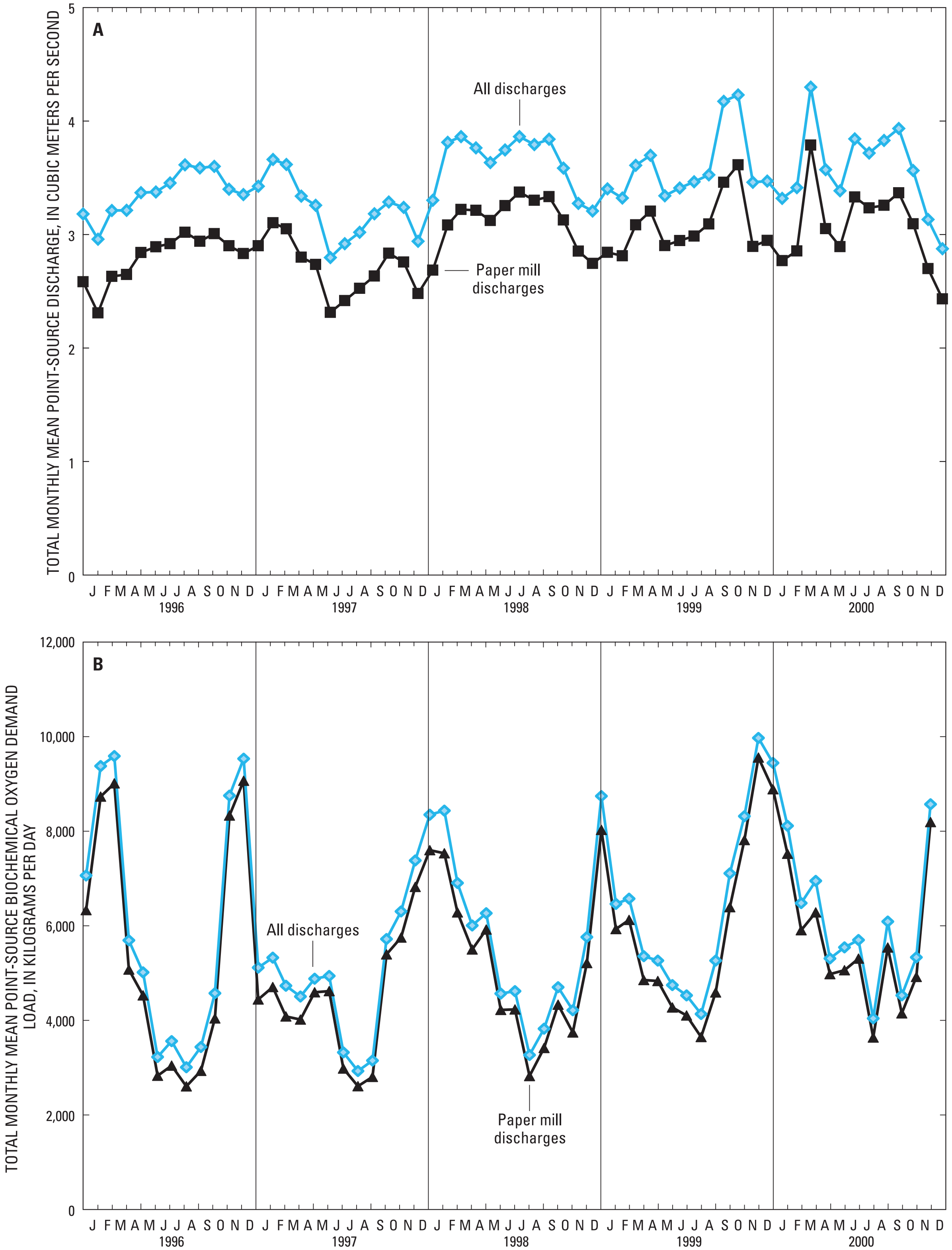


Figure 4. Reported (A) monthly mean flows and (B) biochemical oxygen demand loads to the Roanoke River, North Carolina, from permitted point-source discharges, 1996–2000.

Precipitation and Streamflow, 1997–2001

Rainfall in the lower Roanoke River basin generally was lower than normal during 1997–2001 (fig. 5). Normal precipitation was based on the climatic period 1971–2000 (National Oceanic and Atmospheric Administration, 2002). During the study, November 1997 to about June 1998, depending on the station, was the only sustained period of greater-than-normal monthly precipitation at all three rainfall stations, although precipitation amounts were near or slightly greater than average during April–September 2000. If Hurricane Floyd rainfall totals (September 1999) are removed from the record, the cumulative departure of the rainfall amounts from normal during 1997–2001 is between 339 mm (Williamston) and 906 mm (Plymouth), or between 25 and 70 percent of the annual average rainfall at the three stations.

The largest daily rainfall amounts at all three stations occurred during Hurricane Floyd (September 14–16, 1999) when Lewiston, for example, received 460 mm of rainfall and Williamston received 375 mm. High daily rainfall totals also were measured during October 17–18, 1999, when Hurricane Irene passed east of the North Carolina coast, and June 15–17, 2001, when 265 mm of rainfall occurred at Williamston as Tropical Storm Allison passed through the area from southwest to northeast. Rainfall amounts greater than 1 mm were measured on 25 percent of the days during 1997–2001 at Lewiston and 29 percent of the days at Williamston. Daily rainfall amounts greater than 25 mm occurred on 61 separate occasions during this period at Lewiston and 65 different days at Williamston or, on average, about once per month.

Streamflow has been measured continuously at Roanoke River at Roanoke Rapids since 1911 (table 1; fig. 2). Since 1950, streamflow in the Roanoke River has been regulated by a number of reservoirs (fig. 1). The three downstream-most reservoirs, Kerr Lake, Lake Gaston, and Roanoke Rapids Lake, were completed in 1950, 1962, and 1955, respectively. Dominion Generation operates Gaston Dam and Roanoke Rapids Dam, and the U.S. Army Corps of Engineers operates Kerr Dam. Flows through Gaston Dam and Roanoke Rapids Dam are largely governed by releases from Kerr Lake. Eighty-six percent (21,810 km^2) of the entire Roanoke River drainage basin (25,430 km^2) is upstream from Roanoke Rapids Dam, so releases through the Roanoke Rapids Dam typically compose a greater proportion of the total flow in the river than do inflows from local drainage downstream from the dam. Exceptions occur under flooding conditions, such as following Hurricane Floyd, when water typically is stored in the upstream reservoirs while local flooding downstream from Roanoke Rapids Dam abates.

The mean flow at Roanoke Rapids during calendar years 1997–2001 was 196 m^3/s, or 88 percent of the 1964–2001 mean of 223 m^3/s. (Although continuous streamflow records at Roanoke Rapids extend back to 1911, average flow conditions are calculated by using data beginning in 1964, when the three downstream-most reservoirs were in normal operation.) Annual mean flows in 1997 (239 m^3/s) and 1998 (306 m^3/s) were higher than average. The highest flows in early 1998 coincided with a period of higher-than-normal precipitation in the basin upstream from Kerr Dam. The highest total monthly precipitation for the months of January (202 mm) and February (203 mm) during the period 1971–2000 at Roanoke, Va., occurred in 1998, and January–May 1998 precipitation at Danville, Va., was 354 mm greater than normal, resulting in high flows in the lower Roanoke River (Southeast Regional Climate Center, 2003). Annual mean flows during 1999–2001, however, were much lower than average; the annual mean flow in 2001 was 65 percent of the mean flow during the 1997–2001 study period and 57 percent of the 1964–2001 mean flow.

Since 1964, flows typically have been higher during January–May than during the other months (fig. 6). Flows during 1997 and 1998 followed the typical seasonal pattern, although winter–spring flows were higher than normal, and summer–fall flows were lower than normal (fig. 6). Flows during February–May 1998 were about double average flows. The typical seasonal flow pattern was not present during 1999–2001, and monthly mean flows during all but 4 months of this period were lower than normal.

The median hourly flow during 1997–2001 was 88 m^3/s, and the median daily flow was 125 m^3/s, which is 73 percent of the 1964–2001 median daily flow of 171 m^3/s (fig. 7A). The lowest flows (less than about 80 m^3/s) occurred with about the same frequency during the study period and during the regulated flow period from 1964 to 2001 (fig. 7A). Flows in the range of 570–1,100 m^3/s occurred more frequently during 1997–2001 than during 1964–2001 as a result of the somewhat extended periods of high flows during January–May 1998 (figs. 6A, 7A). During the remaining 55 percent of the 1997–2001 study period, flows were low compared to the entire 1964–2001 regulated period.

On average, flows during the study period were much higher during the first half of the calendar year than during the last half of the year (fig. 7B). For example, hourly flows at the 80th percentile were more than 5 times as large during the first half of the year (January–June 15) than during the remainder of the year, and median hourly flows during January–March and April–June 15 were more than double median flows for other periods (fig. 7B). The lowest 40 percent of hourly flows occurred at about the same frequency for all periods except during the striped bass spawning season, when flows generally are maintained at 100 m^3/s or more. During the summer (June 16–September 1), when lower DO concentrations typically occur in North Carolina streams, hourly flows were quite low—only about 24 percent of the flows were in excess of 100 m^3/s. Flows during the striped bass spawning season (April 1–June 15, fig. 6B) did not exceed 720 m^3/s, but the lower flows (less than 200 m^3/s) were much more sustained than at other times of the year.

Flows in the lower Roanoke River are influenced heavily by hydropower peaking (or load-following) operations. Hydropower peaking at Roanoke Rapids Dam typically is characterized by brief periods (a few hours) of high flows, generally in

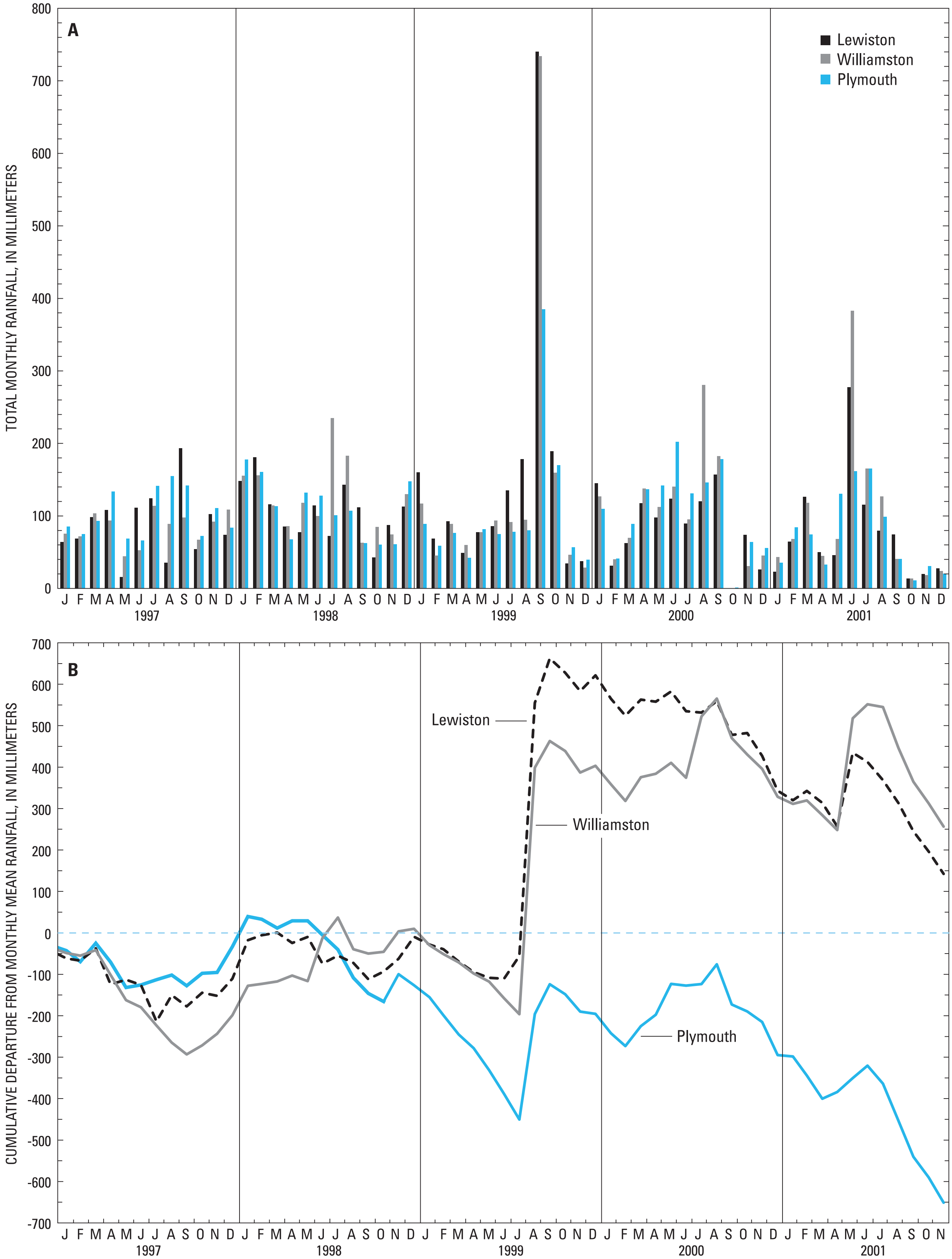


Figure 5. (A) Total monthly rainfall and (B) cumulative departure of monthly rainfall from 1971–2000 normal conditions during 1997–2001 at National Weather Service raingages at Lewiston (site 4), Williamston (site 18), and Plymouth (site 29), North Carolina.

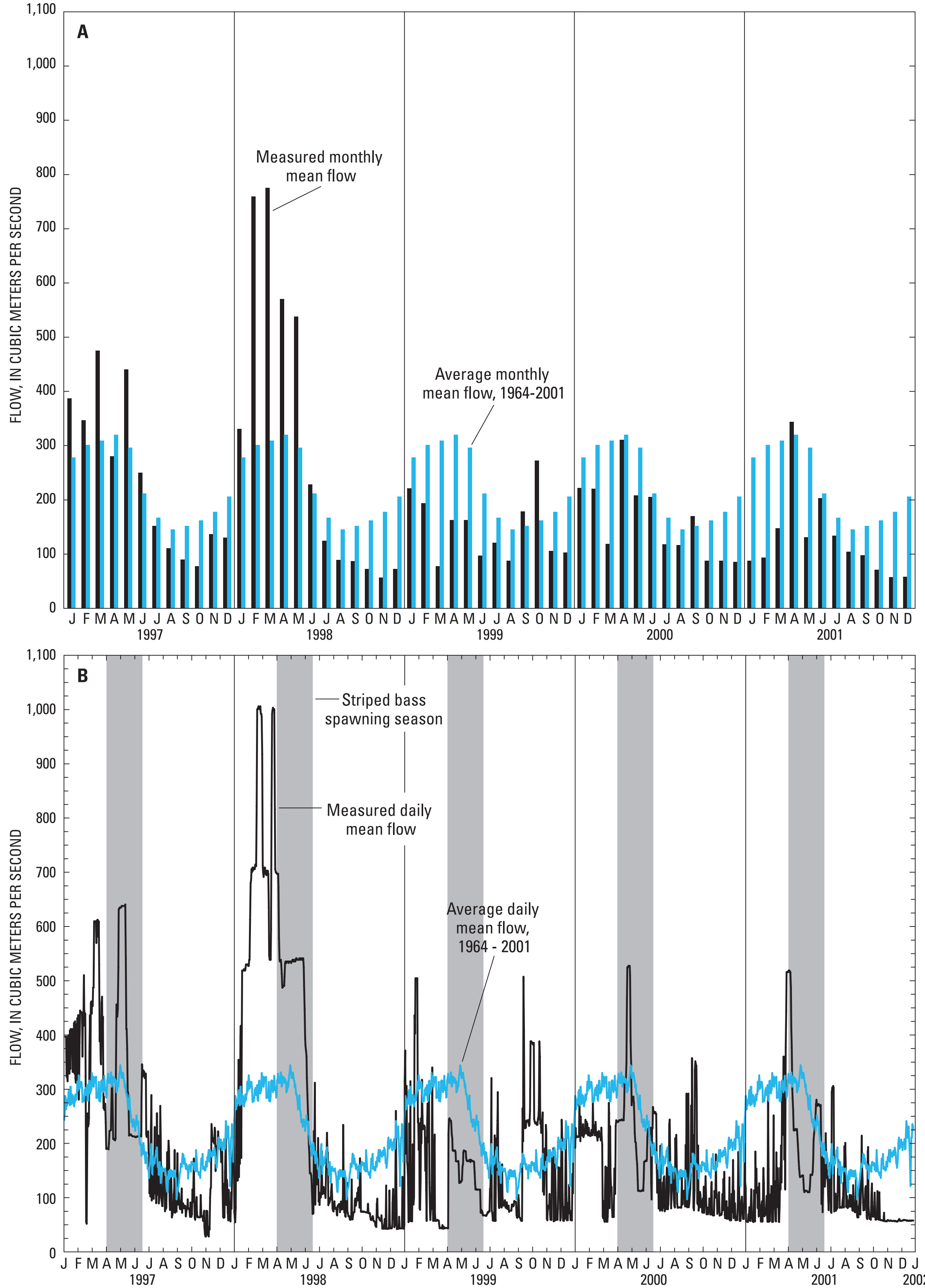


Figure 6. (A) 1997–2001 monthly mean flow and 1964–2001 average monthly mean flow, and (B) 1997–2001 daily mean flow and 1964–2001 average daily mean flow for the Roanoke River at Roanoke Rapids, North Carolina.

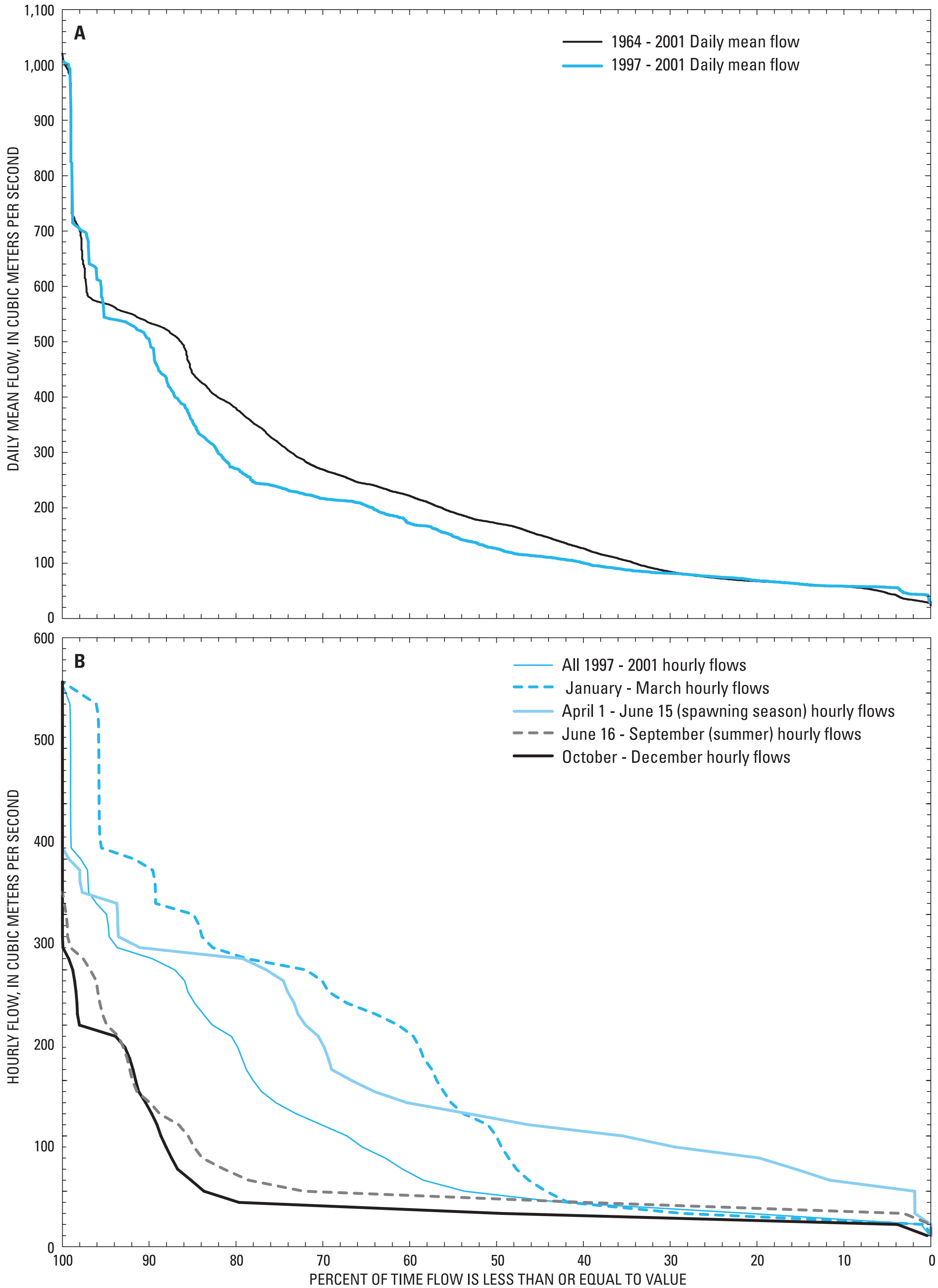


Figure 7. Duration of flows for the Roanoke River at Roanoke Rapids, North Carolina—(A) daily mean flows for 1964–2001 and 1997–2001, and (B) hourly flows for selected periods during 1997–2001.

the range of 225–550 m^3/s, followed by longer periods of lower flows. There are often two high-flow peaks per day (fig. 8). Daily mean flows on days when peaking occurs are much less than the maximum flow for the day and often less than half the daily peak flow (for example, fig. 8).

Since 1989, the U.S. Army Corps of Engineers and Dominion Generation, in cooperation with the North Carolina Wildlife Resources Commission, have operated a trial flow regime to enhance striped bass spawning success during the period April 1–June 15 (figs. 6B, 7B). The spawning-season flow regime is designed to simulate biweekly median pre-impoundment flows, with higher releases in April (a target of about 240 m^3/s in early April) gradually tapering off to lower releases in June (target flow of about 150 m^3/s by the end of June) and no hydropower peaking during the period (U.S. Army Corps of Engineers, 1995, 2001). Since implementation of the regime, in addition to a temporary Federal moratorium on harvesting, striped bass populations have recovered, and hickory shad (which spawn during March) populations have increased to historic levels (North Carolina Department of Environment and Natural Resources, 2001). All parties have agreed to continue to operate under the spawning-season flow regime to the extent possible.

An extensive fish kill occurred over an approximately 122-km reach of the Roanoke River in the summer of 1995, killing an estimated 7,000 striped bass and about 18,000 fish of other species (Kornegay and Jones, 1995). The fish kill occurred after releases from Roanoke Rapids Dam were reduced rapidly from a month-long period of 500-m^3/s flows to flows generally less than 100 m^3/s. Water accumulated in the backswamps during the high flows and became hypoxic during the hot summer days. This water subsequently drained rapidly to the river as flows declined, reducing DO concentrations in the river and resulting in the fish kill. In order to avoid such an event in the future, Dominion Generation, in cooperation with the North Carolina Wildlife Resources Commission and the U.S. Army Corps of Engineers, agreed to implement the "Roanoke River Betterment Plan" (see, for example, Fromm

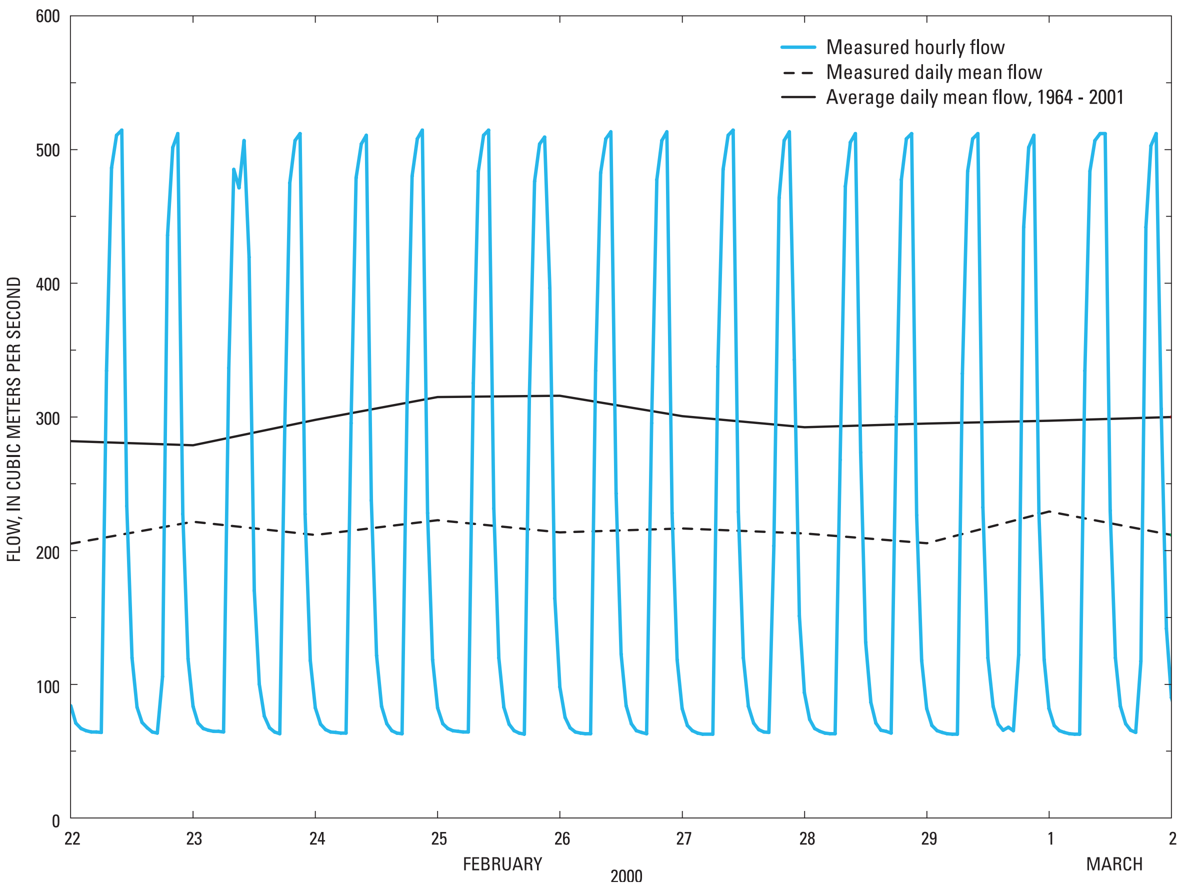


Figure 8. Hourly and daily mean flows at the Roanoke River at Roanoke Rapids, North Carolina, for February 22–March 1, 2000, and associated average daily mean flows calculated from 1964–2001 data.

and Lebo, 1997). According to this plan, reservoir releases will be stepped down over at least a 2-week period during any transition between flood-control (high) releases and hydropower-peaking operations during warm-weather months to allow backswamps to drain slowly and to provide sufficient river water to dilute swamp drainage. Based on DO and BOD data collected along the main stem of the river following Hurricane Fran in 1996, when flows were stepped down from about 1,000 m^3/s to 85 m^3/s over a 6-week period (longer than the original Betterment Plan), Fromm and Lebo (1997) concluded that the longer step-down period prevented the occurrence of extremely low DO concentrations in the river.

Backwater from Albemarle Sound affects flow in the Roanoke River downstream from at least Oak City (site 9, fig. 2; river kilometer 106; Bales and others, 1993). Consequently, flows in the river are not uniquely correlated with river stage throughout much of the lower Roanoke River (fig. 9). For example, during the study, a daily mean flow at Roanoke Rapids of 220 m^3/s (lagged by 2 days to account for travel time) occurred over a range in stage of 4.5 m at Oak City. Conversely, at a river stage of 3 m at Oak City, the 2-day lagged flow ranged from about 50 m^3/s to 290 m^3/s. At flows in the range of 570 to 1,000 m^3/s (fig. 9A), there was very little change in river stage at Oak City regardless of the flow magnitude. The poor relation between Roanoke Rapids flow (lagged by 2 days) and Oak City stage applies to all flows less than 570 m^3/s and cannot be attributed to additional inflow between Roanoke Rapids and Oak City because the drainage area increases only by about 5 percent between these two locations. Likewise, although there is some general relation between Roanoke Rapids flow and water level at Jamesville (site 23, fig. 2; river kilometer 31), the scatter in the relation is such that river stage at Jamesville cannot be reliably predicted from releases at Roanoke Rapids Dam (fig. 9B). The reason that flow and river stage are not related in the downstream-most 106 km of the Roanoke River, which includes three of the study floodplain transects, is that the changing water-level conditions in Albemarle Sound, governed by both wind and tides, result in a variable water-surface gradient in the river. As a result, flow at a given river stage varies, depending on the magnitude of the gradient. In addition to the backwater effects from Albemarle Sound on lower Roanoke River water levels, Lebo (1998) documented tidal fluctuations in river velocity at river kilometer 21, with a typical daily velocity range of 12 cm/s (centimeters per second), including the occurrence of some upstream-directed currents.

Tides at the mouth of the Roanoke River are well correlated with tides in Croatan Sound. There is about a 9-hr (hour) lag between the occurrence of high tide in Croatan Sound and high tide at the mouth of the Roanoke River, but the tidal amplitude at the mouth of the Roanoke River is generally the same as that in Croatan Sound—in the range of 0.1–0.15 m—although tides at the mouth of the Roanoke can be dampened slightly when flows are in excess of 280 m^3/s (Bales and others, 1993).

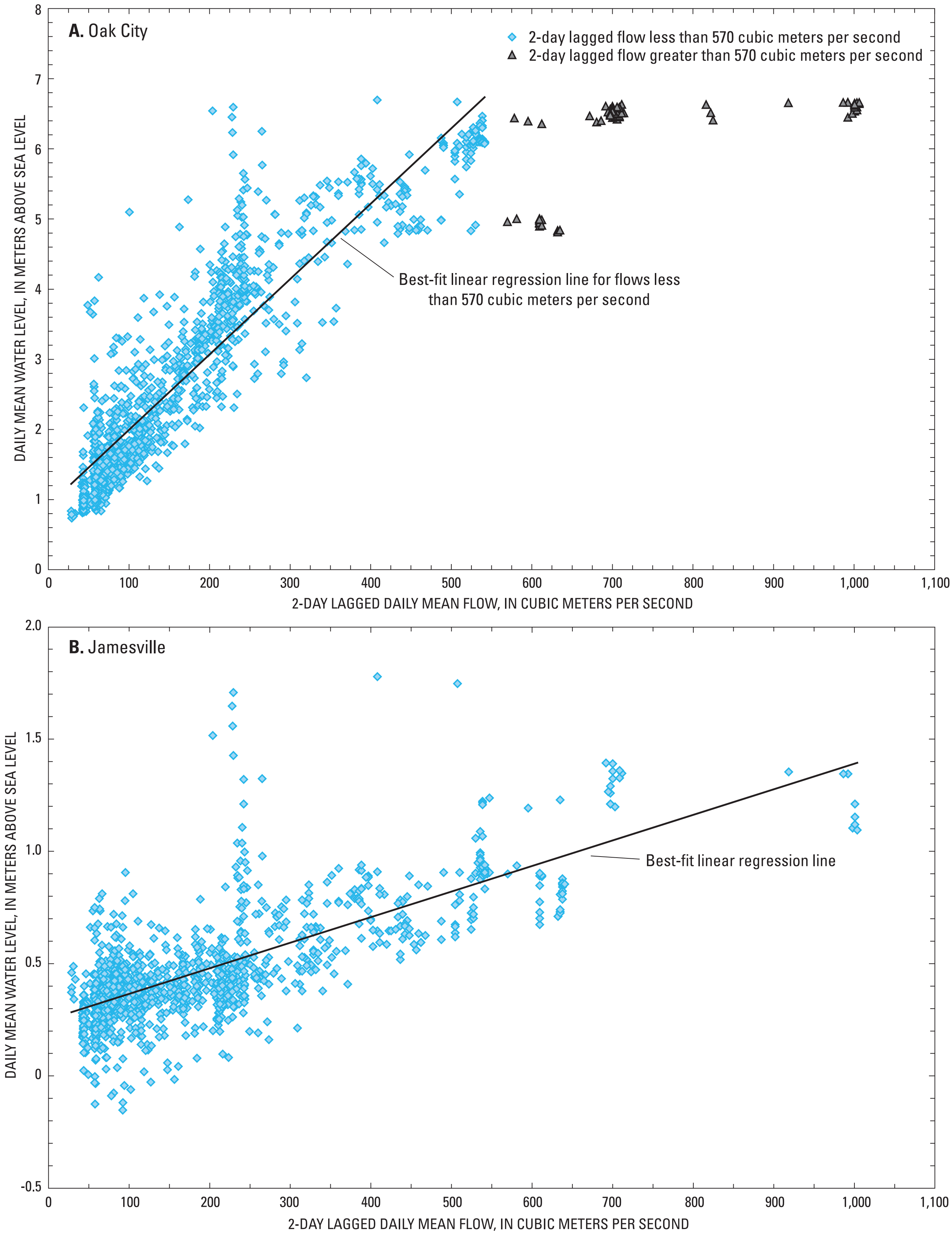


Figure 9. Relation of 2-day lagged daily mean flows at Roanoke River at Roanoke Rapids (site 1), to daily mean water levels at (A) Roanoke River at Oak City (site 9), and (B) Roanoke River at Jamesville (site 23), North Carolina.

Floodplain Water Levels, 1997–2000

Water-level characteristics in the four floodplain transects are described in this section. The temporal and spatial characteristics of floodplain water-level fluctuations and the relation of water levels to location, streamflow, river stage, and precipitation are described. A brief description of each transect precedes the discussion of water-level conditions.

Site Characteristics

Big Swash

The Big Swash transect terminated at the Hills Ferry (site 8; fig. 10) river-stage gage at river kilometer 119. The transect crossed portions of a "significant natural heritage area" in the lower Roanoke River corridor (North Carolina Department of Environment and Natural Resources, 2001). This area contains bottomland and swamp communities characterized by levee forests, backswamps, alluvial flats, sloughs, low and high ridges, and beaver ponds (North Carolina Department of Environment and Natural Resources, 2001).

Water level at Big Swash 1 (site 5, table 1; fig. 10) was seldom above the land surface during 1997–2000 (table 4; fig. 11). The land surface at Big Swash 1 was at least 1 m higher than at the other two Big Swash sites (table 4), and Big Swash 1 was flooded (water level was above land surface) less than 7 percent of the time during the study period, although the site was located within about 700 m of the Roanoke River. Vegetation at Big Swash 1 was predominantly loblolly pine (*Pinus taeda*), which is less tolerant of inundation than the water tupelo (*Nyssa aquatica*) and bald cypress (*Taxodium distichum*) at Big Swash 2 (fig. 10).

The land elevation at Big Swash 2 (site 6, table 1; fig. 10) was lower than at the other two Big Swash sites (table 4), and the site was flooded more frequently than Big Swash 1 but not as often as Big Swash 3 (site 7, table 4). For example, in 1999 when there was no loss of data at Big Swash 2 and 3, Big Swash 2 was inundated about 20 percent of the time, whereas Big Swash 3 was inundated 56 percent of the time. In 2000, Big Swash 2 was flooded 1 percent of the time while Big Swash 3 was flooded almost half the time (table 4; fig. 11). The inundation depth at Big Swash 3 generally was less than 0.3 m (table 4). Big Swash 3 is within 300 m of the river, whereas Big Swash 2 is more than 3 km from the river (fig. 10). This difference in proximity to the river is the reason for at least part of the difference in inundation characteristics at the two sites.

The land around Big Swash 3 was logged between December 1998 and March 1999. Some ditches were installed to drain water away from the site, and a few dirt roads were constructed. Some of the roads acted as dams, restricting the free movement of water through the floodplain. Water-level characteristics at Big Swash 3 likely were changed by this activity. In the late summer and fall of 1997 and 1998 the water level at Big Swash 3 was lower than at the other two Big Swash sites, but water levels in 2000 at Big Swash 3 were higher than at the other two sites. This difference probably is the result of reduced evapotranspiration from trees at Big Swash 3 relative to Big Swash 1 and 2 following logging at Big Swash 3.

Broadneck Swamp

Most of the Broadneck Swamp transect was within a tract of the Roanoke River National Wildlife Refuge. The swamp contains one of the largest swamp forests in the lower Roanoke River corridor, with bald cypress and water tupelo dominating the backswamp canopy, and one of the best mature natural levee forest communities in the lower Roanoke River corridor (North Carolina Department of Environment and Natural Resources, 2001).

Broadneck Swamp 1 (site 11, table 1; fig. 12), which is characterized by tupelo-cypress vegetation, was inundated almost continuously throughout the study (table 5; fig. 13), and inundation depths were greater than at the other two Broadneck sites. Broadneck Swamp 1 was located near a raised road bed, and the road probably acted as a dam that prevented water from freely draining away from Broadneck Swamp 1. It also is likely that water levels at Broadneck Swamp 1 were affected by a beaver dam (J. Richter, U.S. Fish and Wildlife Service, written commun., June 2003). Seventy percent of the time, the inundation depth at Broadneck Swamp 1 was between the land surface and 0.3 m, but 20 percent of the time the inundation depth was greater than 0.6 m (table 5).

Broadneck Swamp 2 and Broadneck Swamp 3, which has a land-surface elevation only 0.15 m higher than Broadneck Swamp 1, were inundated less than 25 percent of the time (table 5). When the sites were inundated, however, inundation depths typically were greater than 0.6 m.

Devils Gut

Devils Gut short circuits the main stem of the Roanoke River, with the head of Devils Gut at about river kilometer 55 and the mouth of Devils Gut at about river kilometer 34. The Devils Gut area (fig. 14) also is listed as a significant natural heritage area and contains alluvial features, such as filled channels, point bars, and natural levees (North Carolina Department of Environment and Natural Resources, 2001). The ridge and swale topography of the area is characterized by various species of oaks along levees bordering parallel sloughs that contain bald cypress and tupelo. The Devils Gut transect was bounded by the Woodard (site 22) and Jamesville (site 23) river-stage gages.

Devils Gut 1 (site 19, fig. 14) was located on the back side of a levee within 200 m of the Roanoke River. Devils Gut 2 (site 20, fig. 14) was adjacent to Devils Gut and had a direct hydraulic connection to the gut. Devils Gut 3 (site 21, fig. 14) is bounded to the west by Gardner Creek, a tributary to Devils Gut, to the north by Devils Gut, and to the east by the Roanoke River (fig. 2). Vegetation differed among the three sites, with

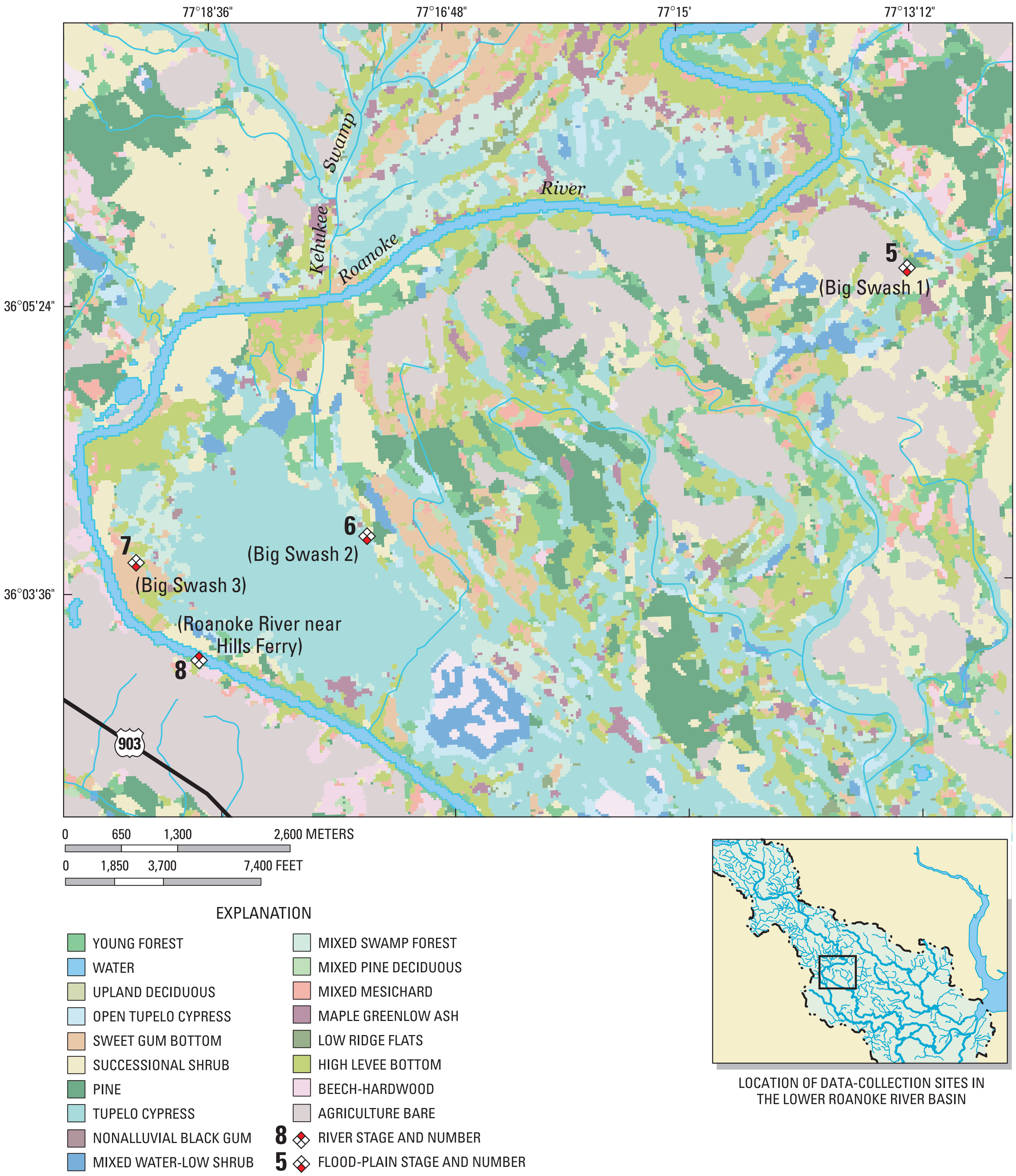


Figure 10. Land use in the vicinity of the Big Swash floodplain transect data-collection sites (from Townsend and Walsh, 1997a, 1997b).

Table 4. Water-level characteristics at the Big Swash transect in the lower Roanoke River basin, North Carolina, 1997–2000.

[m, meters; mean sea level is referenced to National Geodetic Vertical Datum of 1929; %, percent; LSD, land-surface datum]

Measure	1997	1998	1999	2000	1997–2000
Big Swash 1 (site 5; land-surface elevation = 7.53 m above mean sea level)					
Mean (m) above land-surface datum	- 0.90	- 0.53	- 0.56	- 0.77	- 0.64
Median (m) above land-surface datum	- .91	- .64	- .49	- .80	- .64
Maximum (m) above land-surface datum	- .47	.75	.77	.00	.77
Minimum (m) above land-surface datum	-1.28	-1.34	-1.31	-1.27	-1.34
Standard deviation (m) above land-surface datum	.21	.59	.34	.33	.44
% of measurements less than or equal to 0 m above LSD	100	81.1	97.7	100	93.3
% of measurements between 0.01 and 0.15 m above LSD	0	2.8	1.1	0	1.2
% of measurements between 0.16 and 0.3 m above LSD	0	1.7	1.1	0	0.5
% of measurements greater than 0.3 m above LSD	0	14.4	1.1	0	5.0
% of period measured	22	100	100	92	79
Big Swash 2 (site 6; land-surface elevation = 5.36 m above mean sea level)					
Mean (m) above land-surface datum	- 0.82	0.06	- 0.28	- 0.69	- 0.40
Median (m) above land-surface datum	- .98	- .28	- .16	- .85	- .44
Maximum (m) above land-surface datum	.24	1.73	1.89	.07	1.89
Minimum (m) above land-surface datum	-1.30	- .97	-1.31	-1.36	-1.36
Standard deviation (m) above land-surface datum	.44	.84	.56	.46	.70
% of measurements less than or equal to 0 m above LSD	92.5	59.0	81.9	99.0	82.2
% of measurements between 0.01 and 0.15 m above LSD	4.0	2.1	4.2	1.0	2.7
% of measurements between 0.16 and 0.3 m above LSD	3.5	1.6	1.8	0	1.6
% of measurements greater than 0.3 m above LSD	0	37.3	12.1	0	13.5
% of period measured	65	100	100	100	91
Big Swash 3 (site 7; land-surface elevation = 6.40 m above mean sea level)					
Mean (m) above land-surface datum	- 0.87	-1.19	- 0.15	- 0.19	- 0.43
Median (m) above land-surface datum	- .97	-1.39	.06	- .14	- .26
Maximum (m) above land-surface datum	.32	.32	1.40	.45	1.40
Minimum (m) above land-surface datum	-1.88	-1.85	-1.69	- .91	-1.88
Standard deviation (m) above land-surface datum	.72	.57	.59	.43	.69
% of measurements less than or equal to 0 m above LSD	83.7	89.3	44.1	54.5	60.4
% of measurements between 0.01 and 0.15 m above LSD	6.6	2.9	9.6	8.2	7.6
% of measurements between 0.16 and 0.3 m above LSD	9.5	7.4	40.5	25.4	25.8
% of measurements greater than 0.3 m above LSD	.2	.4	5.8	11.9	6.2
% of period measured	37	46	100	97	70

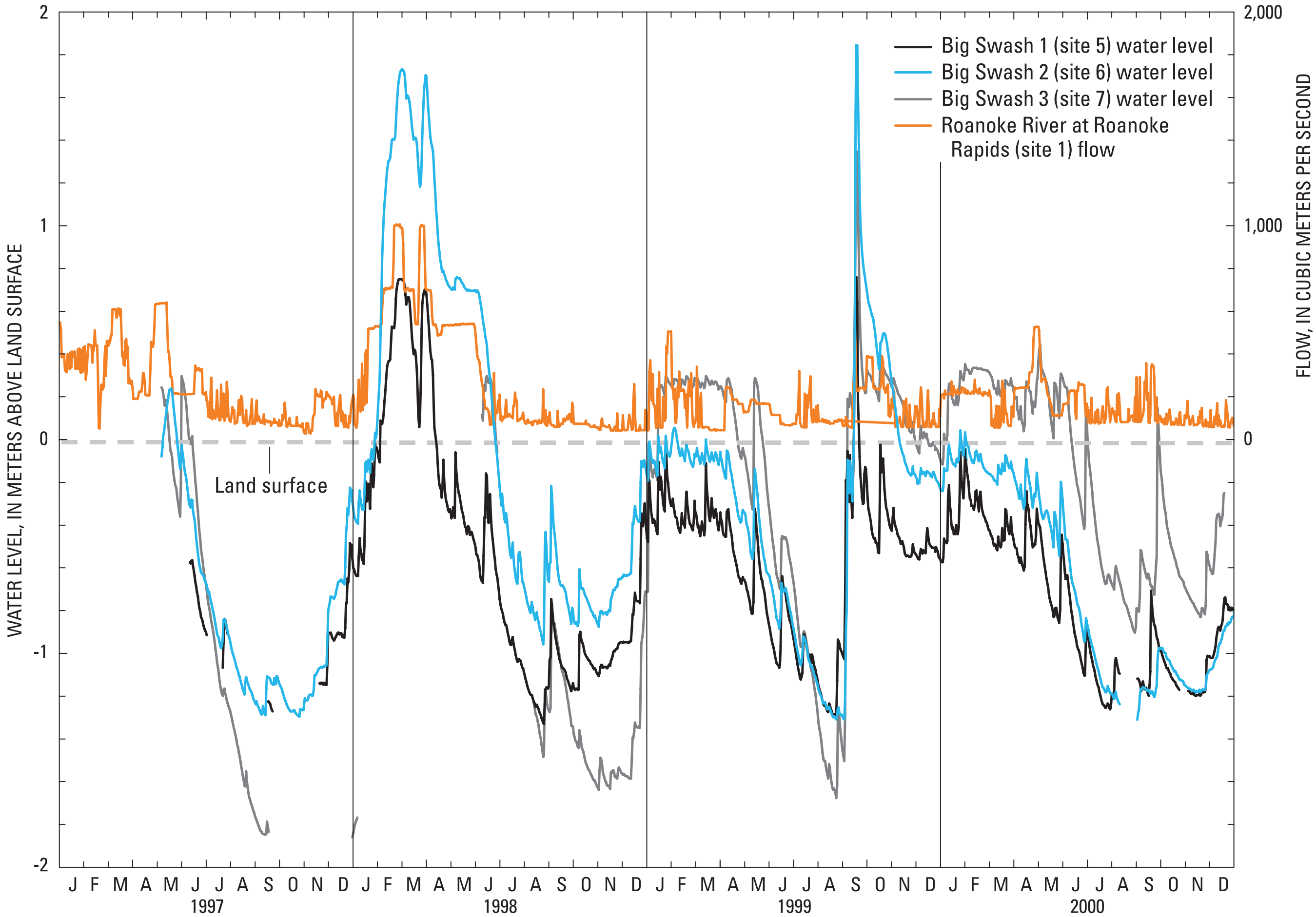


Figure 11. Daily mean water levels relative to land surface at three Big Swash transect sites, and daily mean flows for Roanoke River at Roanoke Rapids (site 1), North Carolina, 1997–2000.

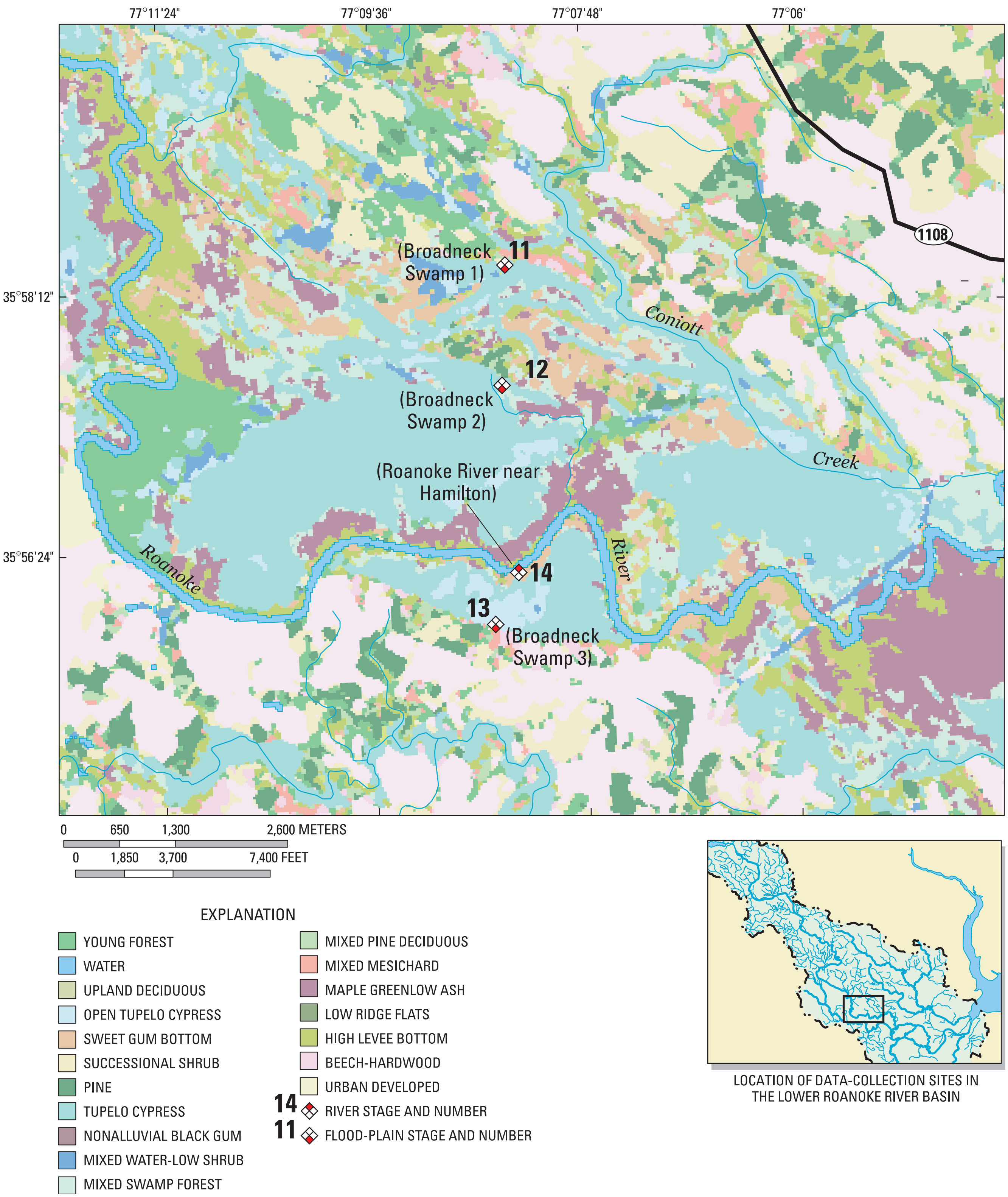


Figure 12. Land use in the vicinity of the Broadneck Swamp floodplain transect data-collection sites (from Townsend and Walsh, 1997a, 1997b).

Table 5. Water-level characteristics at the Broadneck Swamp transect in the lower Roanoke River basin, North Carolina, 1997–2000.

[m, meters; mean sea level is referenced to National Geodetic Vertical Datum of 1929; %, percent; LSD, land-surface datum]

Measure	1997	1998	1999	2000	1997–2000
Broadneck 1 (site 11; land-surface elevation = 3.60 m above mean sea level)					
Mean (m) above land-surface datum	0.26	1.14	0.26	0.13	0.39
Median (m) above land-surface datum	.14	1.48	.16	.07	.16
Maximum (m) above land-surface datum	1.47	1.98	2.07	1.37	2.07
Minimum (m) above land-surface datum	.02	.07	- .23	- .08	- .23
Standard deviation (m) above land-surface datum	.37	.70	.40	.21	.57
% of measurements less than or equal to 0 m above LSD	0	0	16.7	12.3	8.6
% of measurements between 0.01 and 0.3 m above LSD	88.4	31.5	65.8	83.1	69.5
% of measurements between 0.3 and 0.6 m above LSD	5.4	1.7	3.7	1.2	2.1
% of measurements greater than 0.6 m above LSD	10.2	66.8	13.8	3.4	19.8
% of period measured	62	59	83	100	76
Broadneck 2 (site 12; land-surface elevation = 4.18 m above mean sea level)					
Mean (m) above land-surface datum	- 0.79	- 0.23	- 0.43	- 0.38	- 0.43
Median (m) above land-surface datum	- .88	- .53	- .38	- .38	- .43
Maximum (m) above land-surface datum	1.07	1.44	1.57	.97	1.57
Minimum (m) above land-surface datum	-1.80	-1.50	-1.77	-1.15	-1.80
Standard deviation (m) above land-surface datum	.79	.99	.63	.29	.73
% of measurements less than or equal to 0 m above LSD	85.6	69.0	84.1	95.2	83.7
% of measurements between 0.01 and 0.3 m above LSD	0	1.4	3.1	1.4	1.6
% of measurements between 0.3 and 0.6 m above LSD	4.5	1.2	4.9	1.2	2.9
% of measurements greater than 0.6 m above LSD	9.8	28.4	7.9	2.2	11.8
% of period measured	65	86	100	100	88
Broadneck 3 (site 13; land-surface elevation = 3.75 m above mean sea level)					
Mean (m) above land-surface datum	- 0.06	0.29	- 0.12	- 0.12	0.00
Median (m) above land-surface datum	- .19	- .12	- .12	- .12	- .12
Maximum (m) above land-surface datum	.97	1.33	1.42	.88	1.42
Minimum (m) above land-surface datum	- .88	- .41	- .92	- .52	- .92
Standard deviation (m) above land-surface datum	.52	.62	.37	.18	.49
% of measurements less than or equal to 0 m above LSD	68.8	59.7	84.8	95.3	77.2
% of measurements between 0.01 and 0.3 m above LSD	3.1	1.5	4.3	1.2	2.5
% of measurements between 0.3 and 0.6 m above LSD	11.6	1.1	5.9	1.3	5.0
% of measurements greater than 0.6 m above LSD	16.5	27.7	5.0	2.2	12.3
% of period measured	100	100	100	100	100

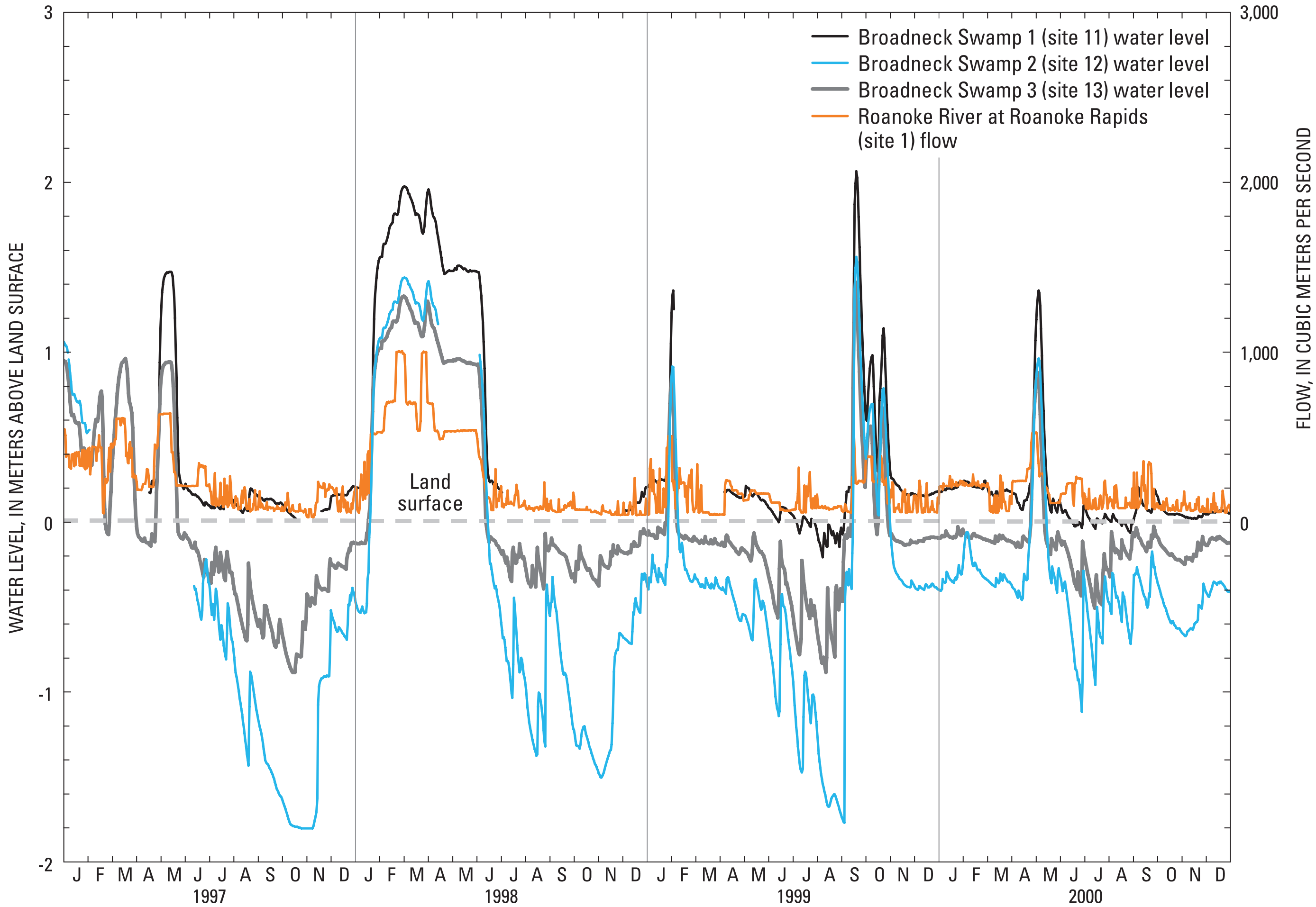


Figure 13. Daily mean water levels relative to land surface at three Broadneck Swamp transect sites, and daily mean flows for Roanoke River at Roanoke Rapids (site 1), North Carolina, 1997–2000.

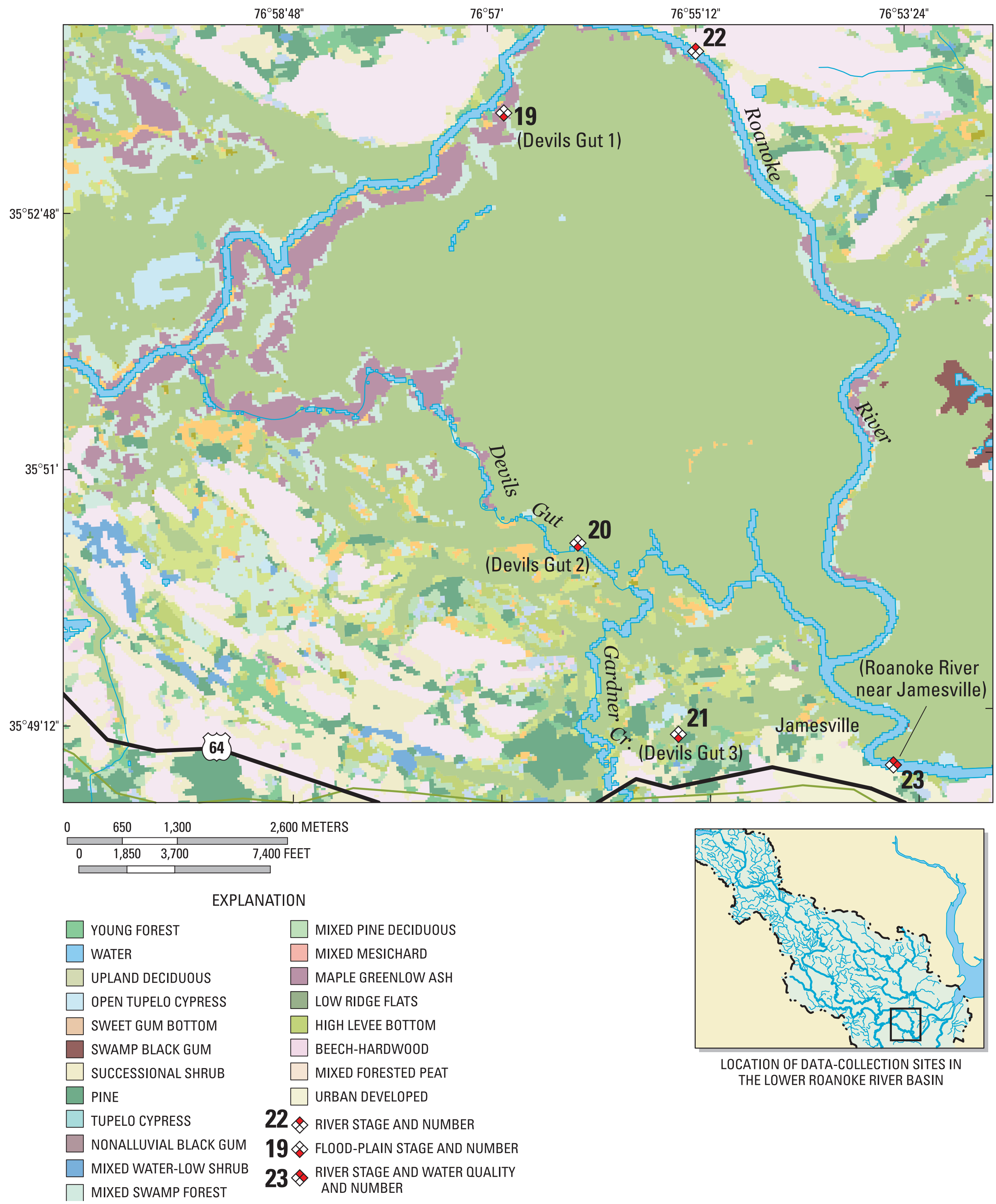


Figure 14. Land use in the vicinity of the Devils Gut floodplain transect data-collection sites (from Townsend and Walsh, 1997a, 1997b).

Table 6. Water-level characteristics at the Devils Gut transect in the lower Roanoke River basin, North Carolina, 1997–2000.

[m, meters; mean sea level is referenced to National Geodetic Vertical Datum of 1929; %, percent; LSD, land-surface datum]

Measure	1997	1998	1999	2000	1997–2000
Devils Gut 1 (site 19; land-surface elevation = 0.85 m above mean sea level)					
Mean (m) above land-surface datum	- 0.22	0.07	- 0.23	- 0.22	- 0.15
Median (m) above land-surface datum	- .12	.07	- .12	- .14	- .12
Maximum (m) above land-surface datum	.56	1.0	1.35	.40	1.35
Minimum (m) above land-surface datum	-1.11	- .84	-1.13	- .79	-1.13
Standard deviation (m) above land-surface datum	.48	.57	.46	.24	.48
% of measurements less than or equal to 0 m above LSD	65.0	56.5	83.6	93.8	74.2
% of measurements between 0.01 and 0.3 m above LSD	19.4	4	8.3	4.2	9.2
% of measurements between 0.3 and 0.6 m above LSD	15.6	17.7	5.3	2.0	10.4
% of measurements greater than 0.6 m above LSD	0	21.8	2.8	0	6.2
% of period measured	100	96	100	86	95
Devils Gut 2 (site 20; land-surface elevation = 0.52 m above mean sea level)					
Mean (m) above land-surface datum	0.20	0.11	0.16	0.11	0.15
Median (m) above land-surface datum	.09	.0	.10	.09	.09
Maximum (m) above land-surface datum	.81	1.24	1.64	.65	1.64
Minimum (m) above land-surface datum	- .38	- .32	- .44	- .19	- .44
Standard deviation (m) above land-surface datum	.30	.36	.31	.13	.28
% of measurements less than or equal to 0 m above LSD	26.2	51.1	18.7	17.8	26.2
% of measurements between 0.01 and 0.3 m above LSD	41.2	33.3	64.4	76.4	56
% of measurements between 0.3 and 0.6 m above LSD	17.5	3.3	8.4	4.4	9
% of measurements greater than 0.6 m above LSD	15.1	12.3	8.3	1.4	8.9
% of period measured	98	63	100	100	90
Devils Gut 3 (site 21; land-surface elevation = 0.52 m above mean sea level)					
Mean (m) above land-surface datum	0.42	0.48	0.44	0.49	0.46
Median (m) above land-surface datum	.41	.42	.48	.50	.48
Maximum (m) above land-surface datum	.67	1.0	1.47	.63	1.47
Minimum (m) above land-surface datum	.15	.28	.00	.33	.00
Standard deviation (m) above land-surface datum	.16	.16	.18	.06	.15
% of measurements less than or equal to 0 m above LSD	0	0	.1	0	0
% of measurements between 0.01 and 0.3 m above LSD	31.6	1.7	19.5	0	13.8
% of measurements between 0.3 and 0.6 m above LSD	58.8	71.3	74.4	97.5	75.7
% of measurements greater than 0.6 m above LSD	9.6	27.0	6.0	2.5	10.5
% of period measured	100	82	100	100	95

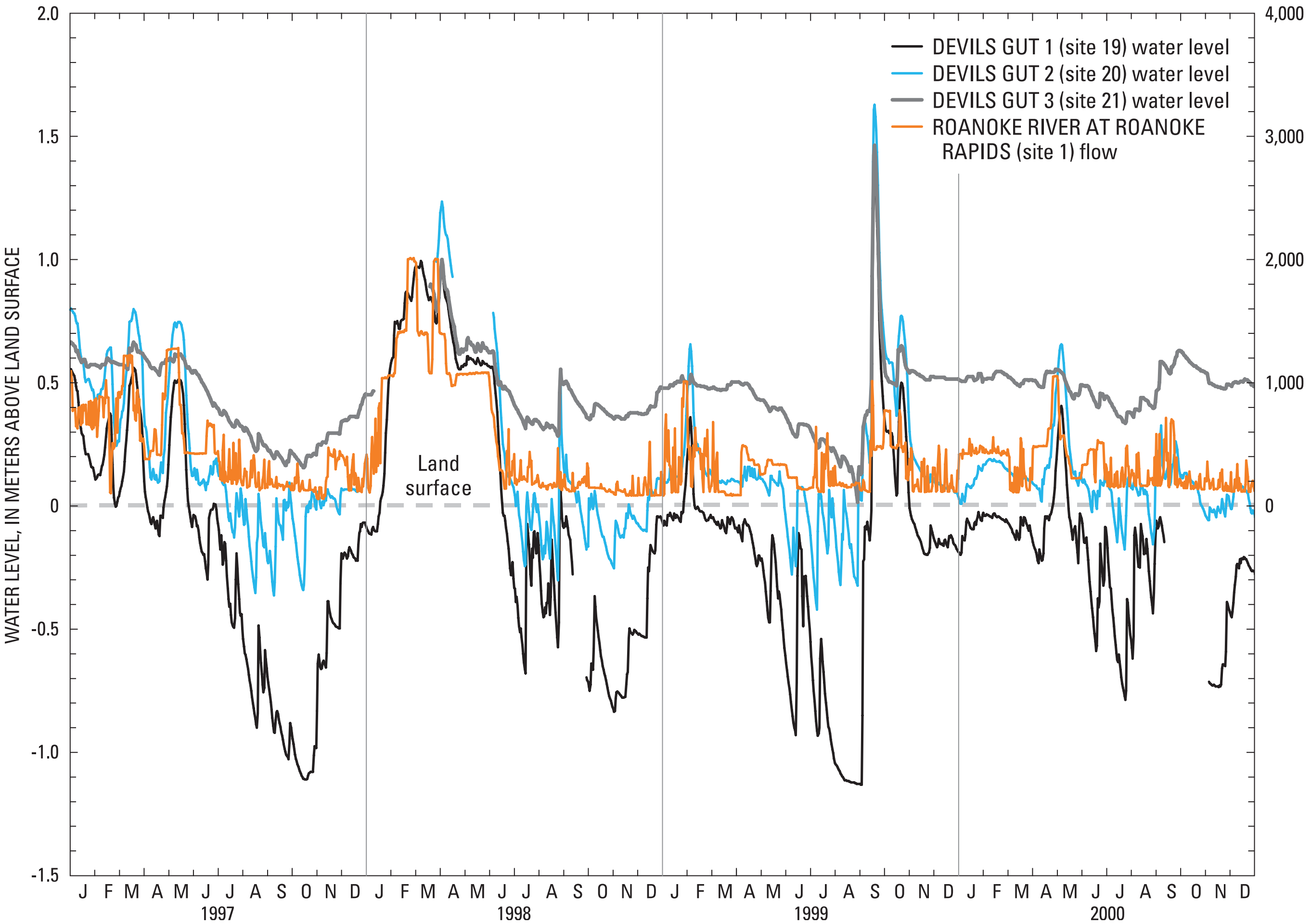


Figure 15. Daily mean water levels relative to land surface at three Devils Gut transect sites, and daily mean flows for Roanoke River at Roanoke Rapids (site 1), North Carolina, 1997–2000.

maple-ash at Devils Gut 1, tupelo and cypress at Devils Gut 2, and a mix of loblolly pine, various shrubs, water tupelo, and bald cypress near Devils Gut 3.

Devils Gut 3, which is at the same land-surface elevation as Devils Gut 2, was continuously inundated throughout the study (table 6; fig. 15), and water levels at this site generally exhibited different temporal characteristics from those at Devils Gut 1 and 2. There were long periods (for example, January–April 1999 and November 1999–May 2000) during which inundation depths remained at 0.5 m or greater and water level fluctuated only slightly, particularly when compared to fluctuations observed at the other two Devils Gut sites and at the upstream transects (figs. 11, 13). During much of the spring and summer, the water surface was covered with algae, indicating very little water movement at the site. The most likely reason that Devils Gut 3 water-level characteristics were different from those at the other two sites is that Devils Gut 3 water levels were controlled more by Gardner Creek than by the Roanoke River, except at river flows greater than about 500 m^3/s. Devils Gut 2 was inundated about three times as much as Devils Gut 1, although the difference in land elevation between the two sites was just 0.33 m (table 6).

Cow Swamp

The Cow Swamp transect was located in the area known as Broad Creek Neck, another natural heritage area in the lower Roanoke River corridor (North Carolina Department of Environment and Natural Resources, 2001), and crosses a tract of the Roanoke River National Wildlife Refuge. The Broad Creek Neck area contains what is likely the largest contiguous cypress-tupelo swamp forest in North Carolina (North Carolina Department of Environment and Natural Resources, 2001). The transect crosses the Roanoke River (fig. 16), and nearby river-stage gages are located at Jamesville (site 23) and Plymouth (site 28, fig. 2).

Cow Swamp 1 (site 24) is located at a land-surface elevation of about 2.5 m above sea level adjacent to an unnamed stream channel (fig. 16), whereas the other three Cow Swamp sites are all at an elevation of 0.43 m (table 7). Cow Swamp 2, 3, and 4 exhibited similar water-level characteristics (table 7). Cow Swamp 2 had slightly higher water levels and was inundated more often than Cow Swamp 3 and 4. At all three sites, water levels rarely fell below 0.3 m below land surface or rose above 0.3 m above land surface (table 7; fig. 17).

Annual and Seasonal Characteristics

Daily mean water levels at Big Swash 2 and 3 (sites 6 and 7) were similar during 1997–2000 (fig. 18A). These sites were typically inundated during February–April, and unflooded during the remainder of the year. The range in water level measured at the Big Swash transect sites on a given calendar day was typically quite large and could be as much as 2.0 m or more. This means that there is a large amount of interannual variability in water-level conditions at the sites.

The difference between the maximum and the minimum observed water levels at Broadneck Swamp 1 for a given calendar date during mid-January through early June varied between about 1.2 and 1.7 m, and the maximum depth of inundation during this time was a meter or more (fig. 18B). During the summer (mid-June through mid-September) and November–December, however, the range in water levels was much less, varying less than 0.3 m. Hence, if the 1997–2000 data are representative, there is greater certainty about what future water levels will be at Broadneck Swamp 1 during the summer and late fall than during other times of the year. In addition, based on the 1997–2000 data, it could be anticipated that Broadneck 1 will always be inundated except from mid-June through August and even then may be inundated. Likewise, the 1997–2000 data indicate that Broadneck Swamp 3 (and Broadneck Swamp 2, which is not shown in fig. 18B) are unlikely to be inundated during mid-June through early September, and the site could be unflooded on any day of the year. Additional data are certainly required to determine if the seasonal patterns observed during 1997–2000 are representative of long-term conditions, although the study period did include a fairly wet winter-spring (1998), a hurricane (1999), and extended dry periods (summer of 1998–summer of 1999, and summer–fall 2000; fig. 7A).

Seasonal inundation patterns at Devils Gut 1 and 2 (fig. 18C) are similar to those at the Broadneck Swamp transect (fig. 18B), with a greater probability of inundation during January–May, corresponding to the typically higher flows during that time (fig. 6). In fact, Devils Gut 2 always was inundated during January–May of 1997–2000, but the water level at Devils Gut 1 was below land surface at least once during every calendar day of the study period (in other words, at least once on one of the four January 1 dates during the study period, and so on). If not for the 1999 hurricanes, both sites would have experienced very little inundation during the last half of the calendar year. The difference between the maximum and minimum water levels measured at Devils Gut 2 during the months of July and August was less than 0.4 m, but the range at Devils Gut 1 was greater, primarily because minimum water levels at Devils Gut 1 during the summer were 0.5–1.0 m lower than at Devils Gut 2. There was little seasonal variation in water level at Devils Gut 3; water levels generally were about 0.5–0.65 m above land surface during the first half of the year and about 0.3–0.4 m above land surface during the last half of the year.

Annual and seasonal minimum water levels relative to land surface at Devils Gut 1 were much lower than at Devils Gut 2, and annual minimum water-surface elevations (relative to sea level) at Devils Gut 1 were 0.3–0.4 m lower than at Devils Gut 2 (table 6). Annual maximum water-surface elevations relative to sea level (table 6), however, at Devils Gut 1 and 2 were within 0.08 m or less of each other, indicating similar flooding characteristics at the two sites but more rapid drainage at Devils Gut 1.

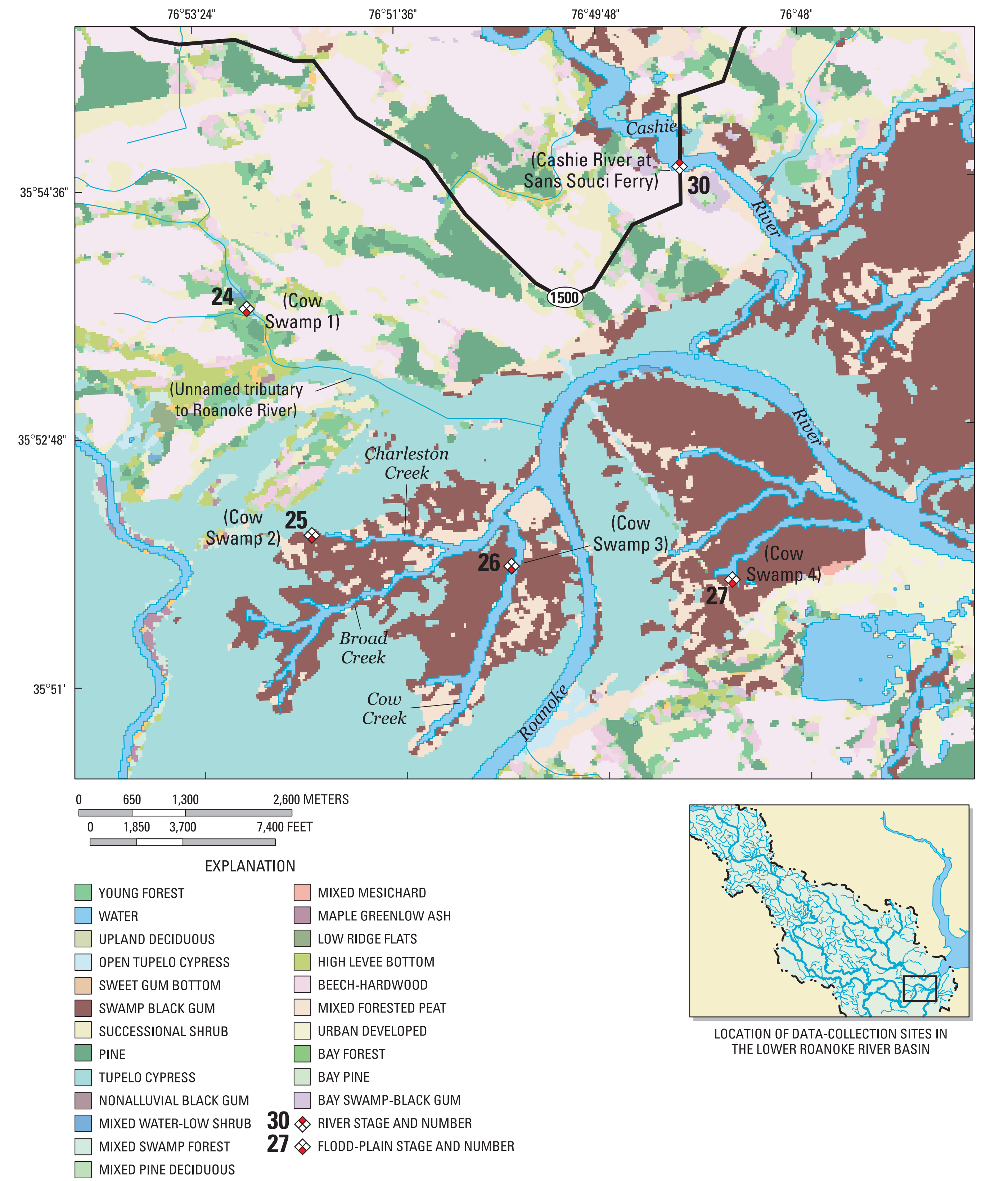


Figure 16. Land use in the vicinity of the Cow Swamp floodplain transect data-collection sites (from Townsend and Walsh, 1997a, 1997b).

Table 7. Water-level characteristics at the Cow Swamp transect in the lower Roanoke River basin, North Carolina, 1997–2000.

[m, meters; mean sea level is referenced to National Geodetic Vertical Datum of 1929; %, percent; LSD, land-surface datum]

Measure	1997	1998	1999	2000	1997–2000
Cow Swamp 1 (site 24; land-surface elevation = 2.49 m above mean sea level)					
Mean (m) above land-surface datum	0.01	0.12	0.07	0.10	0.08
Median (m) above land-surface datum	.04	.12	.12	.12	.11
Maximum (m) above land-surface datum	.19	.42	.72	.33	.72
Minimum (m) above land-surface datum	- .38	- .13	- .33	- .11	- .38
Standard deviation (m) above land-surface datum	.12	.06	.12	.06	.11
% of measurements less than or equal to 0 m above LSD	39.1	3.4	19.6	8.7	16.6
% of measurements between 0.01 and 0.3 m above LSD	60.9	95.5	79.6	91.9	82.7
% of measurements between 0.3 and 0.6 m above LSD	0	1.1	.7	.4	.6
% of measurements greater than 0.6 m above LSD	0	0	.1	0	.1
% of period measured	65	100	91	50	76
Cow Swamp 2 (site 25; land-surface elevation = 0.43 m above mean sea level)					
Mean (m) above land-surface datum	0.01	0.12	0.01	- 0.06	0.02
Median (m) above land-surface datum	.0	- .01	- .04	- .05	- .02
Maximum (m) above land-surface datum	.38	.93	1.32	.32	1.32
Minimum (m) above land-surface datum	- .28	- .30	- .30	- .46	- .46
Standard deviation (m) above land-surface datum	.12	.35	.23	.12	.23
% of measurements less than or equal to 0 m above LSD	51.4	56.1	64.0	65.6	59.4
% of measurements between 0.01 and 0.3 m above LSD	46.1	20.7	28.6	34.3	33.0
% of measurements between 0.3 and 0.6 m above LSD	2.5	3.2	4.6	.1	2.5
% of measurements greater than 0.6 m above LSD	0	20.0	2.8	0	5.1
% of period measured	100	83	100	100	96
Cow Swamp 3 (site 26; land-surface elevation = 0.43 m above mean sea level)					
Mean (m) above land-surface datum	- 0.01	0.13	0.02	- 0.04	0.02
Median (m) above land-surface datum	- .03	- .01	- .05	- .06	- .05
Maximum (m) above land-surface datum	.33	.84	1.21	.31	1.21
Minimum (m) above land-surface datum	- .13	- .16	- .14	- .15	- .15
Standard deviation (m) above land-surface datum	.09	.26	.20	.08	.19
% of measurements less than or equal to 0 m above LSD	63.0	51.3	70.1	74.0	64.6
% of measurements between 0.01 and 0.3 m above LSD	36.9	20.9	23.1	26.0	27.4
% of measurements between 0.3 and 0.6 m above LSD	.1	17.6	4.2	0	5.5
% of measurements greater than 0.6 m above LSD	0	7.2	26.6	0	2.5
% of period measured	99	100	100	100	99

Table 7. Water-level characteristics at the Cow Swamp transect in the lower Roanoke River basin, North Carolina, 1997–2000.—Continued

[m, meters; mean sea level is referenced to National Geodetic Vertical Datum of 1929; %, percent; LSD, land-surface datum]

Measure	1997	1998	1999	2000	1997–2000
Cow Swamp 4 (site 27; land-surface elevation = 0.43 m above mean sea level)					
Mean (m) above land-surface datum	- 0.06	0.03	- 0.06	- 0.10	- 0.05
Median (m) above land-surface datum	- .07	- .03	- .09	- .10	- .08
Maximum (m) above land-surface datum	.27	.86	.99	.29	.99
Minimum (m) above land-surface datum	- .30	- .31	- .30	- .30	- .31
Standard deviation (m) above land-surface datum	.09	.20	.18	.11	.16
% of measurements less than or equal to 0 m above LSD	76.7	55.8	76.9	81.1	72.6
% of measurements between 0.01 and 0.3 m above LSD	23.3	31.2	18.7	18.9	23.0
% of measurements between 0.3 and 0.6 m above LSD	0	12.8	2.5	0	3.9
% of measurements greater than 0.6 m above LSD	0	.2	1.9	0	.5
% of period measured	92	99	100	99	97

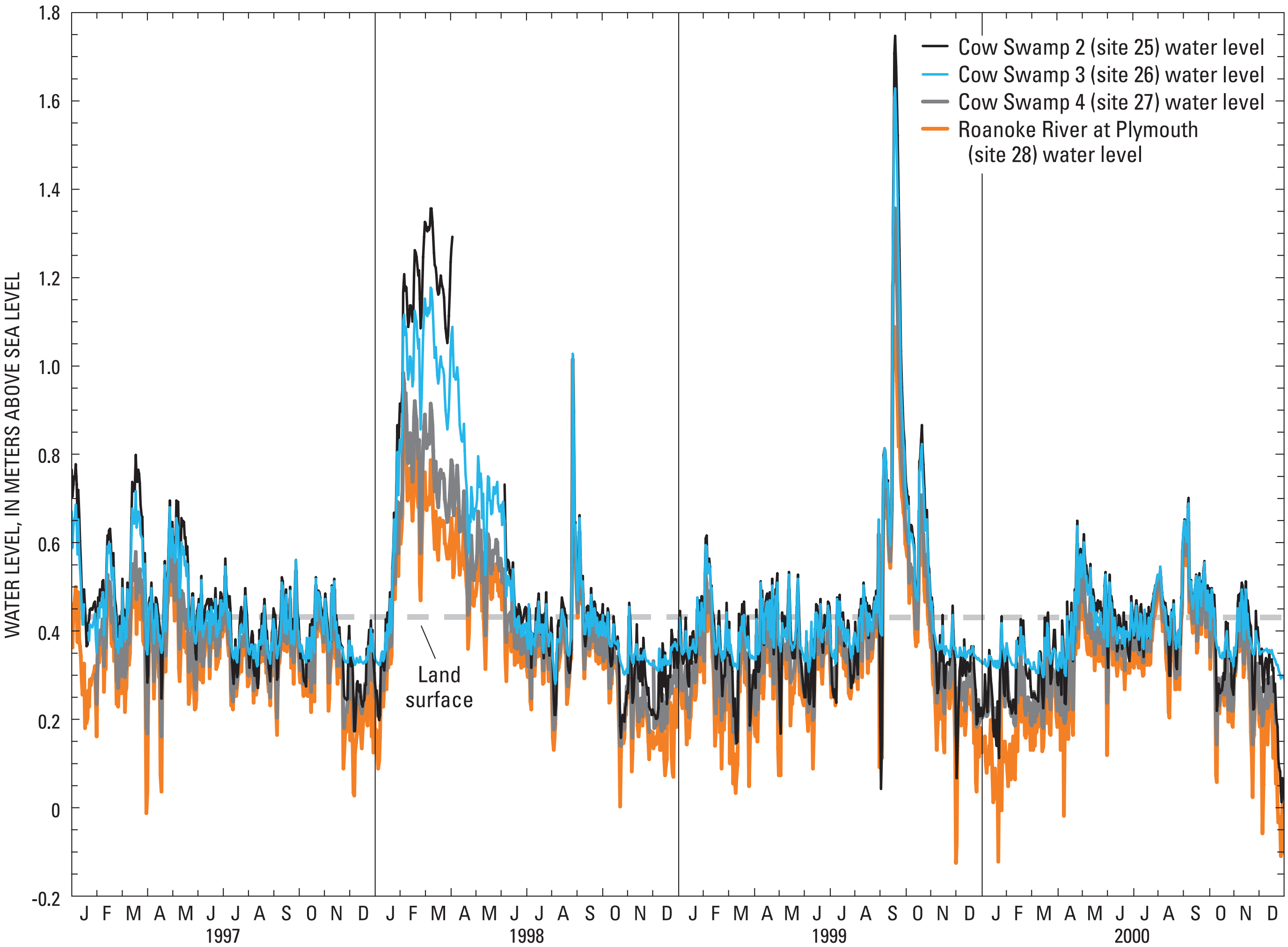


Figure 17. Daily mean water levels relative to sea level at three Cow Swamp transect sites and for Roanoke River at Plymouth (site 28), North Carolina, 1997–2000.

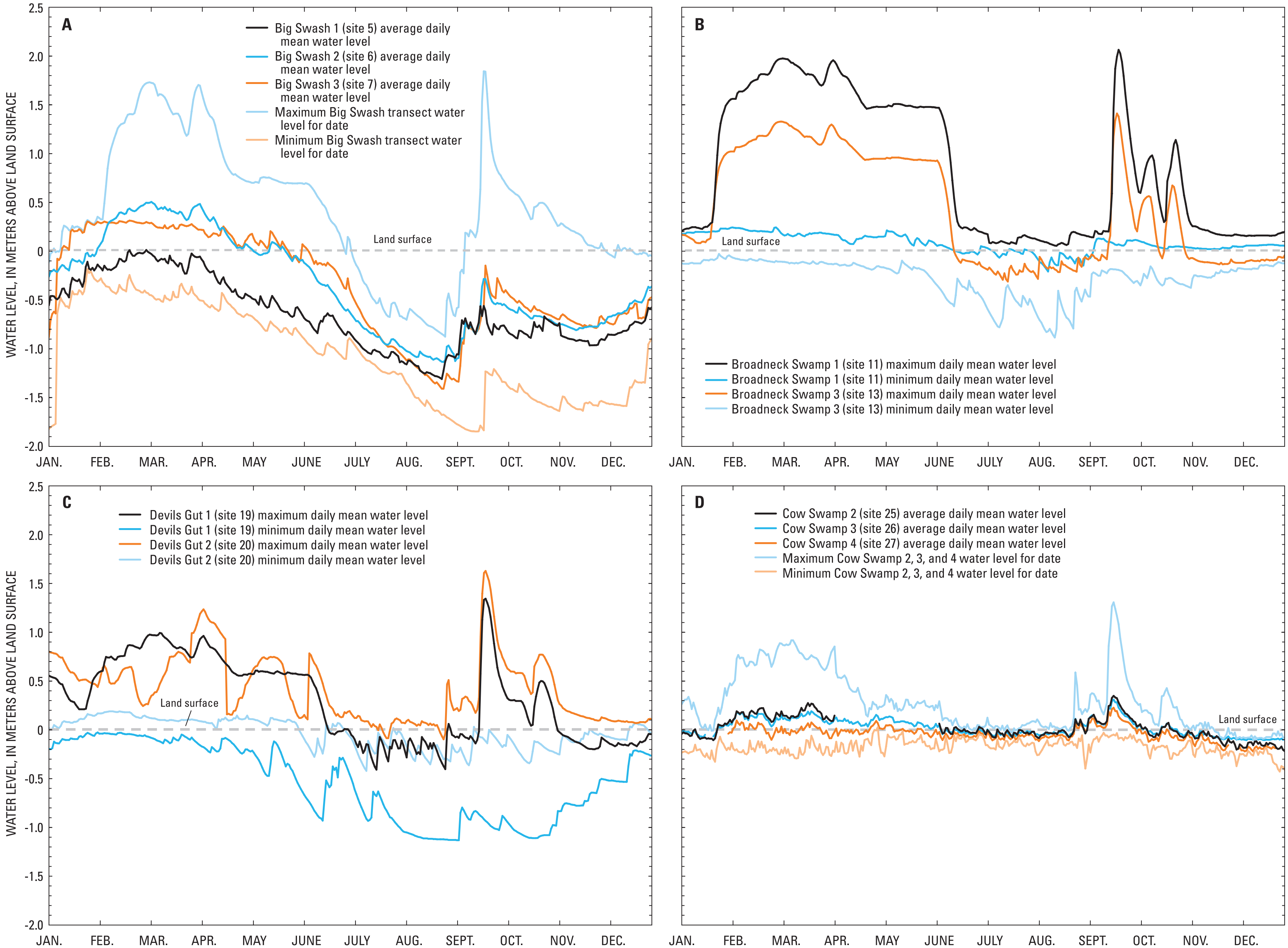


Figure 18. Annual water-level characteristics for 1997–2000 at (A) Big Swash transect (sites 5–7); (B) Broadneck Swamp 1 (site 11) and 3 (site 13); (C) Devils Gut 1 (site 19) and 2 (site 20); and (D) Cow Swamp 2 (site 25), 3 (site 26), and 4 (site 27).

Water levels at Cow Swamp 2, 3, and 4 all had similar seasonal patterns, particularly in January and from June through December (fig. 18D). Mean daily water levels at these three sites typically were below land surface in the summer (June–August) and fall (October–December). Cow Swamp 2 and 3 typically were flooded from mid-January through May, whereas mean daily water levels at Cow Swamp 4 occasionally were below land surface during these times (fig. 18D). Minimum daily water levels did not vary much throughout the year at these three Cow Swamp sites (for example, fig. 18D), but maximum daily water levels had a range of about 1.3 m throughout the year at Cow Swamp 2, 3, and 4 (fig. 18D), with highest maximum daily water levels in the late winter and early spring as a result of high flows and in the early fall from hurricanes. The lowest interannual variation in water levels occurred during the summer months, when the difference between the maximum and minimum daily mean water level for a calendar date was about 0.1–0.3 m, compared to interannual variations of 0.5–1.0 m at the Big Swash transect (fig. 18A).

Floodplain Water Level and River Flow

Flooding occurred at Big Swash 1 only when streamflow at Roanoke Rapids was greater than at least 600 m^3/s for a sustained period (fig. 11). For example, the streamflow during all of May 1998 was about 540 m^3/s, but the water level at Big Swash 1 declined throughout the month, except in response to rainfall.

During mid-February–April 1998 when Big Swash 1 was flooded, water level at the site responded within about 35 hours to sustained increases in flow at Roanoke Rapids. A sustained decrease in flow at Roanoke Rapids was followed within about 48 hours by a decline in water level at this site. In comparison, Lebo (1998) reported that flows in the Roanoke River at river kilometer 17 responded within 2 days to increases in flow at Roanoke Rapids.

Roanoke Rapids daily mean flows lagged by 2, 3, and 5 days, and 5-, 7-, and 10-day Roanoke Rapids mean flows were compared to Big Swash daily mean water levels relative to land surface. The best relations between Roanoke Rapids flows and Big Swash 1 and 3 inundation depths were between *n*-day mean flow and inundation depth rather than lagged flow, although there was little difference among the relations when using 5-, 7-, or 10-day mean flows. Townsend and Foster (2002) suggested that 10-day mean flows were most appropriate for relating Roanoke Rapids streamflow to areal extent of floodplain inundation; thus, the 10-day mean flow was used. (For example, the mean flow for the previous 10 days, including today, was compared with the water level that occurred today.)

There was little relation between Roanoke Rapids streamflow and inundation depth at the Big Swash transect for most conditions (fig. 19A). Although Big Swash 1 was seldom flooded, inundation depth at the site was loosely related to 10-day mean flows between 600 and 900 m^3/s, with a more or less linear increase in inundation depth from about 0 to about 0.6 m over the range of flows (fig. 19A). At Big Swash 2, there was some relation between inundation depth and 10-day mean flows greater than about 550 m^3/s, which are associated with inundation depths greater than about 1.0 m (fig. 19A). At 10-day mean flows greater than 550 m^3/s, Big Swash 2 inundation depths increased more or less linearly with increasing flow, from about 1 m above land surface at 550 m^3/s to about 1.7 m above land surface at 900 m^3/s. Note that Big Swash 2 was inundated at 10-day mean flows ranging from about 120 m^3/s to 1,000 m^3/s and that inundation depth was independent of flow at Big Swash 1 and 2 for 10-day mean flows greater than about 900 m^3/s. Inundation depths at Big Swash 3 were independent of 10-day mean flows, and this site was inundated at some time during the study period for 10-day mean flows ranging from 45 m^3/s to 620 m^3/s.

There was a fairly strong association between streamflow and floodplain inundation at the Broadneck Swamp transect (fig. 19B). Inundation depths greater than 1 m at Broadneck Swamp 1 generally were associated with river flows greater than 500 m^3/s, except during September–October 1999, when Hurricanes Dennis, Floyd, and Irene occurred. Ten-day mean flows greater than 350 m^3/s always resulted in inundation at Broadneck Swamp 2 and 3, and 10-day mean flows greater than 400 m^3/s were associated with inundation depths greater than 0.5 m at Broadneck Swamp 2 (fig. 19B). Ten-day mean flows less than about 220 m^3/s were only infrequently associated with inundation at Broadneck Swamp 2 and 3 (fig. 19B). The times when 10-day mean flows less than 220 m^3/s were associated with inundation generally were occasions when the sites already were inundated from previously occurring high flows or rainfall. Regardless of the streamflow, up to a maximum of 1,000 m^3/s, the maximum inundation depth at both Broadneck Swamp 2 and 3 was about 1.5 m, and increases in 10-day mean streamflow from 600 m^3/s to 1,000 m^3/s resulted in increased inundation of only 0.2 m (fig. 19B). The same was true for Broadneck Swamp 1, except the maximum inundation depth there was about 1.5 m. In comparison, Cannon and Graham (2002) reported that lands adjacent to Coniott Creek, which drains portions of Broadneck Swamp (fig. 12), became inundated when the 24-hr moving average flow exceeded 300 m^3/s for 35 hrs and the stage at Hamilton (site 10) reached 3.35 m, which is slightly lower than the land-surface elevation at Broadneck Swamp 1.

Relations were developed for predicting inundation depths at the three Broadneck Swamp sites from 10-day mean flows at Roanoke Rapids. For Broadneck Swamp 1, all daily mean water level 10-day mean flow data pairs for which water level was less than 0.3 m were dropped from the dataset, because there was no relation between flow and water level less than 0.3 m above land surface (fig. 19B). For Broadneck Swamp 2 and 3, all data pairs for which water levels were below land surface were eliminated from the analysis. For all three sites, water level–flow data pairs associated with Hurricane Floyd, when streamflow was low but inundation was at a maximum because of the combined effects of storm surge and rain, were dropped. The regressions had the form:

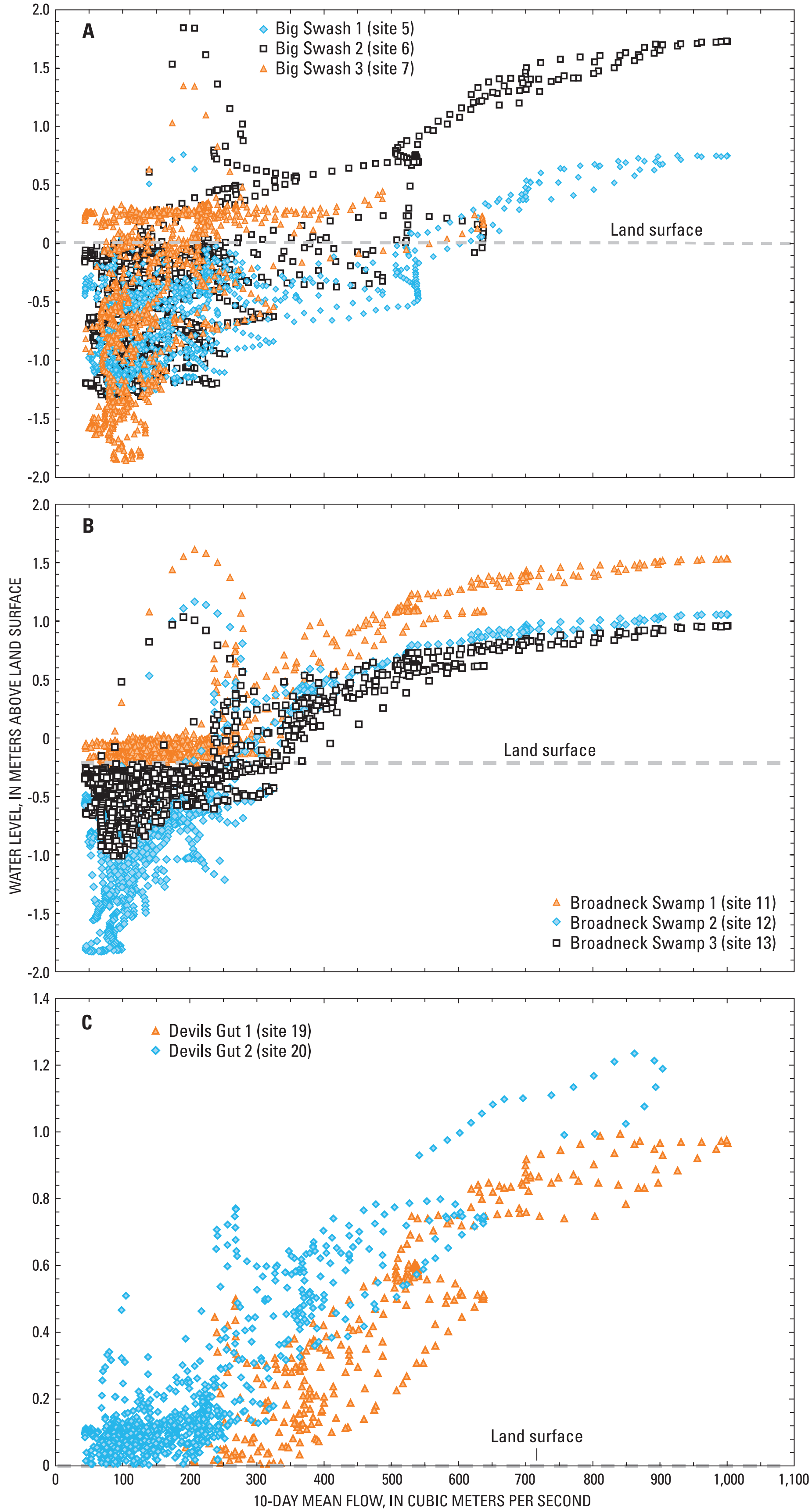


Figure 19. Daily mean water levels relative to land surface and associated 10-day mean flows at Roanoke River at Roanoke Rapids (site 1), North Carolina, 1997–2000, for (A) the Big Swash transect (sites 5–7), (B) the Broadneck Swamp transect (sites 11–13), and (C) Devils Gut 1 (site 19) and 2 (site 20).

Table 8. Information on relations for estimating daily mean inundation depth from 10-day mean flow at three Broadneck Swamp transect sites in the lower Roanoke River basin, North Carolina.

Location	a (eq. 1)	b (eq. 1)	R^2	Standard error of regression (meters)	Number of observations	Range of applicability: 10-day mean flow (cubic meters per second)	Range of applicability: Daily mean water lever (meters above land surface)
Broadneck 1	-5.77	1.15	0.86	0.17	233	200–1,000	0.3–2.0
Broadneck 2	-4.68	0.90	0.88	0.15	189	200–1,000	0–1.45
Broadneck 3	-4.72	0.89	0.82	0.15	311	200–1,000	0–1.3

$$\text{Daily mean inundation depth in meters} = a + b*\ln(\text{10-day mean flow in m}^3\text{/s}), \quad (1)$$

where a and b are best-fit regression coefficients (table 8), and ln is the natural logarithm. Relations for all three sites were significant ($p < 0.01$), and the relations for Broadneck Swamp 2 and 3 were essentially the same (fig. 19B; table 8), indicating that the pathway for water entering these two sites was similar but different from that for Broadneck Swamp 1.

There was no relation between flow and inundation depth for Devils Gut 3 at flows less than 300 m^3/s. For 10-day mean flows between about 300 and 550 m^3/s, the inundation depth at Devils Gut 1 was always within the range of 0.5 to 0.65 m. The relation between inundation depth at Devils Gut 3 and 10-day mean flows greater than 550 m^3/s was essentially the same as that for Devils Gut 1.

Relations between 10-day mean streamflow and inundation depth at Devils Gut 1 and 2 are significant ($p < 0.01$), but there is greater scatter in the relations than for the Broadneck Swamp sites (fig. 19B, C; tables 8, 9). As with the Broadneck Swamp sites, relations were developed by using only inundation depths greater than zero and omitting Hurricane Floyd data. Linear relations (eq. 2) provided a better fit than the logarithmic relations used for the Broadneck Swamp sites. The relation for Devils Gut 2 could be improved slightly if 10-day mean flows less than 200 m^3/s were omitted from the analysis, because inundation depth generally is independent of flow at Devils Gut 2 for the lower flows. Cannon and Graham (2002) reported that a site along Devils Gut became inundated when the 24-hr moving average flow at Roanoke River at Roanoke Rapids was 300 m^3/s for 21 hrs.

$$\text{Daily mean inundation depth in meters} = a + b*(\text{10-day mean flow in m}^3\text{/s}) \quad (2)$$

There was little relation between flows at Roanoke River at Roanoke Rapids and floodplain water levels at the Cow Swamp sites except during the extended high-flow period in the late winter of 1998 (fig. 6). At 10-day mean flows of 460 m^3/s or greater, Cow Swamp 2 was always inundated; at 10-day mean flows of 500 m^3/s or greater, Cow Swamp 3 was always inundated; Cow Swamp 4 was always inundated at 10-day mean flows of 630 m^3/s or greater. For 10-day mean flows of 630 m^3/s or greater, however, inundation depths at all three sites were independent of flow. In addition, Cow Swamp 2, 3, and 4 were inundated at some time during the study period at 10-day mean flows ranging from 45 to 1,000 m^3/s.

Table 9. Information on relations for estimating daily mean inundation depth from 10-day mean flow at two Devils Gut transect sites in the lower Roanoke River basin, North Carolina.

Location	a (eq. 2)	b (eq. 2)	R^2	Standard error of regression (meters)	Number of observations	Range of applicability: 10-day mean flow (cubic meters per second)	Range of applicability: Daily mean water lever (meters above land surface)
Devils Gut 1	-0.23	0.001	0.78	0.13	335	50–1,000	0.0–1.0
Devils Gut 2	-0.08	0.001	0.79	0.11	944	50–1,000	0.0–1.25

Floodplain Water Level and River Stage

Floodplain and river-stage data were examined to determine if floodplain inundation depth could be estimated from measurements of river stage. Daily mean river stage at the Hills Ferry gage (site 8; fig. 10) was a very poor predictor of daily mean inundation depth in the Big Swash transect. Only at river stages greater than about 7.0 m was there any relation between Hills Ferry stage and Big Swash inundation depth, but stages of this magnitude occurred only when flows at Roanoke Rapids were in excess of 700 m^3/s in February and March 1998 and immediately following Hurricane Floyd (September 1999). At Big Swash 1, inundation depth increased linearly from 0 to 0.75 m as Hills Ferry river stage increased from 7.0 m to 7.4 m. Inundation depth at Big Swash 2 increased linearly from 0 to 1.8 m as Hills Ferry river stage increased from 6.8 m to 7.4 m.

The relation between river stage and floodplain inundation depth was somewhat better at the Broadneck Swamp sites (table 10; fig. 20A). Inundation depth at the Broadneck Swamp sites increased almost linearly with river stage between 4.0 m and 5.6 m at Hamilton (site 10) according to the equation:

$$\text{Daily mean inundation depth in meters} = a + b^{*}(\text{river stage in m}). \quad (1)$$

During 1997–2000, river stage at Hamilton was greater than 4.0 m about 25 percent of the time.

The relations between river stage near Woodard (site 22, fig. 2) and inundation depths at the three Devils Gut sites (fig. 20B) also were described by using eq. 3. A fourth- or fifth-order polynomial would give a better prediction of inundation depth from river stage at Devils Gut 1 and 2, but the improved prediction is not worth the added complexity. Although the predictive equations for Devils Gut 1 and 2 apply for river stages greater than 1.0 m, there is a great deal of scatter in the data for stages between 1.0 m and 1.4 m (fig. 20B). Inundation depth at Devils Gut 3 is independent of river stage for stages less than 1.4 m; above this stage, however, Devils Gut 3 inundation depth is the same as Devils Gut 1. Daily mean stage at Woodard (site 22) was between 1.0 and 1.7 m for 25 percent of the time during 1997–2000 and between 1.4 and 1.7 m for 10 percent of the time.

There was no relation between river stage at Plymouth (site 28, fig. 2) and water level at Cow Swamp 1, which as previously noted, generally responds more to upland runoff than to Roanoke River conditions. River stage at Plymouth was a good predictor of water level at Cow Swamp 4 (table 10), even for water levels below land surface (fig. 20C). Cow Swamp 4 (site 27) is closer to the river-stage gage at Plymouth than are Cow Swamp 2 and 3 (sites 25 and 26, respectively, fig. 2). The correlation coefficient (R^2) for the Plymouth–Cow Swamp 2 relation was the poorest of all the river stage–water level relations, but the standard error of regression was relatively small at 0.10 m. River stage at Plymouth was between 0.2 and 1.1 m for 82 percent of the time during 1997–2000.

Table 10. Information on relations for estimating daily mean water level, in meters above land surface, from nearby river-stage data, in meters above sea level, at Broadneck Swamp, Devils Gut, and Cow Swamp transect sites in the lower Roanoke River basin, North Carolina.

Location	a (eq. 3)	b (eq. 3)	R^2	Standard error of regression (meters)	Number of observations	Range of applicability: River stage (meters above sea level)	Range of applicability: Daily mean water lever (meters above land surface)
Relations between Broadneck Swamp water levels and river stage at Roanoke River at Hamilton (site 10)							
Broadneck 1	- 4.24	1.12	0.86	0.17	239	4.0–5.6	0.5–2.1
Broadneck 2	- 3.31	0.85	0.87	0.14	183	4.0–5.6	0–1.5
Broadneck 3	- 3.36	0.84	0.92	0.10	311	4.0–5.6	0–1.5
Relations between Devils Gut water levels and river stage at Roanoke River near Woodard (site 22)							
Devils Gut 1	- 1.77	1.59	0.92	0.08	377	1.0–1.7	0–1.0
Devils Gut 2	- 1.37	1.48	0.90	0.08	263	1.0–1.7	0.15–1.2
Devils Gut 3	- 1.09	1.21	0.95	0.02	110	1.4–1.7	0.6–1.0
Relations between Cow Swamp water levels and river stage at Roanoke River at Plymouth (site 28)							
Cow Swamp 2	- 0.52	1.53	0.82	0.10	1,168	0.2–1.1	- 0.2–1.3
Cow Swamp 3	- 0.46	1.33	0.87	0.07	1,228	0.2–1.1	- 0.2–1.2
Cow Swamp 4	- 0.43	1.11	0.97	0.02	1,203	0.2–1.1	- 0.2–0.9

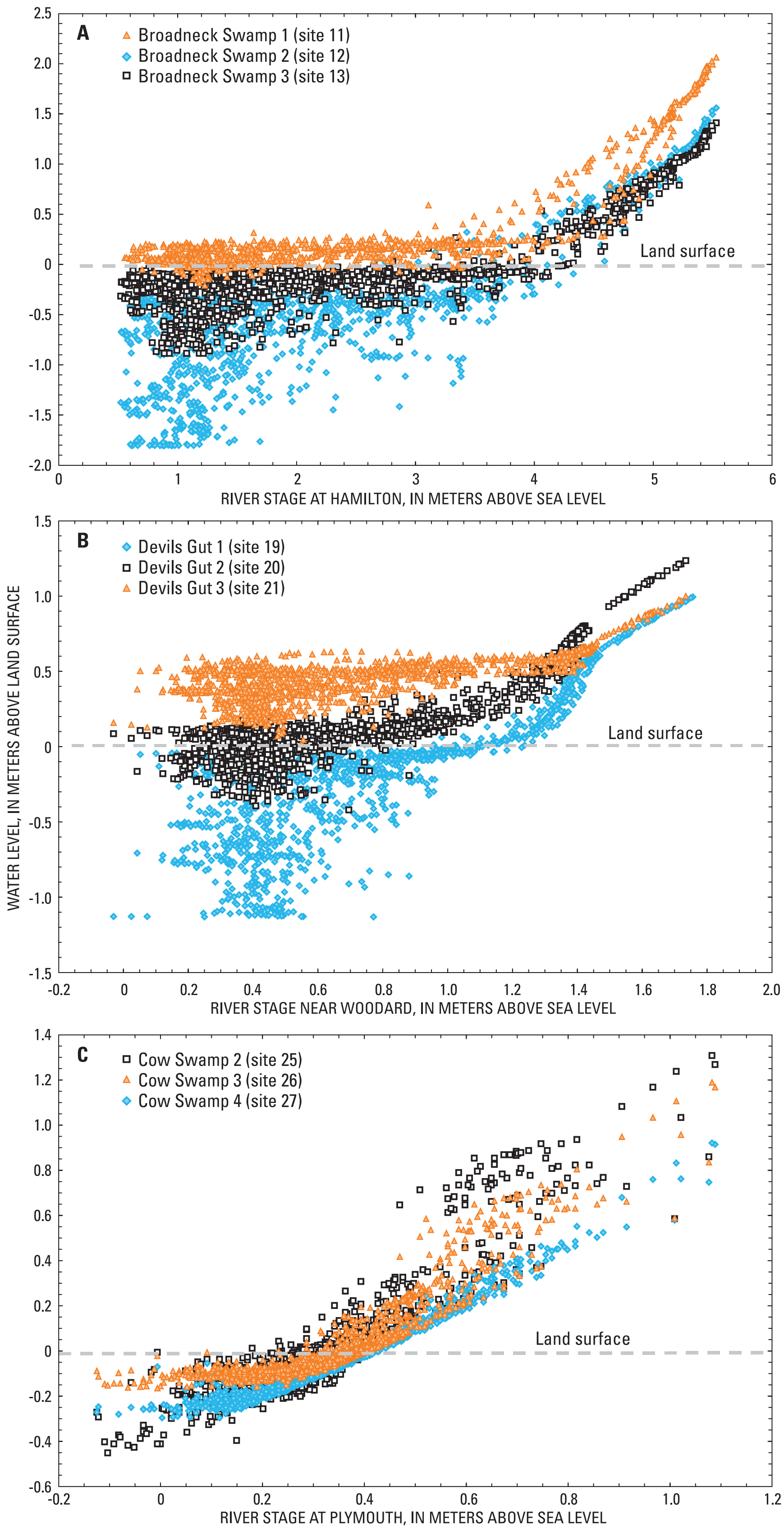


Figure 20. Daily mean water levels relative to land surface and associated daily mean river stages relative to sea level for (A) Broadneck Swamp transect sites (11–13) and Roanoke River at Hamilton (site 10); (B) Devils Gut transect sites (19–21) and Roanoke River near Woodard (site 22); and (C) Cow Swamp transect sites (25–27) and Roanoke River at Plymouth (site 28), North Carolina.

Floodplain Water Level and Precipitation

Rainfall strongly affected water level at Big Swash 1 during unsaturated conditions (when the water level was below land surface) with increases in water level that were substantially greater than associated rainfall totals (fig. 21A). For example, 99 mm of rainfall was measured at Lewiston during February 3–5, 1998, but water level at Big Swash 1 increased more than 200 mm. During May 7–8, 1998, at this site, 37 mm of rainfall was measured, but water level increased by about 300 mm (fig. 21A). The response of the shallow ground-water system to rainfall depends on soil porosity, soil-moisture deficit, rainfall intensity, ground-water level gradients, and perhaps other factors; it is difficult to clearly quantify the effect of each of these factors on ground-water level changes. Nevertheless, given the magnitude of these ground-water level increases in response to rainfall and the fact that these sites probably are downgradient relative to the regional shallow ground-water system, it seems reasonable to conclude that some of the rain that fell in the surrounding area moved as ground water to Big Swash 1. During saturated (flooded) conditions, the effects of rainfall on water level were less obvious (for example, March 9, 1998, fig. 21A), and the increase in water level following rainfall was approximately equal to the rainfall amount. Water levels at Big Swash 2 and 3 responded to rainfall in a manner similar to Big Swash 1. That is, during unsaturated conditions, water levels typically increased more than the rainfall amount, but during saturated conditions, water levels increased only about equal to the rainfall amount.

Water-level response to rainfall at the Broadneck Swamp transect was similar to that at the Big Swash transect—water levels responded more dramatically to rainfall when the site was not flooded (fig. 21B). At Broadneck Swamp 3, rainfall seems to have had a greater effect on water levels 0.3 m or more below land surface than on water levels near, but below, land surface (for example, April–May compared to June–July 2000). It also appears likely that the increased water level near the end of June 2000 was a result of the combined effects of several days of higher river flows and some rainfall (fig. 21B).

Near the Devils Gut transect, it appears that river stage sometimes responds directly to rainfall, unlike the transects farther upstream. For example, on May 28–30, water level at Woodard increased about the same amount as water level at Devils Gut 1 (fig. 21C). During this time, flow at Roanoke Rapids was low and steady at about 100 m^3/s (fig. 21B). At other times, the causes for a water-level increase in the river are less clear because of unsteady flows in the river at Roanoke Rapids occurring in conjunction with rain events (for example, June 20 and July 24, fig. 21C). Note that much of the time during April–August 2000, water level in the floodplain at Devils Gut 1 was higher than in the river, meaning that ground-water movement was from the river into the floodplain.

Water levels at Cow Swamp 1 generally increased in response to runoff from upland areas rather than to Roanoke

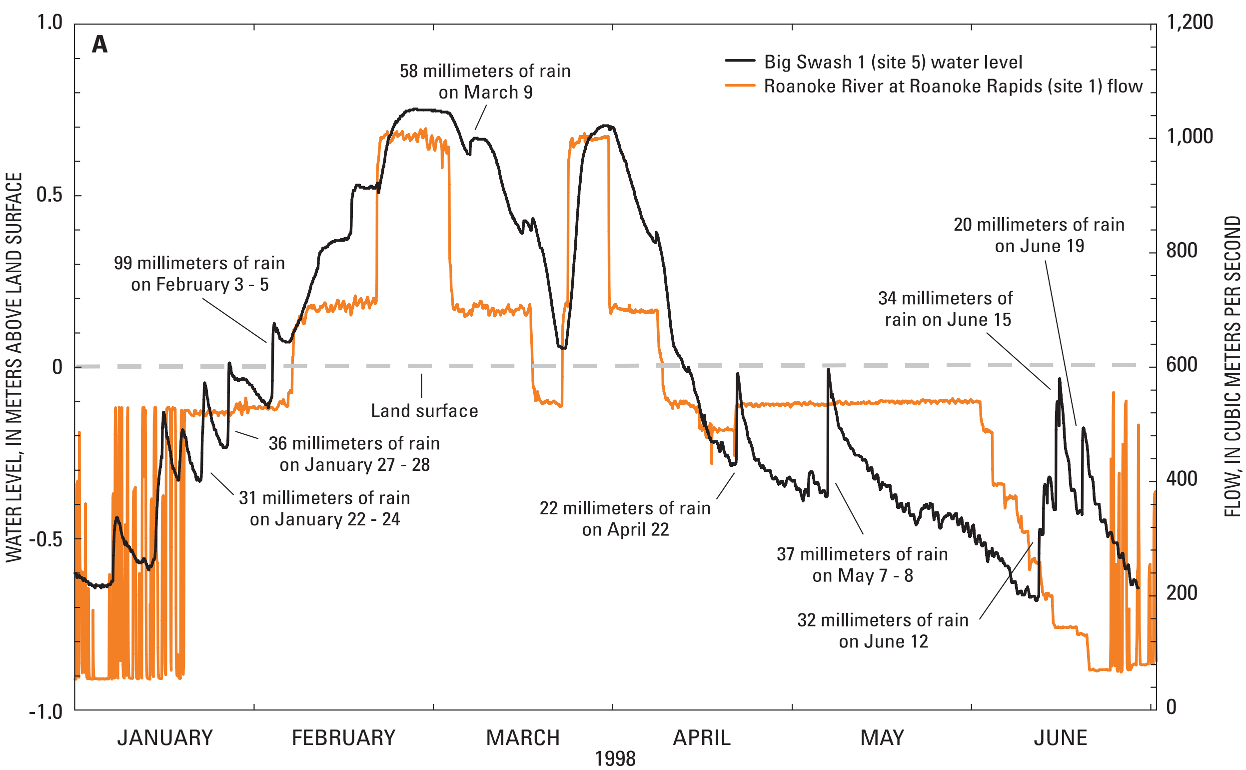


Figure 21. (A) Hourly water levels at Big Swash 1 (site 5), hourly streamflow at Roanoke River at Roanoke Rapids (site 1), and daily rainfall for selected dates at the raingage at Lewiston (site 4), North Carolina, January–June 1998.

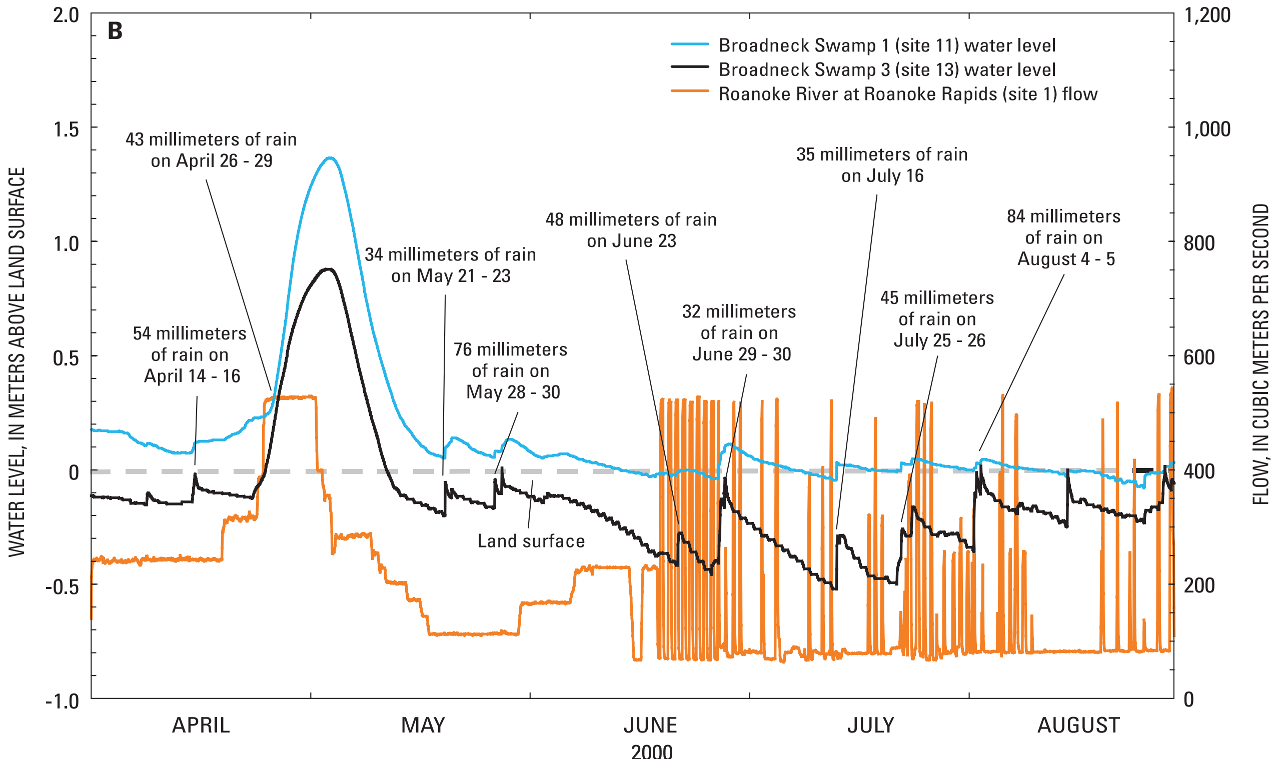


Figure 21. (Continued) (B) Hourly water levels at Broadneck Swamp 1 (site 11) and 3 (site 13), hourly streamflow at Roanoke River at Roanoke Rapids (site 1), and daily rainfall for selected dates at the raingage at Williamston (site 18), North Carolina, April–August 2000.

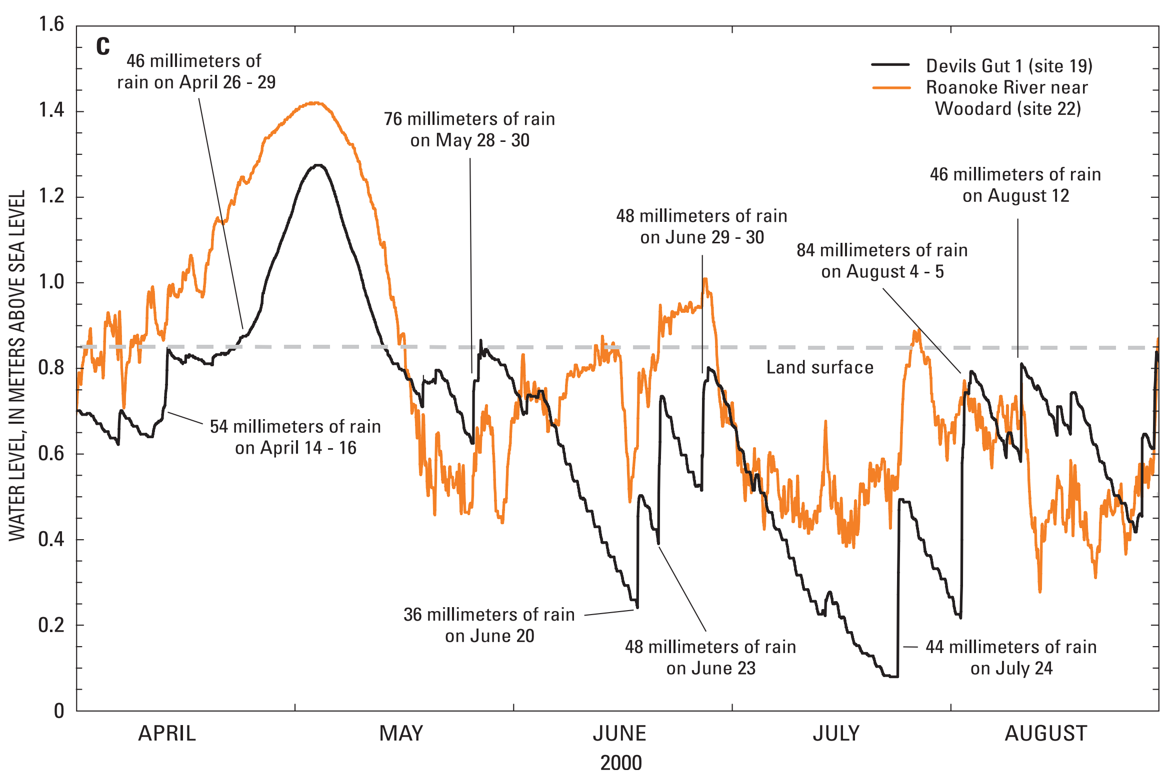


Figure 21. (Continued) (C) Hourly water levels at Devils Gut 1 (site 19) and Roanoke River near Woodard (site 22), and daily rainfall for selected dates at the raingage at Williamston (site 18), North Carolina, April–August 2000.

River water levels, primarily because the elevation of the site is more than 2.5 m above sea level (table 7). Water levels at Cow Swamp 2, 3, and 4 were affected only slightly by rainfall.

Ground-Water Level Gradients

During the summer months, evapotranspiration contributed to water-level declines at all sites. When the water level was above land surface and the site was draining, water levels declined at a fairly uniform rate during the day. When the water level fell below the land surface, however, water levels exhibited a clear daily pattern, with most of the water-level decline occurring between about 10:00 a.m. and 7:00 p.m. (for example, fig. 22) as a result of evapotranspiration from vegetation. At lower water-surface elevations, ground-water levels sometimes recovered slightly during the night (fig. 22), possibly indicating continuing ground-water flow into the site. Similar daily patterns in ground-water level declines were present at all of the floodplain-monitoring sites throughout the study area.

After the water level fell below land surface, ground water declined at almost the same rate at all three Big Swash sites, with rates slightly greater at Big Swash 3. The rate of decline was somewhat consistent from year to year, with rates being the greatest in 1997 (fig. 11). During June 21–July 3, 1998 (fig. 22), ground water declined at a rate of 3.6 cm/d (centimeters per day) at Big Swash 1 and 4.1 cm/d at Big Swash 2. During this period, water level declined slightly faster at Big Swash 2 under flooded conditions, reflecting the combined effects of surface drainage and evapotranspiration. Rates of shallow ground-water decline can vary from site to site and seasonally and are a function of the soil type, vegetation at the site, and daily weather conditions.

Rates of ground-water decline differed between Broadneck Swamp 2 and 3 (sites 12 and 13, respectively), unlike the Big Swash sites where ground-water recession rates

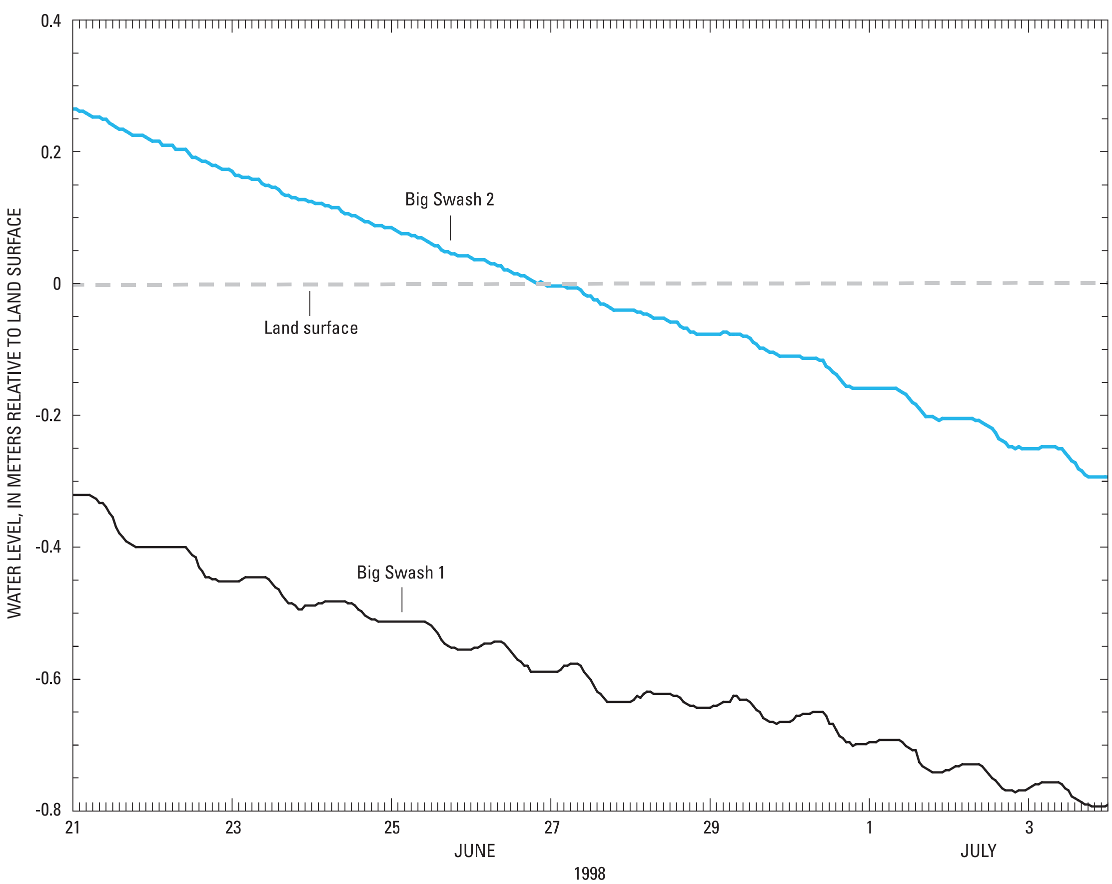


Figure 22. Hourly water levels relative to land surface at Big Swash 1 (site 5) and Big Swash 2 (site 6), North Carolina, June 21–July 3, 1998.

were fairly similar from site to site. Recession rates were much greater at Broadneck Swamp 2 than at Broadneck Swamp 3, which was closer to the Roanoke River than Broadneck Swamp 2. For example, from April through September 1999, ground-water levels declined about twice as much at Broadneck 2 compared to those at Broadneck 3. This pattern was evident during the other summers of the study period (fig. 13), with the exception of 2000 when apparently sufficient rainfall during April–July (fig. 5) prevented large declines.

Summer evapotranspiration at Devils Gut 1 and 2 (sites 19 and 20, respectively) is effective at lowering water levels in the absence of rainfall (fig. 21C), with ground-water levels declining at a rate of about 3–3.5 cm/d during summer months—slightly less than those observed at the Big Swash transect. Because Devils Gut 2 was adjacent to Devils Gut (fig. 14), water levels at the site are more responsive to changes in river stage than at Devils Gut 1. The water-surface elevation at Devils Gut 2 was greater than the elevation at Roanoke River at Jamesville (site 23), indicating a downstream movement of water through Devils Gut. The only exceptions typically occurred when (but not always when) Devils Gut 2 water levels were at least 0.2 m below the land surface. At Cow Swamp 1, water level often declined 4–5 cm during the day, but continuing ground-water flow into the site resulted in a recovery of 2–3 cm during the night.

Whereas minimum water levels at the Big Swash sites were all about the same depth below land surface (table 4), the minimum water levels at the Broadneck Swamp sites varied from 0.23 m below land surface at Broadneck Swamp 1 to 1.8 m below land surface at Broadneck Swamp 2 (table 5). Even so, the lowest ground-water levels measured in Broadneck Swamp were still more than 1.5 m higher than the simultaneously measured river stage at the nearest river-stage gage, indicating a strong potential for ground-water movement from the floodplain to the river during unsaturated conditions.

Simultaneously measured water-surface elevations (relative to sea level) at the three Big Swash sites and the nearby river gage (Roanoke River at Hills Ferry, site 8) were substantially different. For example, at the beginning of April 1999, the water-surface elevation in the river at Hills Ferry was almost 6 m lower than at Big Swash 1. Water-surface elevations at the three Big Swash sites exhibited a consistent gradient throughout the study, with elevations highest at Big Swash 1 and lowest at Big Swash 2, which was the lowest topographically. There also was a strong gradient between Big Swash 3 and the river, with water-surface elevation differences of 2–3 m, indicating ground-water discharge from the area around the site to the river.

Unlike the Big Swash transect, water-surface elevations (relative to sea level) during unsaturated conditions in the Broadneck Swamp transect were relatively uniform from site to site, indicating lower potential for ground-water movement within Broadneck Swamp. In 2000, for example, water-surface elevations at the Big Swash sites generally differed by about 2 m, but the difference among sites at the Broadneck Swamp transect was less than 0.2 m. Likewise, water levels in the Roanoke River were almost always lower than those at the Cow Swamp sites, indicating a continuous potential for ground-water movement from the floodplain to the river.

With only a few exceptions at very high flows, Roanoke River stages near the Big Swash, Broadneck Swamp, and Cow Swamp transects were lower than water-surface elevations in the adjoining floodplain, indicating that both surface- and ground-water drainage were from the floodplain to the river. The water-surface elevations relative to sea level at Devils Gut 1 and 2, however, often were exceeded by the water-surface elevation in the Roanoke River at Woodard (for example, fig. 21C). For example, in July 2000, the elevation in the river exceeded the elevation in Devils Gut 1 by as much as 0.4 m, indicating the potential for river water to move through the ground-water system into the floodplain. Although Devils Gut 1 was located within about 200 m of the river (fig. 14), a natural levee separates the river from Devils Gut 1 so that there is no direct communication between the river and Devils Gut 1 at lower stages.

Summary and Conclusions: Floodplain Water Levels

Some general patterns were evident in the floodplain transect water-level data, but fairly major differences in the relation of inundation to flow occurred both among sites at a given transect and among transects. Big Swash 3 (site 7) was inundated for the full range of 10-day mean flows measured during the study period. This means that the site was inundated on at least one occasion when a 7-day mean flow in the range of 45 to 620 m^3/s occurred (the range of flows for which water levels at Big Swash 3 were measured). The same was true (for 10-day mean flows) at Broadneck 1 (site 11), Devils Gut 2 and 3 (sites 20 and 21, respectively), and Cow Swamp 2, 3, and 4 (sites 25–27). The range of observed 10-day mean flows at these seven sites was 45–1,000 m^3/s.

Big Swash 2 (site 6) was inundated only for 10-day mean flows greater than 120 m^3/s, but the site was not inundated every time a flow of that magnitude or greater occurred. Likewise, Big Swash 1 (site 5) was never inundated for 10-day mean flows less than 500 m^3/s. Broadneck 2 and 3 (sites 12 and 13, respectively) were never inundated at 10-day mean flows less than 230 m^3/s, and Devils Gut 3 (site 21) was never inundated at 10-day mean flows less than 200 m^3/s.

Devils Gut 3 was always inundated during the study (fig. 15), and Broadneck 1 was inundated about 91 percent of the time (table 5). Other sites that were inundated more than half of the time were Cow Swamp 1 (83 percent of the time, table 7) and Devils Gut 2 (74 percent of the time, table 6). All other sites were inundated no more than 41 percent of the time during the study.

The relation of floodplain inundation depth to Roanoke River at Roanoke Rapids flow was highly variable among sites. There was no relation between flow and inundation depth at Big Swash 1 or the four Cow Swamp sites. At Big Swash 2 and 3, there was some relation between inundation depth and 10-day mean flow for flows greater than 600 m^3/s. A relatively strong relation between inundation depth and 10-day mean flow occurred at Broadneck 2 and 3 and, to a lesser extent, at Devils Gut 1 and 2. At Broadneck 1, which was inundated 91 percent of the time during the study, inundation depths greater than 0.2 m were strongly related to 10-day mean flow. The inundation depth at Broadneck 2 and 3 was independent of the flow rate for 10-day mean flows between 600 and 1,000 m^3/s, and the inundation depth was relatively constant at 1.5 m for these flows. At Devils Gut 3, inundation depth was always between 0.5 and 0.65 m for 10-day mean flows between 300 and 550 m^3/s; at flows greater than 550 m^3/s, the relation between inundation depth at Devils Gut 3 and 10-day mean flow was the same as that for Devils Gut 1.

There was much greater interannual variability in floodplain water levels, as represented by the difference between the maximum and minimum daily water level for a date (fig. 18) during January–May and September–October than during the summer and late fall months. If data from this study are representative of long-term conditions, then this means that there is less uncertainty about what future floodplain water levels will be during June–August and November–December than during other months. Additional data are needed to determine if 1997–2000 conditions represent long-term floodplain water-level characteristics.

Rates of ground-water decline, primarily from evapotranspiration, were fairly similar at all sites, ranging from about 3 to 4 cm/d. The Townsend and Foster (2002) relation for estimating inundated area in the upper Roanoke River floodplain (upstream from about Plymouth, but including most of the Cow Swamp transect) gives an estimate of 330 km^2 inundated at a 10-day mean flow of 500 m^3/s. If the evapotranspiration rate in this entire 330-km^2 area were 2 cm/d (a conservative estimate based on floodplain transect observations), as much as 75 m^3/s of water could be lost to the atmosphere during the growing season; at a 10-day mean flow of 300 m^3/s, the loss rate would be about 56 m^3/s. These estimates of water loss through evapotranspiration are in general agreement with the conclusion that at daily mean flows greater than 230 m^3/s, between 10 (Lebo, 1999) and 20 percent (Lebo, 1998) of the river flow released at Roanoke Rapids Dam is lost between the dam and river kilometer 17 near Plymouth. Evapotranspiration rates are, of course, much lower during the fall and winter months, so losses of river flow to floodplain processes likely would be much lower than 2 cm/d during that time. Data from this study, however, also suggest that evapotranspiration rates could be as high as 4 cm/d during the summer. Daily mean flows in excess of 500 m^3/s occurred only about 10 percent of the time during the study period, and daily mean flows in excess of 300 m^3/s occurred less than 20 percent of the time (fig. 7A).

The ground-water gradient at most sites was from the floodplain to the river, indicating a potential for ground-water movement into the river from the floodplain. At two of the Devils Gut sites, however, the water level often was higher in the river than in the floodplain when floodplain sites were not inundated. This indicates that there is a potential for river water to move as ground water from the river into the floodplain. It seems likely that this feature observed at the Devils Gut transect occurs elsewhere in the lower Roanoke River corridor.

Instream Dissolved-Oxygen Conditions, 1998–2001

Dissolved-oxygen conditions during 1998–2001 at the five continuous, in situ water-quality monitoring stations in the Roanoke River are described in this section. The stations shown in figure 2, from upstream to downstream, include Halifax (site 2), near Oak City (site 9), near Grabtown (site 15), Jamesville (site 23), and the NC-45 bridge (site 31). Summaries of DO conditions at each site are provided, the occurrences of DO concentrations less than 5 mg/L are discussed, and seasonal and annual characteristics are summarized. The relation of DO to river flow and to floodplain water-level conditions is discussed, and the distribution of DO along the Roanoke River is characterized for selected conditions.

Sites Characteristics

Halifax

The Halifax gage (site 2, table 1; fig. 2) is located at river kilometer 187, or about 25 km downstream from Roanoke Rapids Dam. Four permitted point sources (sites 2, 9, 11, and 22, table 3; fig. 3) are located between Roanoke Rapids Dam and the gage. The gage is located on the right bank of the river, and the sensor is approximately 2 m from the bank at low flow. There was good agreement between DO measured by the in situ monitors and DO measurements made near the water surface by the North Carolina Division of Water Quality (NCDWQ; fig. 23).

The median hourly DO concentration at Halifax was 8.4 mg/L, and 90 percent of the measured concentrations were greater than 6 mg/L (table 11). The summer (June–September) median concentration was 6.5 mg/L (table 12), but the summer median concentration (80 percent of saturation concentration) remained relatively high (table 13).

Supersaturated DO conditions (DO concentration greater than 100 percent of saturation concentration) occurred more frequently at Halifax than at the other sites. In 1999, for example, 28 percent of the measured concentrations were at or above saturation concentration (table 11). Periods of fairly consistent supersaturated conditions included June–July 1998, September 1998–July 1999, December 1999, and May 2000. Flows generally were lower than normal during these periods (fig. 6).

During winter months, DO concentrations at Roanoke Rapids typically were higher than concentrations at Halifax (fig. 23). On days when DO concentrations at Halifax were about 9 mg/L or less, concentrations at Roanoke Rapids and at Scotland Neck were similar to concentrations at Halifax.

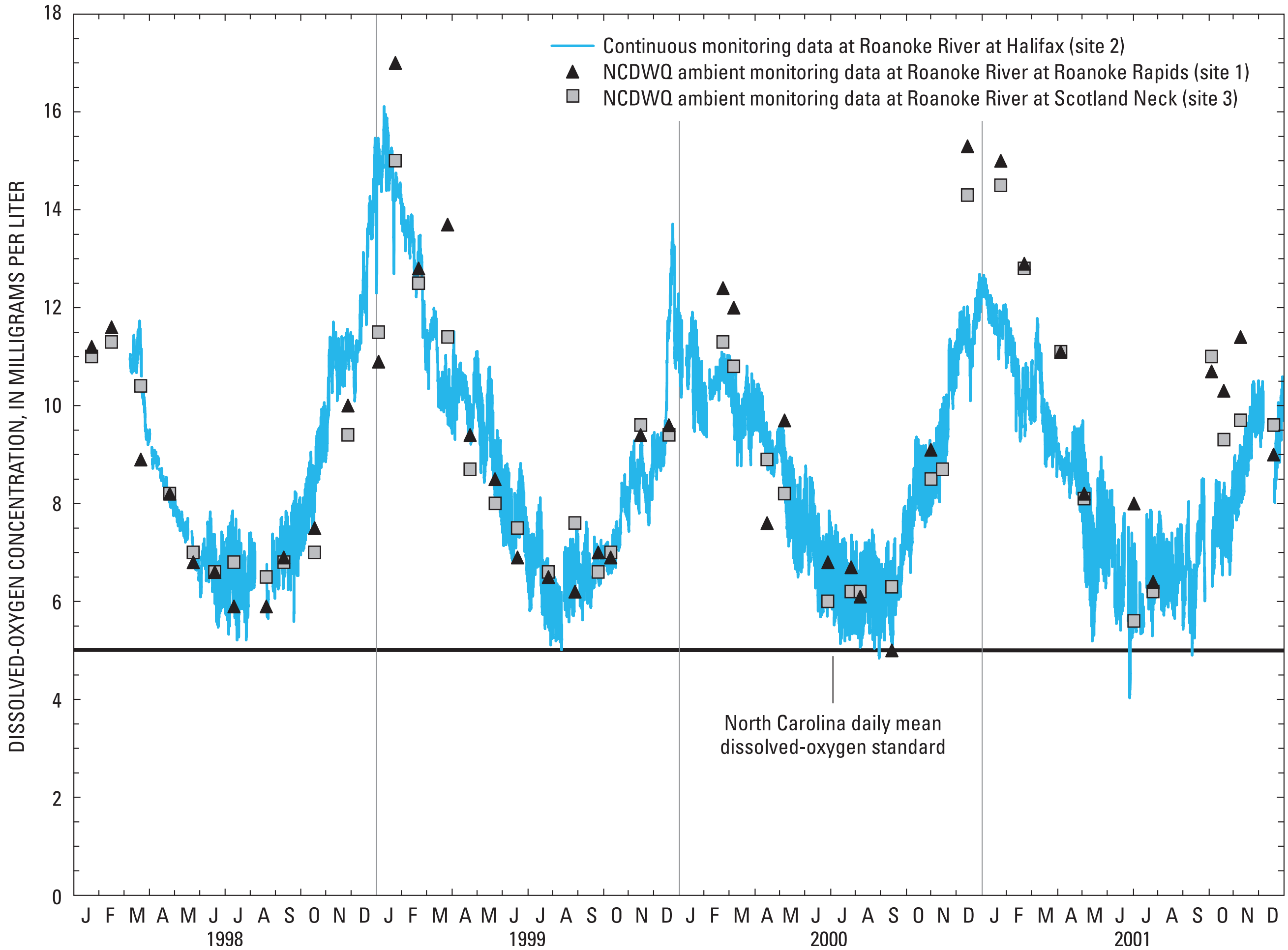


Figure 23. Hourly dissolved-oxygen concentrations at Roanoke River at Halifax (site 2), and instantaneous dissolved-oxygen concentrations measured by the North Carolina Division of Water Quality at Roanoke River at Roanoke Rapids (site 1) and at Scotland Neck (site 3), North Carolina, 1998–2001.

Table 11. Summary of hourly dissolved-oxygen measurements at five in situ continuous monitoring sites in the Roanoke River, North Carolina, 1998–2001.

[mg/L, milligrams per liter; <, less than]

Location (fig. 2)	Concentrations, in mg/L, at percentile shown					Percent of measurements less than value shown		Percent of measurements greater than 100-percent saturation concentration	Percent of period measured
	90	75	50	25	10	5 mg/L	4 mg/L		
					1998				
Halifax (site 2)	11.3	10.5	7.8	6.7	6.2	0	0	25	71.0
Oak City (site 9)	11.1	10	8.0	7.2	6.8	0	0	3	61.8
Grabtown (site 15)	9.5	8.6	7.2	6.4	6.1	0.4	0	1	79.7
Jamesville (site 23)	10.2	8.9	6.7	5.8	4.9	11.3	2.1	2	78.2
NC-45 bottom (site 31)	10.4	9.0	6.3	5.2	4.5	19.7	6.6	7	77.0
					1999				
Halifax (site 2)	13.9	11	8.7	7.0	6.2	0	0	28	99.0
Oak City (site 9)	11.3	9.7	8.5	7.0	6.1	5.4	2.0	4	67.2
Grabtown (site 15)	11.1	9.4	8.3	6.6	6.0	4.9	0	18	75.6
Jamesville (site 23)	11.0	9.0	6.8	5.7	4.4	16.0	5.5	5	90.4
NC-45 bottom (site 31)	11.3	9.3	6.6	4.4	2.8	31.1	21.8	7	89.0
					2000				
Halifax (site 2)	11	10.3	8.7	6.8	5.3	0.1	0	2	97.7
Oak City (site 9)	11.7	10.2	8.0	6.4	5.8	.5	0	0	91.6
Grabtown (site 15)	11.4	10.1	7.6	6.3	4.6	12.0	6.0	7	82.2
Jamesville (site 23)	10.8	9.3	7.4	5.6	5.1	6.1	0	0	99.9
NC-45 bottom (site 31)	12.5	10.0	7.4	5.6	5.1	8.2	.2	12	86.2
[a]NC-45 mid-depth (site 31)	10.0	6.9	6.2	5.6	5.1	6.0	0	<1	98.5
					2001				
Halifax (site 2)	11.4	9.8	8.2	6.7	6.0	0.4	0	1	90.4
Oak City (site 9)	11.2	9.2	7.7	6.4	6.2	1.6	.1	0	95.6
Grabtown (site 15)	11.2	9.6	7.6	6.5	6.1	.7	.2	2	76.7
Jamesville (site 23)	10.8	9.0	7.1	5.6	5.0	10.3	2.7	0	95.9
NC-45 bottom (site 31)	11.0	9.3	6.5	5.2	3.7	22.4	14.5	2	89.1
[a]NC-45 mid-depth (site 31)	10.0	8.3	6.5	5.7	4.5	14.0	4.2	<1	95.8
					All data				
Halifax (site 2)	11.5	10.2	8.4	6.8	6	0.1	0	14	89.5
Oak City (site 9)	11.3	9.7	8.0	6.7	5.9	1.8	.4	2	79.1
Grabtown (site 15)	11.0	9.4	7.6	6.4	5.9	4.6	1.7	7	78.5
Jamesville (site 23)	10.7	9.0	7.0	5.6	5.0	10.8	2.6	1	91.1
NC-45 bottom (site 31)	11.4	9.5	6.6	5.3	3.9	20.0	10.4	7	94.5
[a]NC-45 mid-depth (site 31)	10.0	8.0	6.4	5.6	4.9	10.9	2.6	<1	98.9

[a]The mid-depth sensor was installed in May 2000.

Table 12. Summary of summer (June–September) hourly dissolved-oxygen concentrations at five in situ continuous monitoring sites in the Roanoke River, North Carolina, 1998–2001.

[mg/L, milligrams per liter]

Location (fig. 2)	Percent of measurements less than value shown		Mean (mg/L)	Median (mg/L)
	5 mg/L	4 mg/L		
Halifax (site 2)	0.4	0	6.5	6.5
Oak City (site 9)	5	1	6.3	6.3
Grabtown (site 15)	6	0.2	6.6	6.4
Jamesville (site 23)	24	4.8	5.4	5.5
NC-45 bottom (site 31)	45	24	4.8	5.1
[a]NC-45 mid-depth (site 31)	24	6	5.5	5.7

[a]The mid-depth sensor was installed in May 2000.

Table 13. Summary of hourly dissolved-oxygen saturation concentrations, in percent, at five in situ continuous monitoring sites in the Roanoke River, North Carolina, 1998–2001.

[<, less than; %, percent; summer months are June–September]

Location (fig. 2)	Mean (percent saturation)		Median (percent saturation)		Percentage of values <80% saturation		Percentage of values <50% saturation	
	All data	Summer	All data	Summer	All data	Summer	All data	Summer
Halifax (site 2)	88	80	87	80	25	51	0	1
Oak City (site 9)	85	78	84	78	31	58	0.8	2
Grabtown (site 15)	83	81	83	80	41	49	3	0.3
Jamesville (site 23)	75	67	77	69	65	93	5	8
NC-45 bottom (site 31)	73	59	74	64	62	96	12	24
[a]NC-45 mid-depth (site 31)	72	68	72	70	78	91	3	6

[a]The mid-depth sensor was installed in May 2000.

Oak City

The Oak City gage (site 9, table 1; fig. 2) is located at river kilometer 106, or about 81 km downstream from the Halifax gage. The gage is located on the right bank of the river, and the sensor is located near mid-depth at low flows (100 m^3/s or less). Seven permitted point sources (sites 10, 13–16, 18, and 20, table 3; fig. 3) are located between the Halifax gage and the Oak City gage. The Big Swash transect is between the Halifax and Oak City gages; Big Swash 3 (site 7) is located about 14 km upstream from the Oak City gage.

A set of detailed DO measurements was made in the river channel at the Oak City gage on December 4, 2001. The maximum depth in the cross section at the time of measurement was 4.25 m, and the daily mean flow during December 2–4 was 58 m^3/s. Near-surface, mid-depth, and near-bottom measurements were made at 12 stations equally spaced across the channel. Measured DO at the 36 measurement points (3 points in the vertical at each of 12 stations) ranged from 8.1 to 8.4 mg/L, so the DO concentration under this relatively low-flow condition was uniform throughout the cross section. Similar but less detailed measurements were made throughout the study period with the same results—DO was uniformly mixed laterally and vertically at the Oak City measurement section. Dissolved-oxygen concentrations from the continuous monitor also were in very good agreement with individual measurements made by the NCDWQ using a field meter (fig. 24) at the same site.

The median DO concentration at Oak City during 1998–2001 was 8.0 mg/L (table 11), and the median concentration during summer months was 6.3 mg/L—about the same as at Halifax (table 12). The median percentage for saturation concentration was 84 percent for the full period of record and 78 percent for summer months. The percentage of measurements having a DO concentration less than 80 percent of saturation concentration, however, was almost twice as large for summer conditions as for the full period of record; the same was true for DO concentrations less than 50 percent of saturation concentration (table 13; fig. 25).

Grabtown

The Grabtown gage (site 15, table 1; fig. 2) is located at river kilometer 74, or about 32 km downstream from the Oak

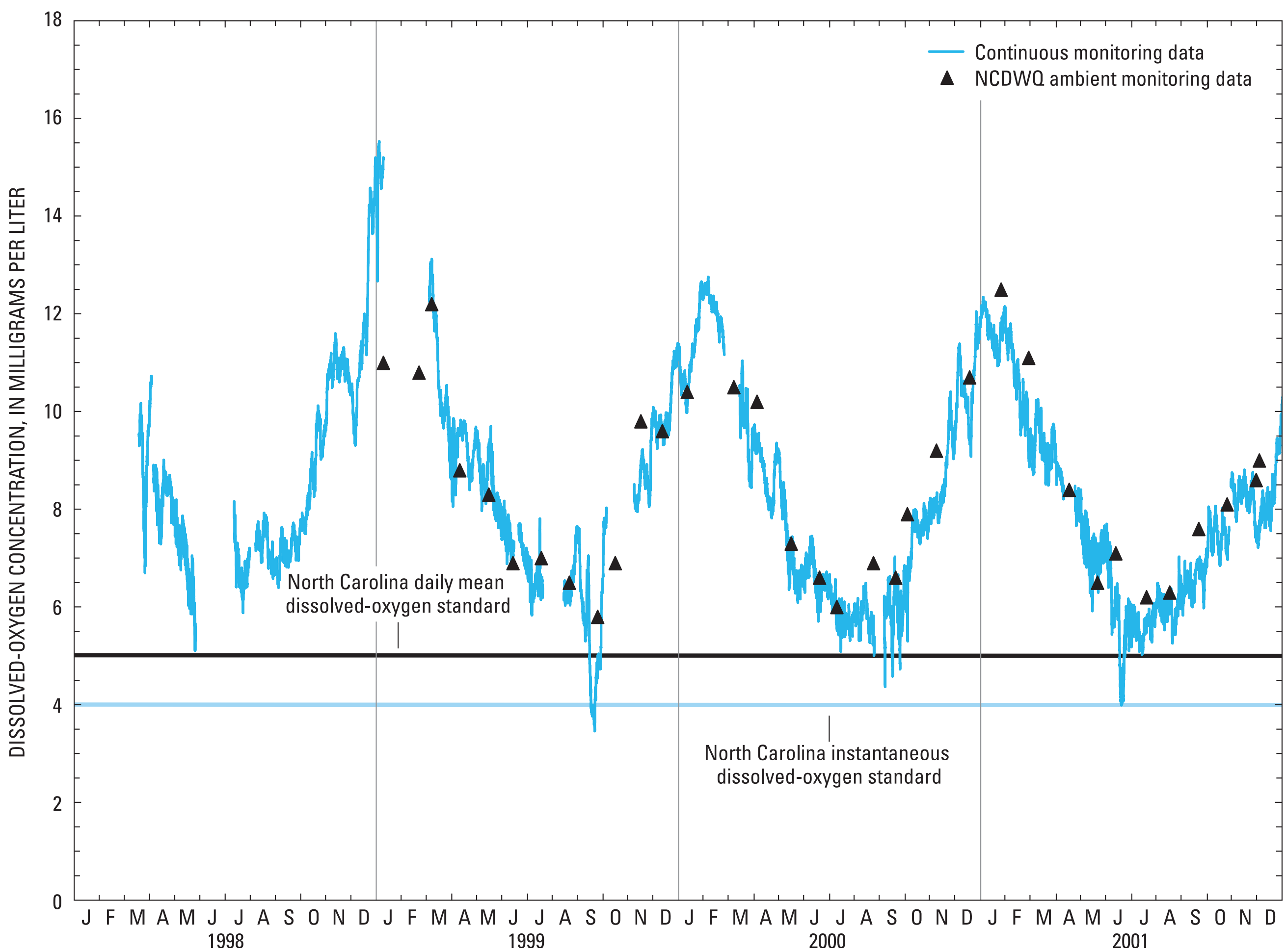


Figure 24. Hourly dissolved-oxygen concentrations at Roanoke River near Oak City (site 9), and instantaneous dissolved-oxygen concentrations measured by the North Carolina Division of Water Quality at the site, 1998–2001.

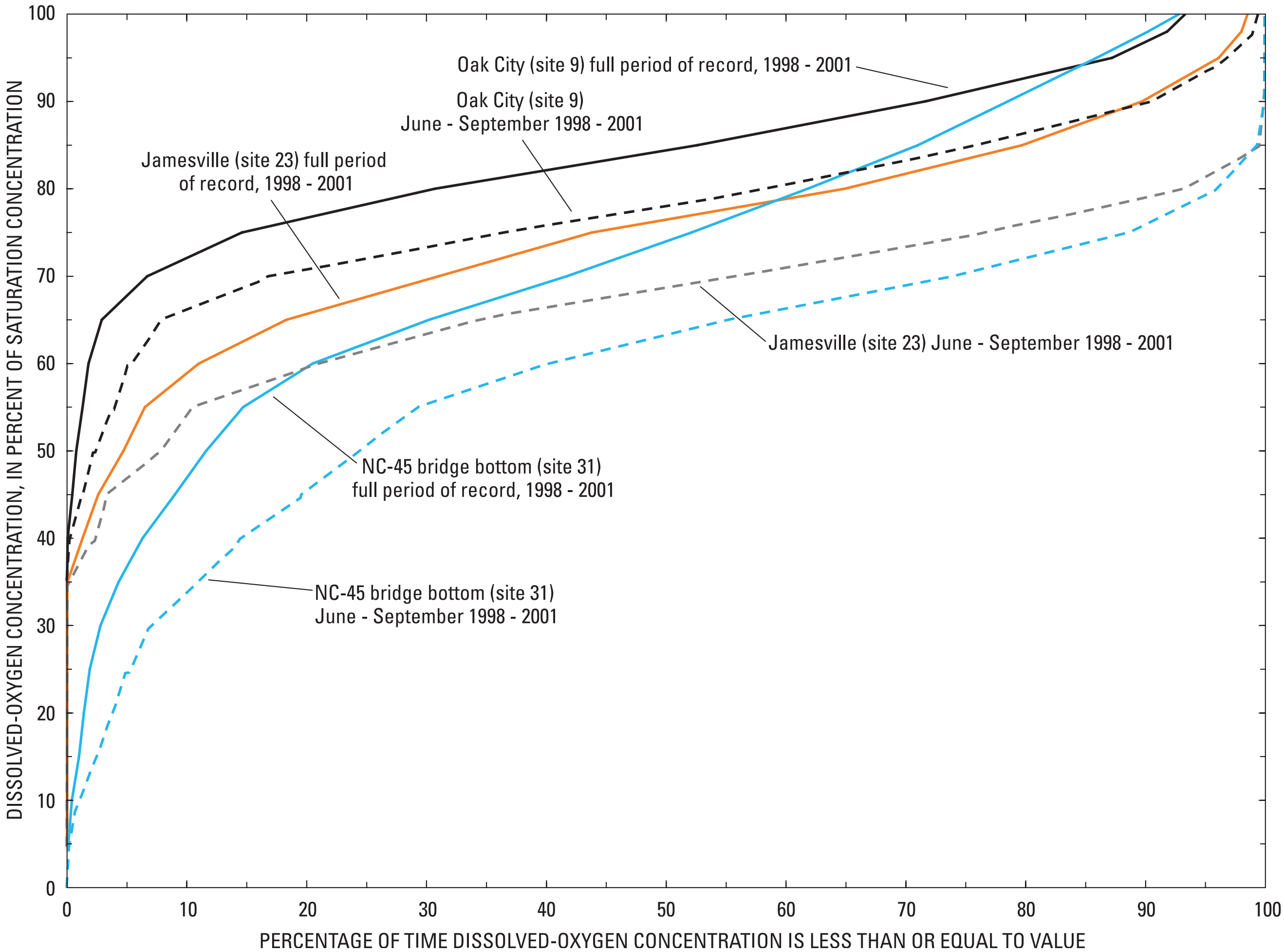


Figure 25. Frequency of occurrence of dissolved-oxygen concentrations, in percent of saturation concentration, at Roanoke River near Oak City (site 9), Roanoke River at Jamesville (site 23), and Roanoke River at the NC-45 bridge near-bottom sensor (site 31), North Carolina, for the full period of record and for summer (June–September) conditions, 1998–2001.

City gage (site 9). The Grabtown gage is on the left bank of the river, and the sensor is located about 2 m from the streambank. Coniott Creek (fig. 2) enters the Roanoke River about 50 m upstream from the gage. Two small permitted point sources (sites 3 and 19, table 3; fig. 3) are located between the Oak City gage and the Grabtown gage. The Broadneck Swamp transect (sites 11–13, fig. 2) is between the Oak City and Grabtown gages; Broadneck Swamp 3 (site 13) is about 21 km upstream from the Grabtown gage.

A set of detailed DO measurements was made in the river channel at the Grabtown gage on December 5, 2001. The maximum depth in the cross section at the time of measurement was 11 m, and the daily mean flow during December 3–5 was 58 m^3/s. Near-surface, mid-depth, and near-bottom measurements were made at 10 stations equally spaced across the channel. Measured DO at the 30 measurement points (3 points in the vertical at each of 10 stations) ranged from 7.8 to 8.1 mg/L, indicating that the DO concentration under this low, steady-flow condition was uniform throughout the cross section. Cannon and Graham (2002) also found the water column to be well mixed during July 2001 at flows ranging from about 70 to 530 m^3/s. Specific conductance, which is a measure of conservative mixing, was constant throughout the cross section at 145 µS/cm (microsiemens per centimeter at 25 degrees Celsius). It is possible that inflow from Coniott Creek, which enters the Roanoke River on the side of the river on which the gage is located, occasionally resulted in point DO readings at the gage that were unrepresentative of the cross-sectional mean DO concentration in the river. There was, however, no evidence in the somewhat limited field measurements to indicate a lateral or vertical DO gradient at the site. Cannon and Graham (2002) noted that the DO concentration in the river upstream from the mouth of the creek was about the same as the DO concentration in the river 100 m downstream from the mouth of the creek, even when the creek was draining. Their measurements were made during experimental, high-volume load-following flow releases from Roanoke Rapids Power Station, which resulted in flooding and drainage of the backswamps adjacent to Coniott Creek.

The median DO concentration at Grabtown during 1998–2001 was 7.6 mg/L. Hourly DO concentrations were greater than 100-percent saturation concentration 7 percent of the time during 1998–2001, and 18 percent of the time in 1999 (table 11; fig. 26).

Considering the entire period of record, daily mean DO concentrations at Grabtown were only slightly less than at Oak City (table 11). During summer conditions, the mean and median DO concentrations at Grabtown were slightly greater than at Oak City (table 12). The average difference between daily mean concentrations at Oak City and Grabtown for 1998–2001 was 0.2 mg/L, which was calculated by taking the difference in daily mean concentrations at the two sites for each day during 1998–2001 for which both sites had record and computing the average over the period. In 2001, Grabtown daily mean DO concentrations averaged 0.45 mg/L greater than those at Oak City. Grabtown and Oak City did, however, have the highest percentage of missing record (table 11), with much of the data missing during warm-weather months, so comparisons between the two sites would be more meaningful if complete data were available.

Jamesville

The Jamesville gage (site 23, table 1; fig. 2) is located at river kilometer 31, or about 43 km downstream from the Grabtown gage (site 15). The gage is on the right bank of the river, and the channel is about 3 m deep at the gage. The Devils Gut transect (sites 19–21) is between the Grabtown and Jamesville gages, and there are three point-source discharges between these two gages. Devils Gut 1 (site 19, fig. 2) is about 14.7 km upstream from the Jamesville gage, and Devils Gut 2 (site 20, fig. 2) is located adjacent to Devils Gut and about 6.8 km upstream from the Jamesville gage. The river generally was well-mixed near the Jamesville gage, with little lateral and vertical variations in specific conductance and DO concentration.

The median DO concentration at Jamesville during 1998–2001 was 7.0 mg/L, or 0.6 mg/L less than the median at Grabtown (table 11). The summer median DO concentration at Jamesville was 0.9 mg/L less than at Grabtown (table 12), and 93 percent of all of the summer measurements at Jamesville were less than 80 percent of saturation concentration, compared to 49 percent at Grabtown (table 13).

A unique characteristic of water-quality conditions at Jamesville was the occurrence of lower-than-normal pH during periods of low DO concentration. During the low DO events of August–September 1998, September–November 1999, and June 2001, pH at Jamesville was as low as 6.0 standard units, whereas the average pH at the site during the entire study period

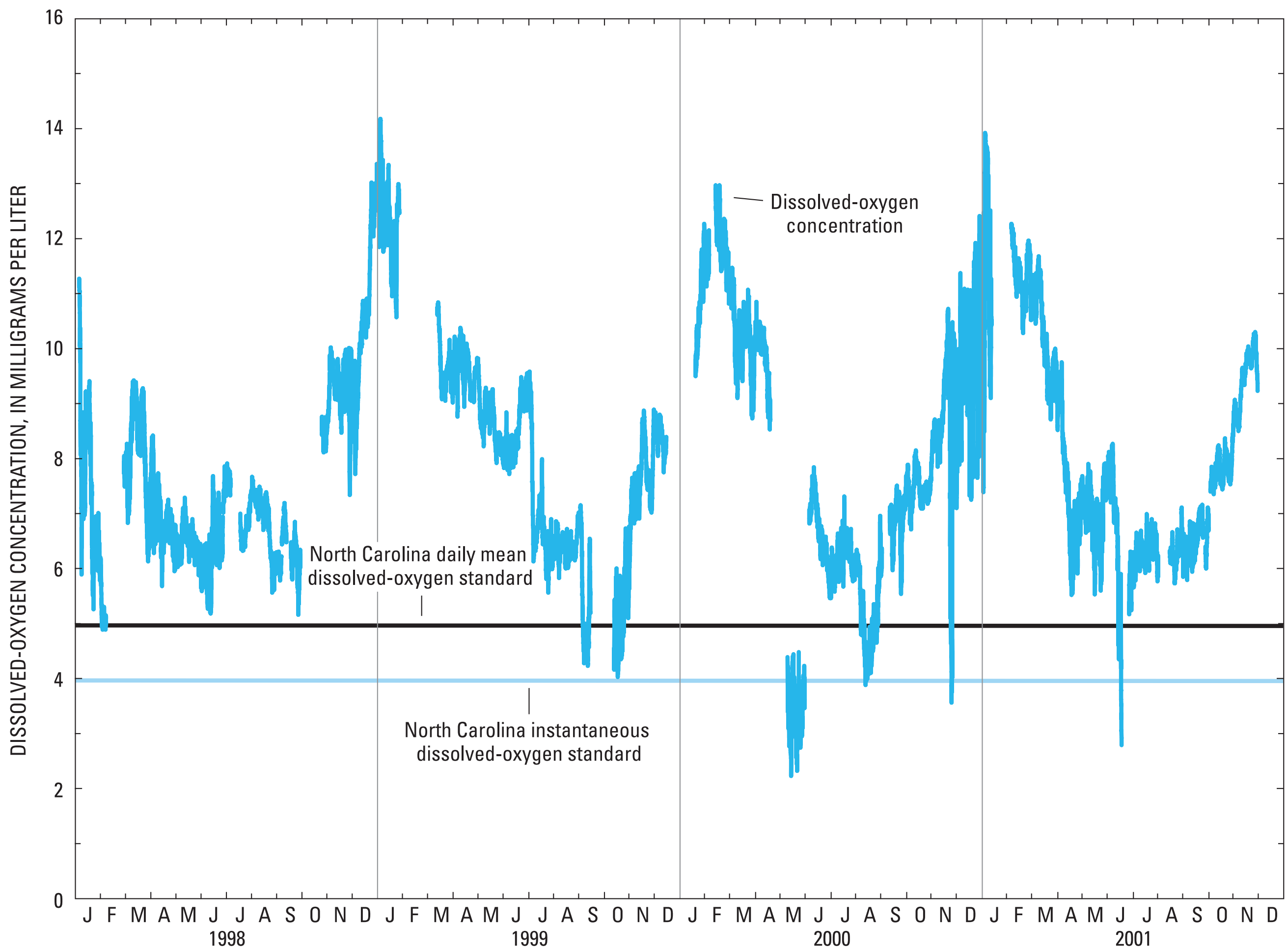


Figure 26. Hourly dissolved-oxygen concentrations at Roanoke River near Grabtown (site 15), North Carolina, 1998–2001.

was 6.85. The pH was about 6.5 during May and August–September 2000, when daily mean DO concentrations of less than 5 mg/L occurred. The lower pH is consistent with increased presence of floodplain drainage in the river. For example, Cannon and Graham (2002) observed that the pH in Devils Gut was lower when the floodplain was draining than during other conditions, whereas there was only a slight drop in pH in Coniott Creek as Broadneck Swamp drained. The pH in Devils Gut was about 6.2 during floodplain drainage conditions in July 2001 (Cannon and Graham, 2002).

Dissolved-oxygen concentrations at Jamesville were lower than those measured at Williamston (fig. 27), but the general temporal patterns were the same at both locations. Likewise, daily mean DO concentrations at Jamesville were almost always less than those at Grabtown. The median difference between daily mean DO at Jamesville and at Grabtown was 0.9 mg/L, and 40 percent of the time the difference was greater than 1 mg/L.

NC-45 Bridge

The NC-45 gage (site 31, table 1; fig. 2) is located at river kilometer 2.6, or about 28 km downstream from the Jamesville gage (site 23). Two point-source discharges, including the largest discharge in the study area, are between the Jamesville and NC-45 gages. The Cow Creek transect (sites 24–27, fig. 2) is about midway between the Jamesville and NC-45 gages.

The NC-45 gage is located near the center of the channel on a pier fender at the NC-45 bridge. The bottom sensor, which was in place throughout the entire study period, was about 0.6 m above the river bottom, and the mid-depth sensor, installed on May 10, 2000, was about 4.2 m above the bottom. On average, the river is about 6.4 m deep at the gage site. Directly upstream from the NC-45 bridge, the river is about 4.5 m deep (Lebo, 2000). A short distance downstream from the gage, the river deepens to about 9 m; moving downstream, the river depth gradually decreases to about 5.5 m (Lebo, 2000).

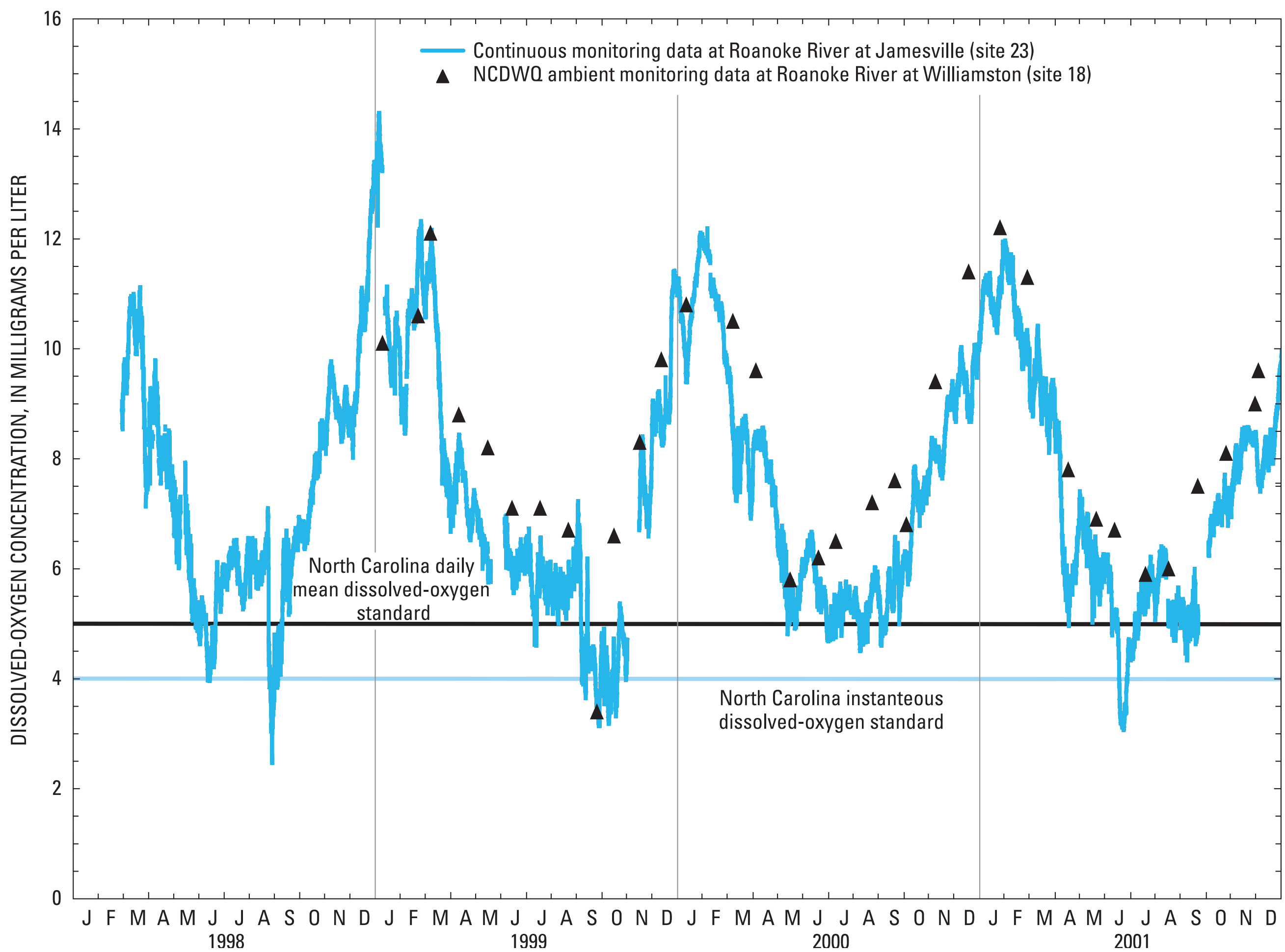


Figure 27. Hourly dissolved-oxygen concentrations at Roanoke River at Jamesville (site 23), and instantaneous dissolved-oxygen concentrations measured at Roanoke River at Williamston (site 18) by the North Carolina Division of Water Quality, 1998–2001.

Lebo (2000) suggested that the abrupt increase in depth directly downstream from the gage enhances the potential for vertical gradients in DO at the gage.

The Roanoke, Eastmost, Middle, and Cashie Rivers are hydraulically connected along the length of the NC-45 bridge. Although limited flow data have been collected in this part of the river, the flow patterns in this distributary undoubtedly are complex. Upstream flows and instantaneous discharges of only 1 m^3/s have been measured in the distributary (Miller and Walters, 2001). The water surface between Jamesville and the NC-45 bridge also has been observed to slope upstream. For example, during October 1990, the water level at Jamesville was lower than that measured simultaneously at NC-45 about 10 percent of the time (Bales and others, 1993). The presence of higher water levels downstream relative to those upstream indicates that reverse flows likely occurred. Upstream flow velocities were observed at river kilometers 3, 6, and 20 during August–September 1997 (Lebo, 1998). Tidal fluctuations in velocity were observed at all three locations, and flow reversals occurred almost daily at river kilometer 2. This complex flow pattern and the absence of continuous DO data elsewhere along the NC-45 bridge complicate interpretation of the NC-45 data.

The median DO concentration at the bottom NC-45 sensor during 1998–2001 (fig. 28) was 6.6 mg/L, and the median DO concentration for the mid-depth sensor was 6.4 mg/L for the period May 10, 2000–December 31, 2001 (table 11). The summer median DO concentration was 5.1 mg/L at the bottom sensor and 5.7 mg/L at the mid-depth sensor.

Data from the mid-depth and bottom sensors were compared for times when data were available at both locations (May 11, 2000–December 31, 2001, excluding periods with missing data). The median DO concentration at the mid-depth sensor during this time was 6.3 mg/L, and the median concentration at the bottom sensor was 6.1 mg/L. Hourly DO concentrations were less than 4 mg/L for 2.6 percent of the time at the mid-depth sensor and 8.7 percent of the time at the bottom sensor. Daily mean DO concentrations were less than 5 mg/L for 12 percent of the time at the mid-depth sensor and 18 percent of the time at the bottom sensor during this common data period.

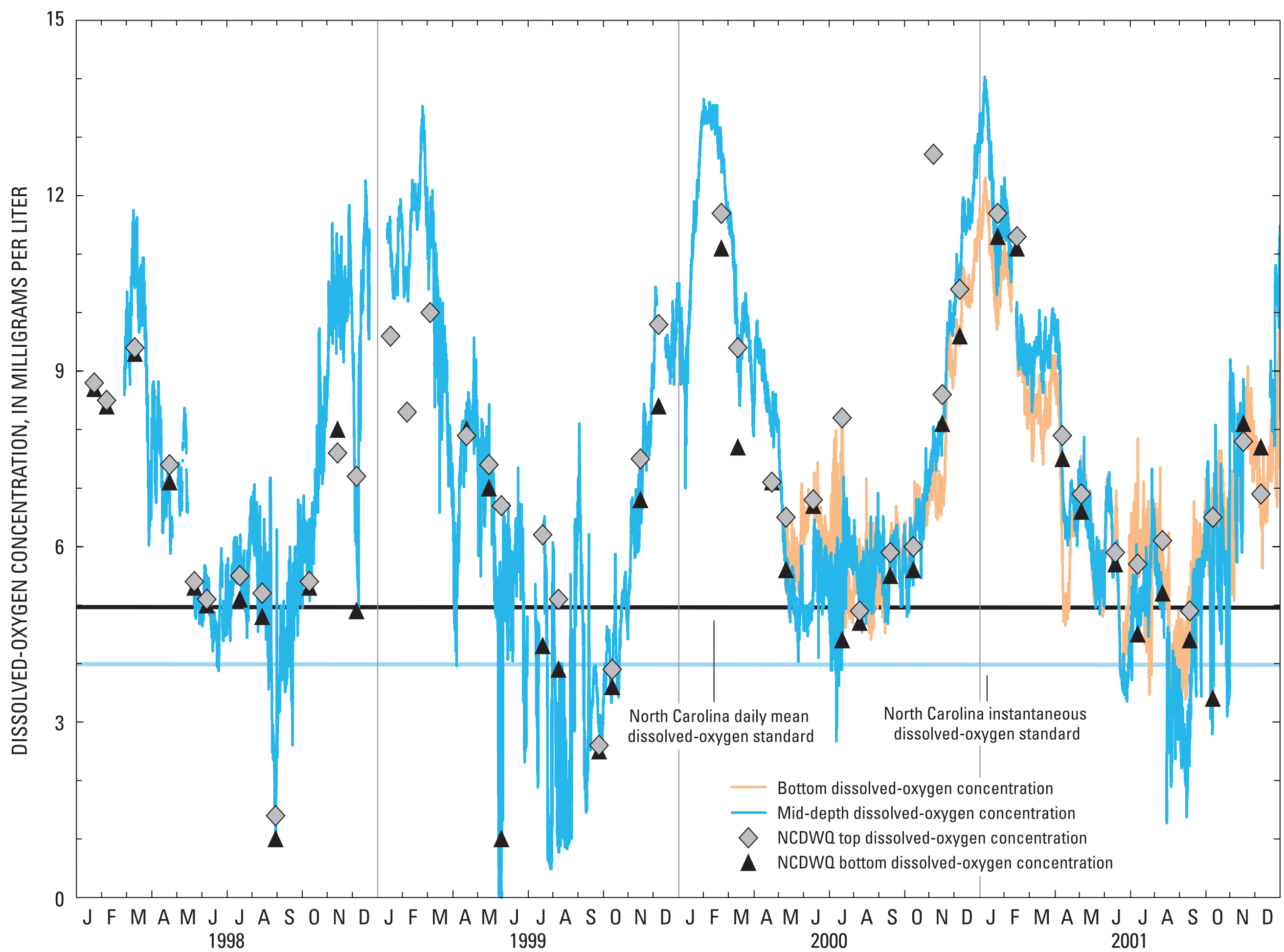


Figure 28. Hourly dissolved-oxygen concentrations at Roanoke River at the NC-45 bridge (site 31), and instantaneous dissolved-oxygen concentrations measured by the North Carolina Division of Water Quality at the site, 1998–2001.

This information does not, however, give a complete picture of the relation of the mid-depth to bottom DO concentration at the NC-45 bridge. Simultaneously measured DO concentrations were often higher at the bottom sensor than at the top sensor. During the time when both sensors were operating, 54 percent of the hourly DO concentrations at the bottom were greater than those at mid-depth, and the median difference between bottom and mid-depth DO concentrations was 0.1 mg/L (bottom greater than mid-depth). In comparison, Lebo (2000) analyzed 114 vertical profiles of DO measured at this site from 1996 to 1999 during the months of June–November and found the mean difference between DO at measured depths of 3 m and 6 m to be 0.9 mg/L (3-m DO concentration was greater than 6-m concentration). During this study, bottom DO was greater than mid-depth DO almost continuously during November 2000–April 2001. The absence of data during the entire year in Lebo's analysis explains why results on DO differences at mid-depth and bottom are not consistent between the earlier study (Lebo, 2000) and this study.

During May 2000–December 2001, bottom DO concentrations were at least 1 mg/L greater than those at mid-depth 19 percent of the time, whereas hourly DO concentrations at mid-depth were at least 1 mg/L greater than those at the bottom 13 percent of the time. Finally, hourly DO concentrations greater than 8 mg/L occurred 38 percent of the time at the bottom, compared to 25 percent of the time at mid-depth.

Vertical gradients in DO concentrations at NC-45 (figs. 29, 30A) are caused, in part, by density stratification resulting from vertical differences in specific conductance, a measure of dissolved solids concentration. Water in Albemarle Sound has a higher specific conductance (or salinity) than in the Roanoke River (Bales and others, 1993); saline water is more dense than freshwater. Water can move from Albemarle Sound upstream along the bottom of the Roanoke River under favorable conditions, resulting in vertical density stratification at the NC-45 gage. High (greater than 300 μS/cm) specific conductance was measured at the NC-45 gage during August–December 1998, May–September 1999, and August–September 2001 (fig. 30B). Specific conductance remained low throughout 2000, and high flows associated with Hurricanes Dennis and Floyd (fig. 6) likely kept specific conductance low in the fall of 1999.

During May 2000–December 2001, there was little difference between mid-depth and bottom specific conductance (fig. 30A) and, thus, density when the bottom conductance was less than 300 μS/cm (fig. 30B). Vertical differences in DO concentration occurred at NC-45, however, even when there was no density stratification (fig. 30). In the summers of 2000 and 2001, bottom DO concentration was as much as 2 mg/L lower than mid-depth DO concentration, despite the absence of density stratification or elevated specific conductance. In the fall and winter months of 2000–2001, bottom DO concentration was higher than mid-depth DO concentration. During November 2000–April 2001, specific conductance was not elevated when bottom DO exceeded mid-depth DO (fig. 30). During November–December 2000, specific conductance was elevated, however, suggesting that the source of the higher DO water at the bottom was from Albemarle Sound.

Data for September 1–20, 1998, when flows were steady at about 85 m^3/s, illustrate the effects that the upstream movement of water from Albemarle Sound can have on conditions at NC-45 (fig. 31). On September 4, specific conductance briefly increased from 150 to 950 μS/cm (a salinity of about 2 parts per thousand, ppt). Simultaneously, water temperature dropped about 1.2 °C and DO concentration increased about 4 mg/L. The increase in specific conductance and simultaneous decrease in water temperature suggest that water from Albemarle Sound was intruding into the Roanoke River. Each time (September 8, 12, 13, and 16) specific conductance increased during the period, water temperature decreased. This phenomenon also was reported by Lebo (1998). All occurrences of decreasing water temperature at NC-45 are not, however, associated with the intrusion of water from Albemarle Sound. DO concentration also increased concurrently with increases in specific conductance, but the magnitude of the increase varied because DO conditions at NC-45 and in Albemarle Sound also varied with time.

The median and the mean differences between daily-mean bottom DO concentrations at NC-45 and those measured at Jamesville were 0 (fig. 32). In other words, half the time during the study period, daily mean DO concentrations at Jamesville were equal to or lower than concurrently measured DO concentrations at the NC-45 bottom sensor. The NC-45 bottom DO concentrations exceeded concurrently measured Jamesville daily mean DO concentrations by 1 mg/L or more 20 percent of the time, and the Jamesville DO concentrations exceeded those at the NC-45 bottom sensor by 1 mg/L or more 16 percent of the time. The NC-45 bottom DO concentrations were most likely to exceed those at Jamesville during the late-fall to early-spring months (fig. 32), which is the time that high concentrations of DO in water in Albemarle Sound are most likely to be moving into the Roanoke River. During the remainder of the year, Jamesville DO concentrations typically exceeded those at the NC-45 bottom sensor. The mean and median differences between daily mean DO concentrations at Jamesville and those at the NC-45 mid-depth sensor were 0.1 mg/L (Jamesville DO concentrations exceeded those at NC-45 mid-depth). The range in differences between DO concentrations at these two sites was lower than the range in differences between Jamesville and NC-45 bottom DO concentrations.

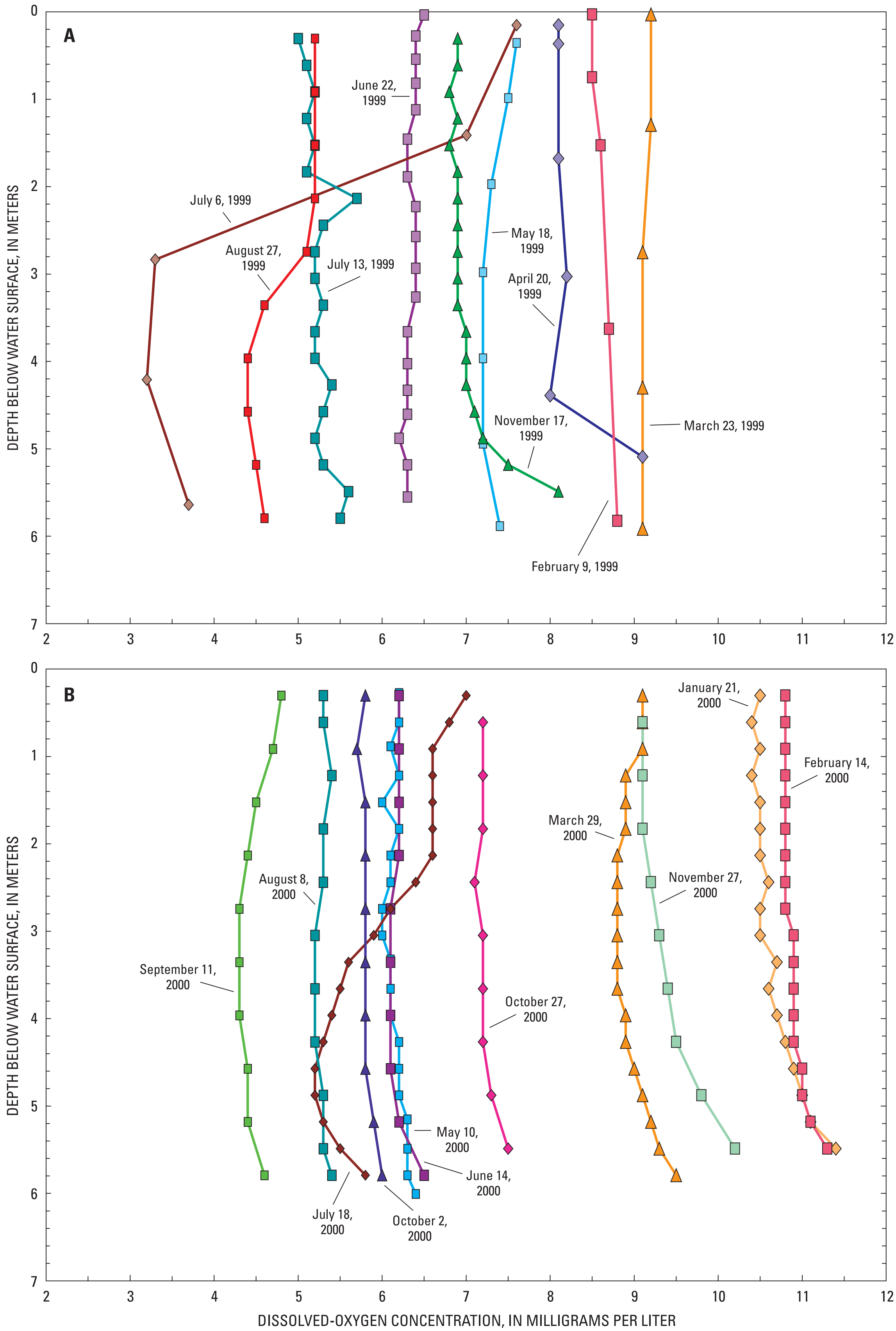


Figure 29. Vertical profiles of dissolved-oxygen concentration at Roanoke River at the NC-45 bridge (site 31), North Carolina, during (A) 1999 and (B) 2000.

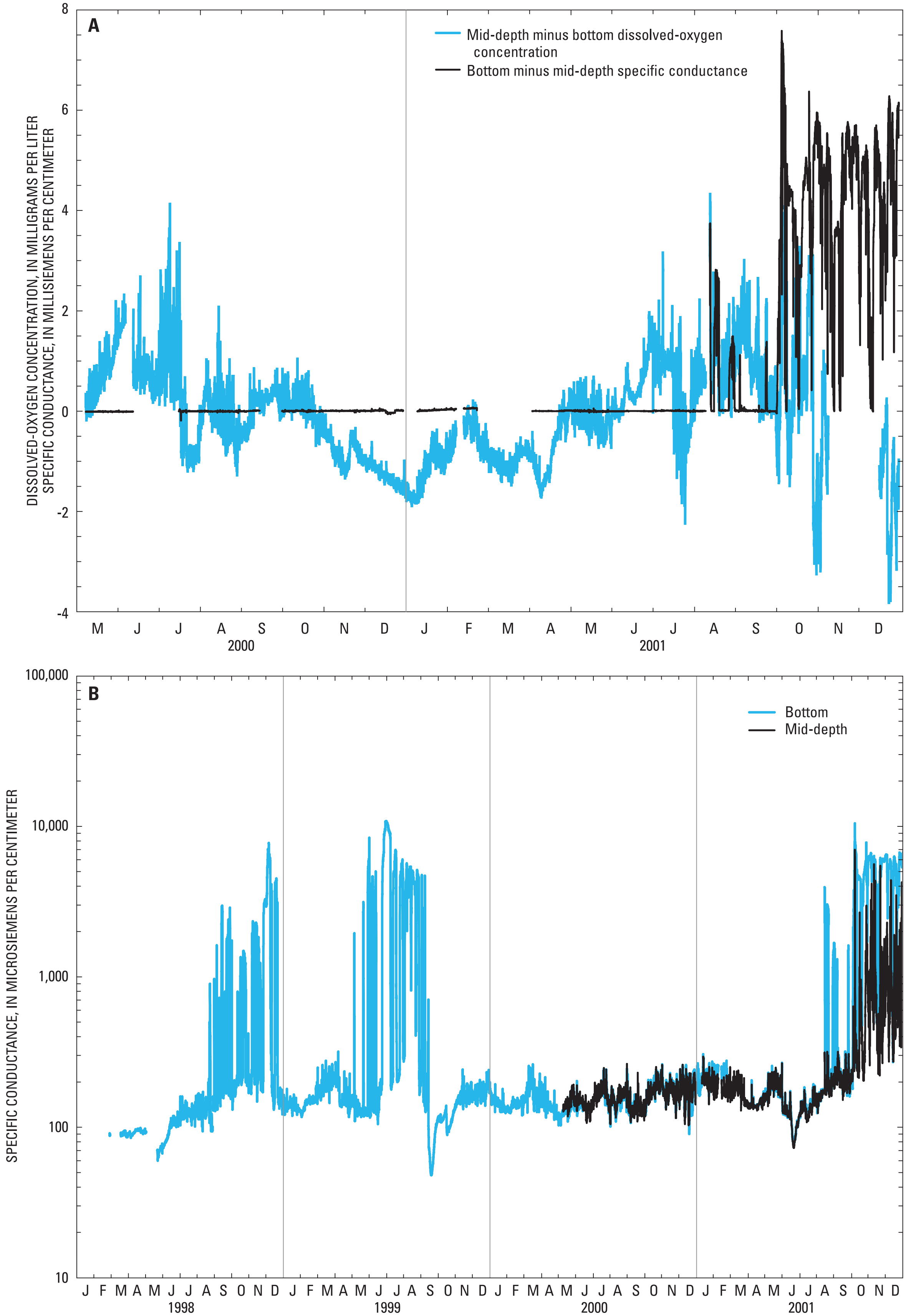


Figure 30. (A) Difference between hourly mid-depth and hourly bottom dissolved-oxygen concentration, and between hourly mid-depth and hourly bottom specific conductance, 2000–2001; and (B) hourly specific conductance during 1998–2001 at Roanoke River at the NC-45 bridge (site 31), North Carolina.

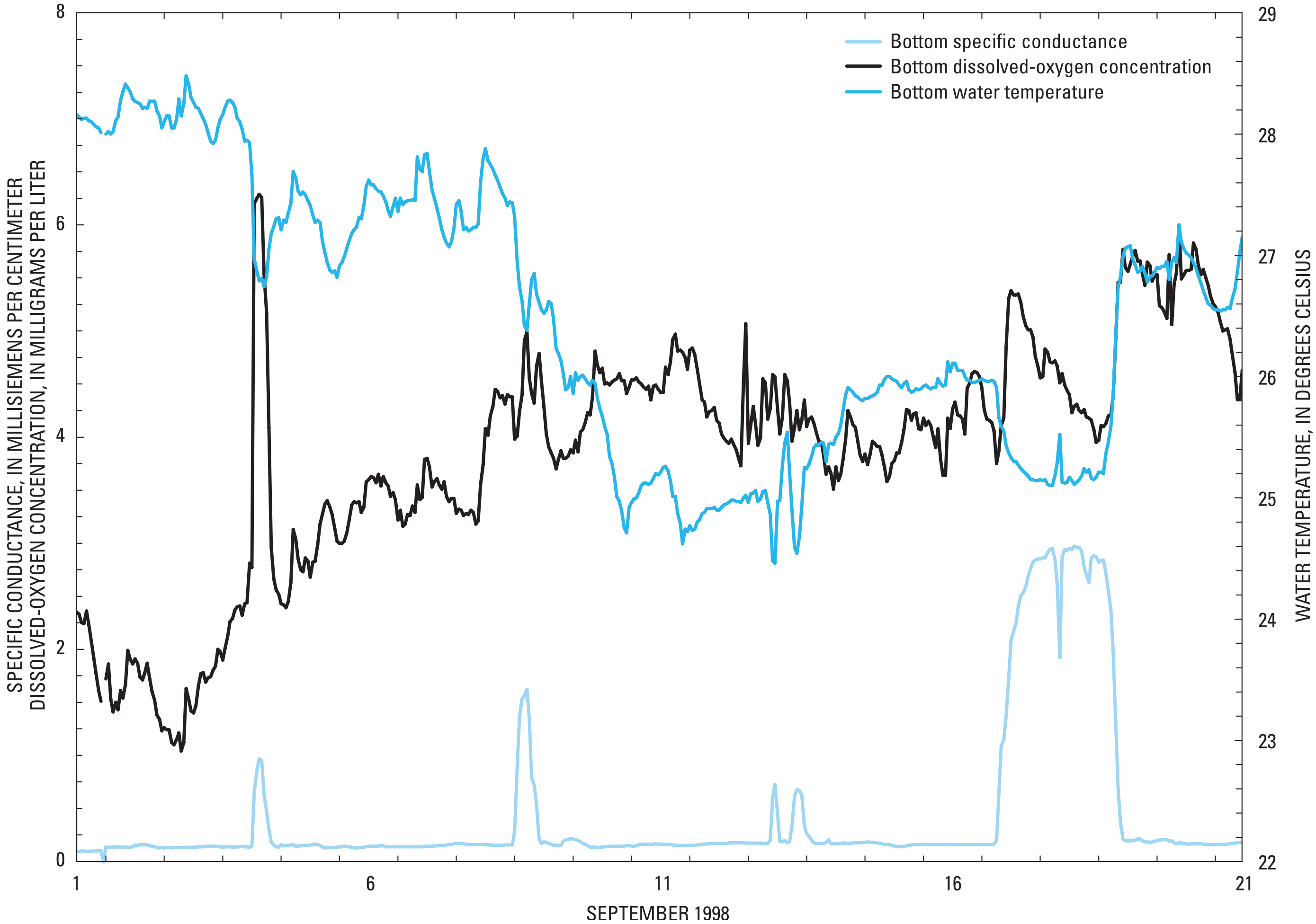


Figure 31. Bottom specific conductance, dissolved-oxygen concentration, and water temperature at Roanoke River at the NC-45 bridge (site 31), North Carolina, September 1–20, 1998.

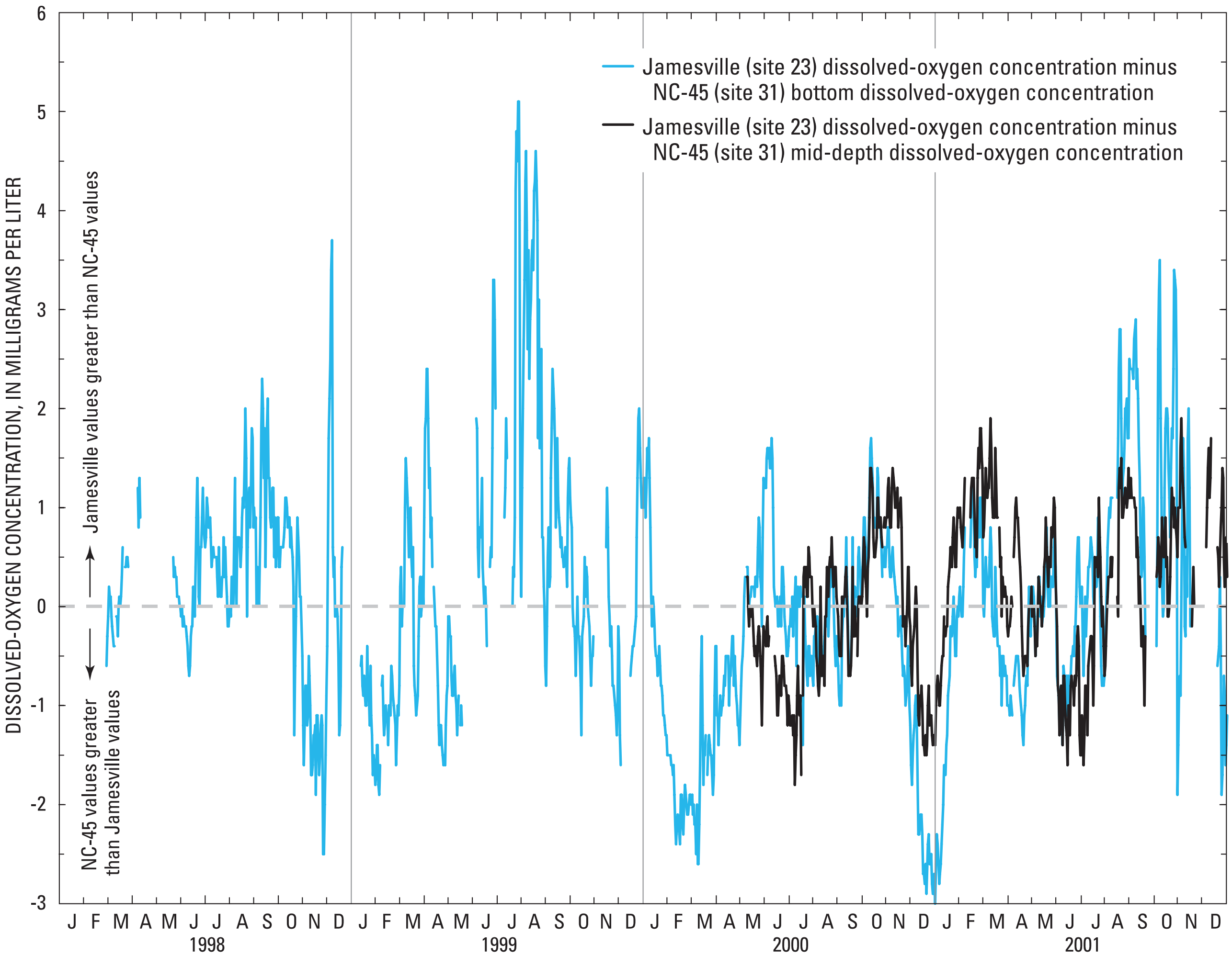


Figure 32. Difference between daily mean dissolved-oxygen concentrations at Roanoke River at Jamesville (site 23) and Roanoke River at the NC-45 bridge (site 31), North Carolina, 1998–2001.

Occurrences of Dissolved-Oxygen Concentrations Less than 5 Milligrams per Liter

Only 0.1 percent of the hourly DO concentrations measured at Halifax during 1998–2001 were less than 5 mg/L (table 11), and the State standard of 5 mg/L for daily mean DO concentration was exceeded on 2 days during the study period—August 30, 2000, and June 28, 2001. No concentrations of 4 mg/L or less were measured. Almost all (35 of 39) hourly occurrences of DO less than 5 mg/L were at flows of 260 m^3/s or less. Concentrations less than 6 mg/L occurred only in the months of May–September (fig. 23).

Hourly DO concentrations at Oak City were less than 5 mg/L for 1.8 percent of the time and less than 4 mg/L for 0.4 percent of the time (table 11) during the study period. Hourly DO concentrations of less than 5 mg/L occurred in September 1999 (Hurricane Floyd), September 2000, and June 2001 (Tropical Storm Allison; figs. 23, 33), and daily mean DO concentrations less than 5 mg/L occurred for 13 consecutive days following Hurricane Floyd in September 1999, and again for 6 consecutive days in June 2001 following Tropical Storm Allison.

Hourly DO concentrations at Grabtown were less than 5 mg/L for 4.6 percent of the time (almost three times more frequently than at Oak City) and less than 4 mg/L for 1.7 percent of the time (table 11) during the study period. Instantaneous concentrations less than 4 mg/L occurred in May, August, and November 2000 and in June 2001 (fig. 26). Daily mean DO concentrations less than 5 mg/L occurred at the site in the months of September and October 1999, May and August 2000, and June 2001 (fig. 26) for a total of 45 days. Daily mean DO concentrations less than 5 mg/L also occurred at the Oak City gage in September 1999 and June 2001.

Hourly DO concentrations at Jamesville were less than 5 mg/L for 10.8 percent of the time (more than twice as frequently as at Grabtown) and less than 4 mg/L for 2.6 percent of the time (table 11) during 1998–2001. Instantaneous concentrations less than 4 mg/L occurred in June 1998, August–September 1998, September–October 1999, and June 2001 (fig. 27). June 2001 (Tropical Storm Allison) was the

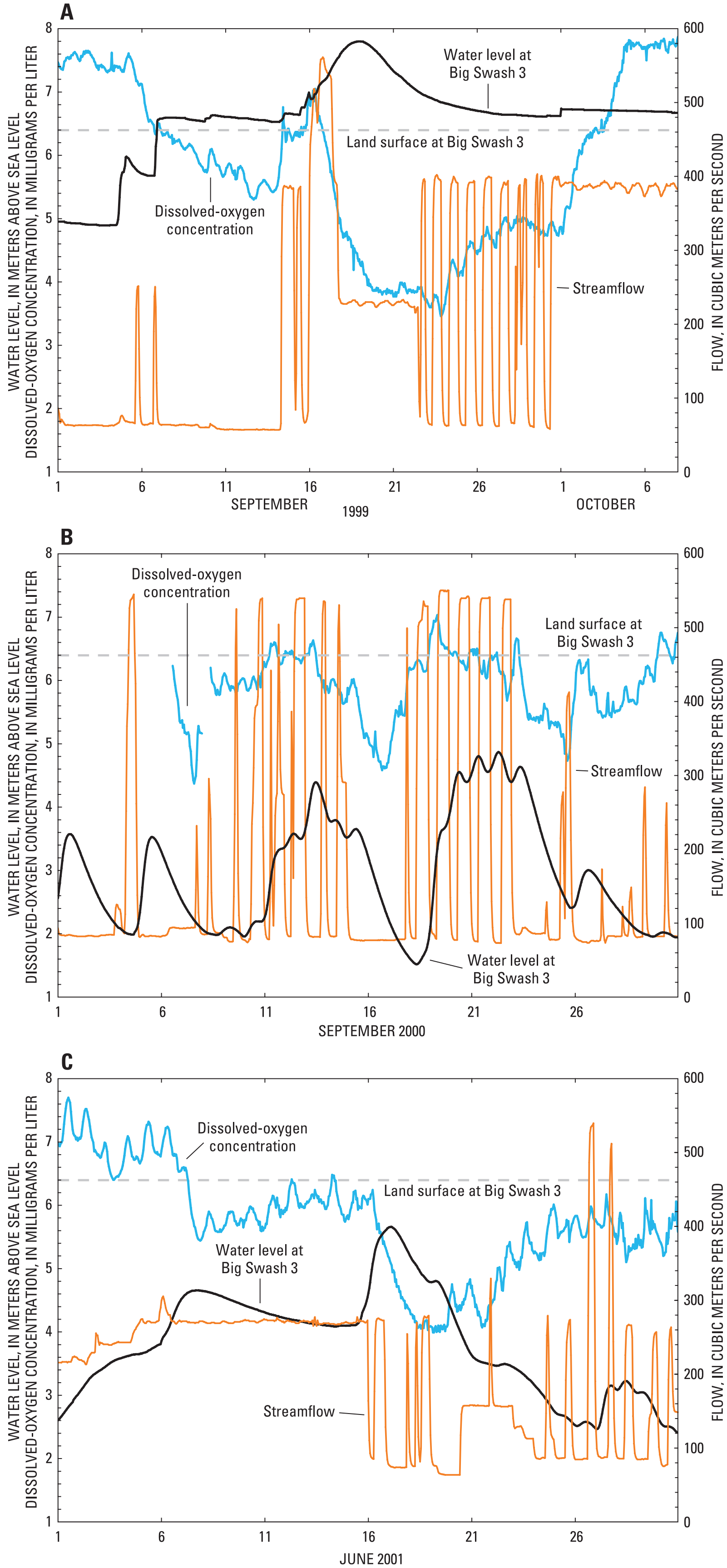


Figure 33. Hourly streamflow at Roanoke River at Roanoke Rapids (site 1), hourly water level at Big Swash 3 (site 7), and hourly dissolved-oxygen concentrations at Roanoke River near Oak City (site 9), North Carolina, for periods when dissolved-oxygen concentrations were less than 5 milligrams per liter during 1998–2001: (A) September 1–October 7, 1999; (B) September 1–30, 2000; and (C) June 1–30, 2001.

only month during the study period when hourly DO concentrations less than 4 mg/L occurred at both Jamesville and Grabtown. Daily mean DO concentrations less than 5 mg/L occurred at Jamesville in the months of June, August, and September 1998; September–November 1999; July–September 2000; and June–September 2001, or during 14 separate months for a total of 136 days.

Hourly DO concentrations at the NC-45 bottom sensor were less than 5 mg/L for 20 percent of the time, and less than 4 mg/L for 10.4 percent of the time (table 11) during 1998–2001. Instantaneous concentrations less than 4 mg/L occurred at the bottom sensor only during the months May–October (fig. 28); these concentrations were measured during 15 of the 24 months, May–October 1998–2001. Daily mean DO concentrations less than 5 mg/L occurred at the bottom sensor during 18 of the 24 months, May–October 1998–2001, and in April 1999 for a total of 235 days.

During 2000, hourly DO concentrations less than 4 mg/L were not measured at the mid-depth sensor, which was installed May 10, 2000, but DO concentrations less than 4 mg/L did occur during June–September 2001 (fig. 28). Daily mean DO concentrations less than 5 mg/L occurred at the mid-depth sensor on 44 of 571 days (7.7 percent) with complete record from May 11, 2000, to December 31, 2001. Daily mean DO less than 5 mg/L occurred during 2 days in August 2000 and during the months of April–September 2001, which was a period of lower-than-normal flows (fig. 6). On the days in April (1 day), May (1 day), and July (2 days) 2001 when the daily mean DO concentration at the mid-depth sensor was less than 5 mg/L, the daily mean DO at the bottom sensor was greater than 5 mg/L.

Temporal Patterns

In most biologically productive lotic systems, maximum daily DO concentrations typically occur at about solar noon, corresponding to the time of maximum photosynthesis and DO production (for example, Wetzel and Likens, 2000). In contrast to these expected conditions, daily DO variations at Halifax exhibited an unusual pattern—maximum daily DO concentrations often occurred at night (fig. 34). This characteristic of the daily DO cycle was present during warm-weather months (fig. 34A–C) and cold-weather months (fig. 34D) and during both steady-flow (fig. 34A) and load-following conditions (fig. 34B).

Daily DO concentrations associated with load-following releases from Roanoke Rapids Dam also generally exhibited a different pattern from those associated with steady-flow conditions (fig. 34B). When flow at Roanoke Rapids Dam was steady, the time between two successive minimum values was about equal to the time between the two maximum values on the same 2 days (for example, July 2–3, 2001; fig. 34B). When load-following, or hydropower peaking, operations were underway, the daily DO curves exhibited a steeper rise and fall and a longer time between successive minimum values (for example June 26–27, 2001; fig. 34B) than for steady-flow conditions. This characteristic of the daily DO variation is evident throughout the study period; for example, in August 2001 (fig. 34C), when hydropower peaking flows greater than 250 m^3/s occurred on August 3, 5–8, 17, 19, 24, and 31 (although peaking flow on August 7 continued for 12 hours, whereas peaking flows typically last 4–6 hours).

Daily maximum water temperatures at Halifax also typically occurred at night, and maximum temperatures were in phase with maximum DO concentrations (fig. 34C, D). In addition, there were often two temperature maximums during a day. This was most evident during steady low-flow conditions, such as during August 25–29, 2001 (fig. 34C), when there were no hydropower peaking releases and the flow was about 80 m^3/s, and November 2001 (fig. 34D) when the flow was constant at about 55 m^3/s for the entire month. These secondary maximums also are present but less evident in the DO record, particularly during these same periods (fig. 34C, D).

Water-temperature and DO-concentration data measured hourly at Roanoke Rapids Dam tailrace about 100 m downstream from the dam during June–August 2000 were provided by Dominion Generation (B. Graham, written commun., February 19, 2003). A submerged weir is located about 75 m upstream from Roanoke Rapids Dam, and the top of the weir is about 8 m below the normal water-surface elevation in Roanoke Rapids Lake (Virginia Power and others, 1995). As a result, water released through Roanoke Rapids Dam to the Roanoke River is withdrawn from the more oxygenated epilimnion of Roanoke Rapids Lake. Although the turbines in Roanoke Rapids Dam have no oxygen or air-injection systems, dam operators can make adjustments to increase turbulence at the turbine intakes, thus increasing reaeration (B. Graham, written commun., February 19, 2003). These adjustments are not routinely done, however, because the increased turbulence results in cavitation that damages turbines.

Dissolved-oxygen concentrations measured in the tailrace did not exhibit the fairly consistent daily pattern evident at Halifax (fig 35). During the steady-flow period in early June 2000, there was some indication of a daily variation in DO (fig. 35A), and on most days in June–August 2000 the daily range in DO concentration was at least 0.5 mg/L, with the maximum concentration often occurring during midday. Variations in DO at frequencies lower than daily also occurred, such as in August 2000 (fig. 35B) when there was about a 3-day frequency in variations in DO concentration. A clear relation between DO in the tailrace and flows was not evident (fig. 35), but the previously discussed effect of load-following releases on DO at Halifax is evident in the data from late June 2000 (fig. 35A). During June–July 2000, the median DO concentration in the tailrace was 6.6 mg/L, whereas the median concentration at Halifax was 6.2 mg/L. Concentrations in the tailrace during this time ranged from 4.4 to 9.5 mg/L, and the range at Halifax was from 4.8 to 8.8 mg/L.

One possible reason that the DO concentrations and temperatures at Halifax are out of phase with expected conditions

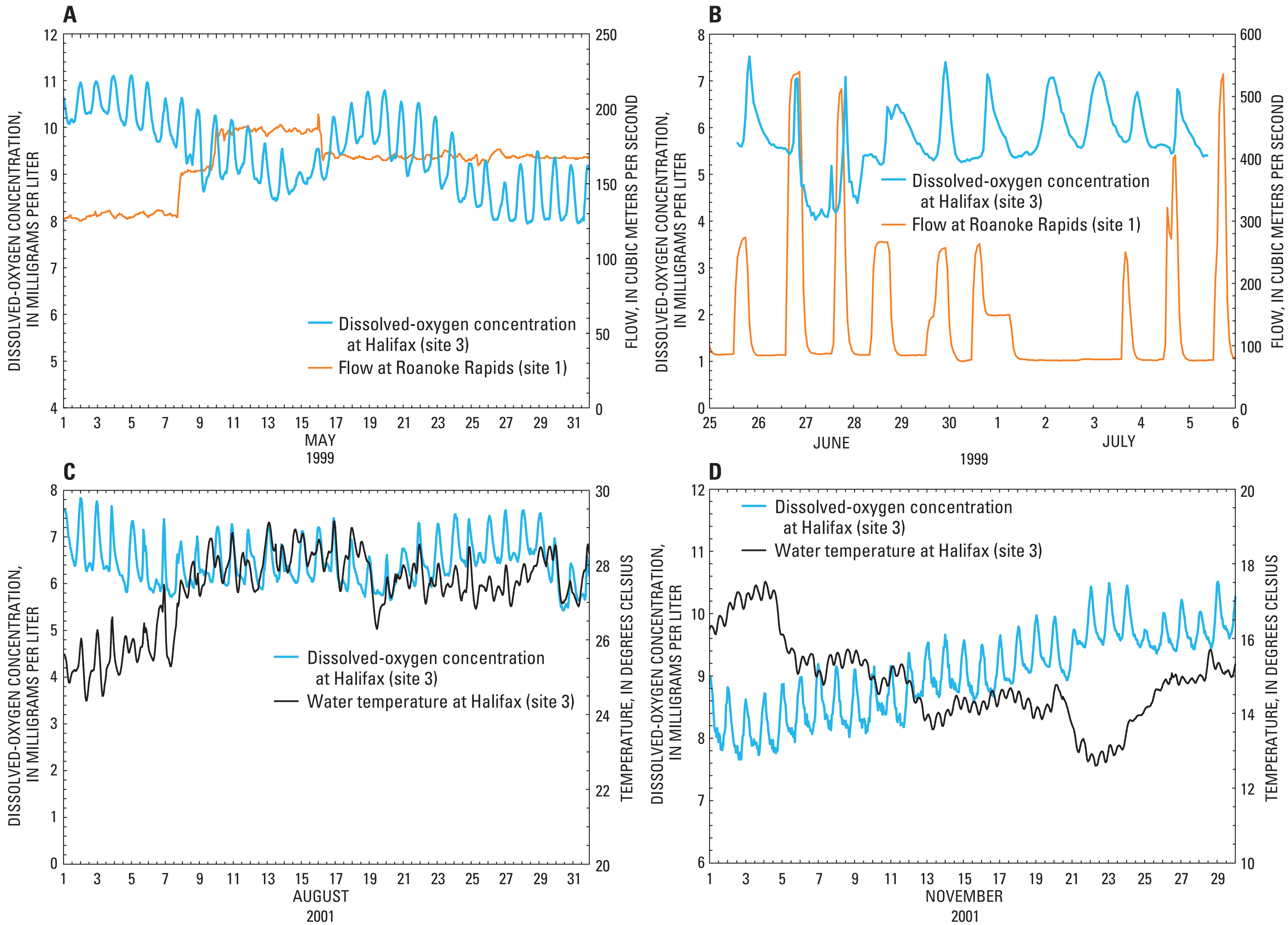


Figure 34. Hourly dissolved-oxygen concentrations at Roanoke River at Halifax (site 2) in relation to hourly flows at Roanoke River at Roanoke Rapids (site 1), during (A) May 1999 and (B) June 25–July 5, 1999; and hourly water temperatures at Roanoke River at Halifax (site 2), North Carolina, during (C) August 2001 and (D) November 2001.

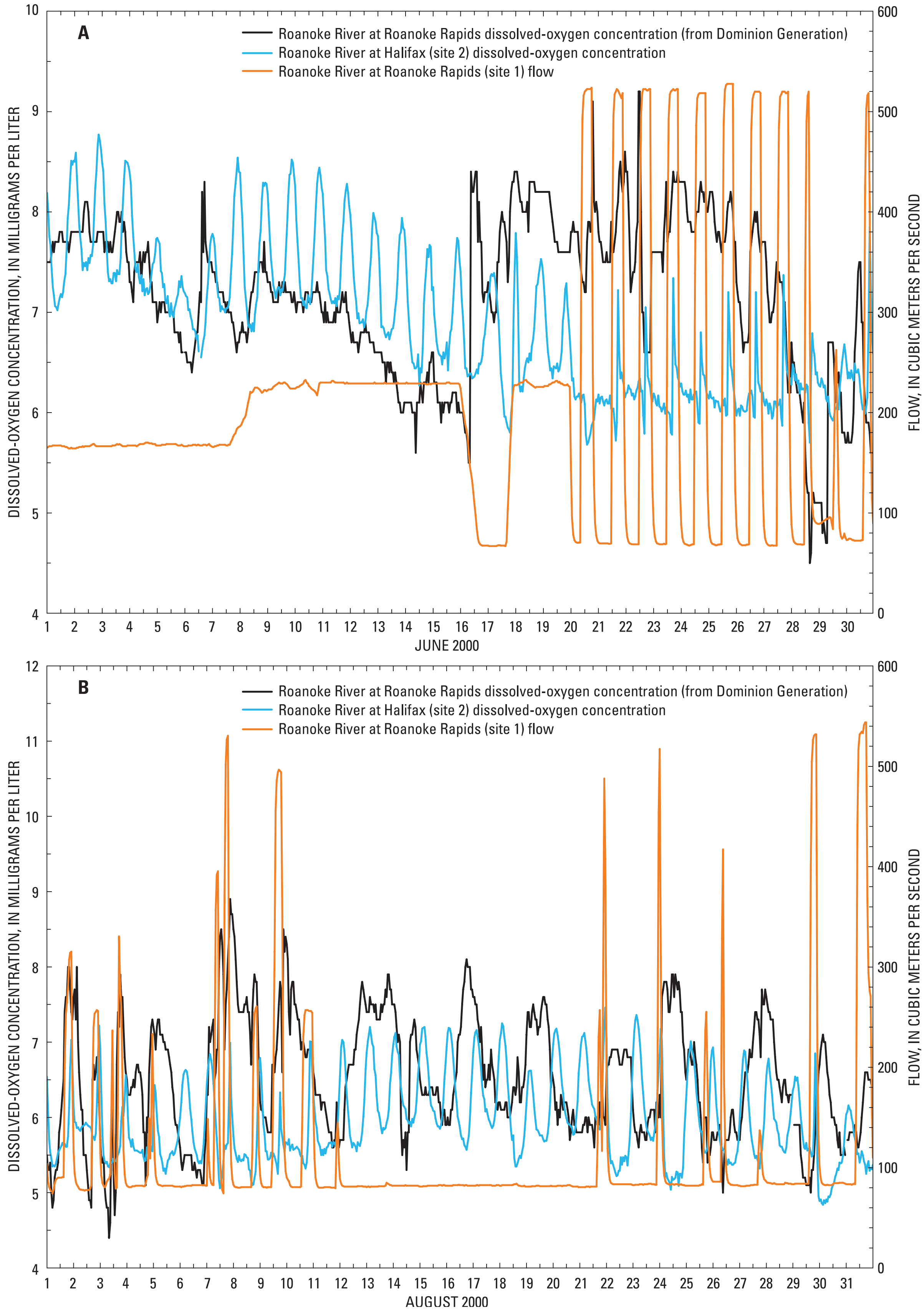


Figure 35. Hourly dissolved-oxygen concentrations in the Roanoke River 100 meters downstream from Roanoke Rapids Dam and at Halifax (site 2), and hourly flow at Roanoke River at Roanoke Rapids (site 1), North Carolina, for (A) June and (B) August 2000.

(maximum values occurring at about solar noon) is that releases from Roanoke Rapids overwhelm natural variations in the river. The daily temperature and DO variations in Roanoke Rapids Lake, and perhaps even Lake Gaston, are passed through Roanoke Rapids Dam, translated downstream, and arrive at Halifax at a rate such that the daily maximum temperature and DO concentration occur at night. Physical (heat exchange, mixing and dispersion, oxygen transfer at the air-water interface) and biochemical (photosynthesis, respiration, chemical- and sediment-oxygen demand) processes occur in the channel between Roanoke Rapids Dam and Halifax, and these processes modify the temporal distribution of the temperature and DO concentrations, as is evident by the difference between concentrations measured in the tailrace of Roanoke Rapids Dam and at Halifax (fig. 35). The secondary maximums in temperature and DO concentrations, which are evident in some of the data and occur during daylight hours (for example, fig. 34D), are likely the result of these instream physical and chemical processes. The travel time between Roanoke Rapids and Halifax may be such, however, that the physical and chemical processes do not have time to completely overcome the strength of the temperature and DO signals in the water released through Roanoke Rapids Dam.

The NCDWQ conducted time-of-travel studies in the Roanoke River between Roanoke Rapids Dam and Hamilton in 1993 and 1994 (North Carolina Department of Environment, Health, and Natural Resources, 1996). At a flow of 44 m^3/s, the time of travel through the 24-km reach between Roanoke Rapids Dam and the town of Halifax was 12.7 hours. The travel time through the same reach during a steady flow of 57 m^3/s was 11.0 hours. These travel times generally are consistent with the hypothesis that the midday maximum temperature and DO concentration in Roanoke Rapids Lake are shifted in time to midnight as a result of transport downstream from Roanoke Rapids Dam to Halifax. The argument against this hypothesis, however, is that the times of occurrence of the daily DO maximums at Halifax do not seem to be affected by flow conditions, whereas travel times should decrease with increased flow rates. A numerical model that can continuously simulate unsteady flow and water-quality transport is required to better explain the DO dynamics in this reach and in the remainder of the lower Roanoke River.

Unlike conditions at Halifax, daily maximum water temperatures and DO concentrations at Oak City (site 9) typically occurred during the daylight hours (fig. 36) as expected. The travel time between Roanoke Rapids Dam and site 9 is about 81 hours (3.4 days) at a steady flow of 44 m^3/s, and 72 hours (3 days) at a steady flow of 57 m^3/s (North Carolina Department of Environment, Health, and Natural Resources, 1996), which apparently is sufficient time for instream physical and chemical processes to become dominant over the DO and water-temperature signal from Roanoke Rapids Lake. Secondary maximums in water temperature are, however, still evident under some conditions (for example, several days during August 15–25, 2001, fig. 36B).

The mean daily range in DO concentration at Oak City was 0.47 mg/L, and the median range was 0.4 mg/L. The daily range was less than 0.5 mg/L for 73 percent of the time and less than 1 mg/L for 97 percent of the time.

Daily variations in DO concentration at Grabtown (site 15) were small, and on many days clear evidence of a daily pattern was absent (fig. 37). The mean daily range in DO concentration at Grabtown for 1998–2001 was 0.7 mg/L, and the median range was 0.5 mg/L. The daily range was less than 1 mg/L for 87 percent of the time. These ranges are slightly greater than those observed upstream at Oak City. Daily DO variations in Coniott Creek and the Roanoke River at Grabtown also were less than 1 mg/L during experimental flow releases, ranging from about 70 to 530 m^3/s July 2001 (Cannon and Graham, 2002). Similar to Grabtown, daily variations in DO concentration at Jamesville were typically less than 1 mg/L, and diurnal variations exhibited very little consistency.

The only months of the year during which daily mean DO concentrations at Oak City (site 9) were less than 6 mg/L were May–September (fig. 38). Even so, DO concentrations during summer months could be as great as 7 mg/L at Oak City. DO concentrations in July and August of 2000 and 2001 were almost continuously less than 6 mg/L (fig. 24), most likely because of the low-flow conditions during those times. Interannual variations in DO concentrations were greatest during the late-fall (October–November) and early-winter months (December–January), most likely reflecting the wide range in flow conditions during these months.

The interannual variations in DO concentrations at Grabtown (fig. 39) were greater than at Oak City (fig. 38) and Halifax. The range in daily mean DO concentrations (difference between maximum and minimum daily mean concentrations) on a particular calendar day was as much as 6 mg/L, with larger ranges observed during January–June and October–November. The average daily mean DO concentrations for 1998–2001 were almost always greater than 6 mg/L; daily mean concentrations less than 5 mg/L occurred in the months of May, June, and August–October (fig. 39).

The interannual variations in DO concentrations at Jamesville (fig. 40) were smaller than at Grabtown (fig. 39). As at the other sites, the larger ranges were during the cool-weather months. The average daily mean DO concentrations for 1998–2001 were typically less than 6 mg/L during May–September. During these same months, hourly DO concentrations were less than 5 mg/L for 21 percent of the time, compared to 8 percent of the time at Grabtown.

The interannual variations in bottom DO concentrations at NC-45 (fig. 41) were the largest of the five sites. Unlike the other sites, the larger interannual ranges at NC-45 were in the summer and early-fall months, with year-to-year ranges of 5–6 mg/L not uncommon. The average daily mean bottom DO concentration for 1998–2001 was less than 5 mg/L during most of August and September, and consistently less than 6 mg/L from mid-May through mid-October. Minimum daily bottom DO concentrations were almost always less than 5 mg/L from mid-May through October, which means that during the study

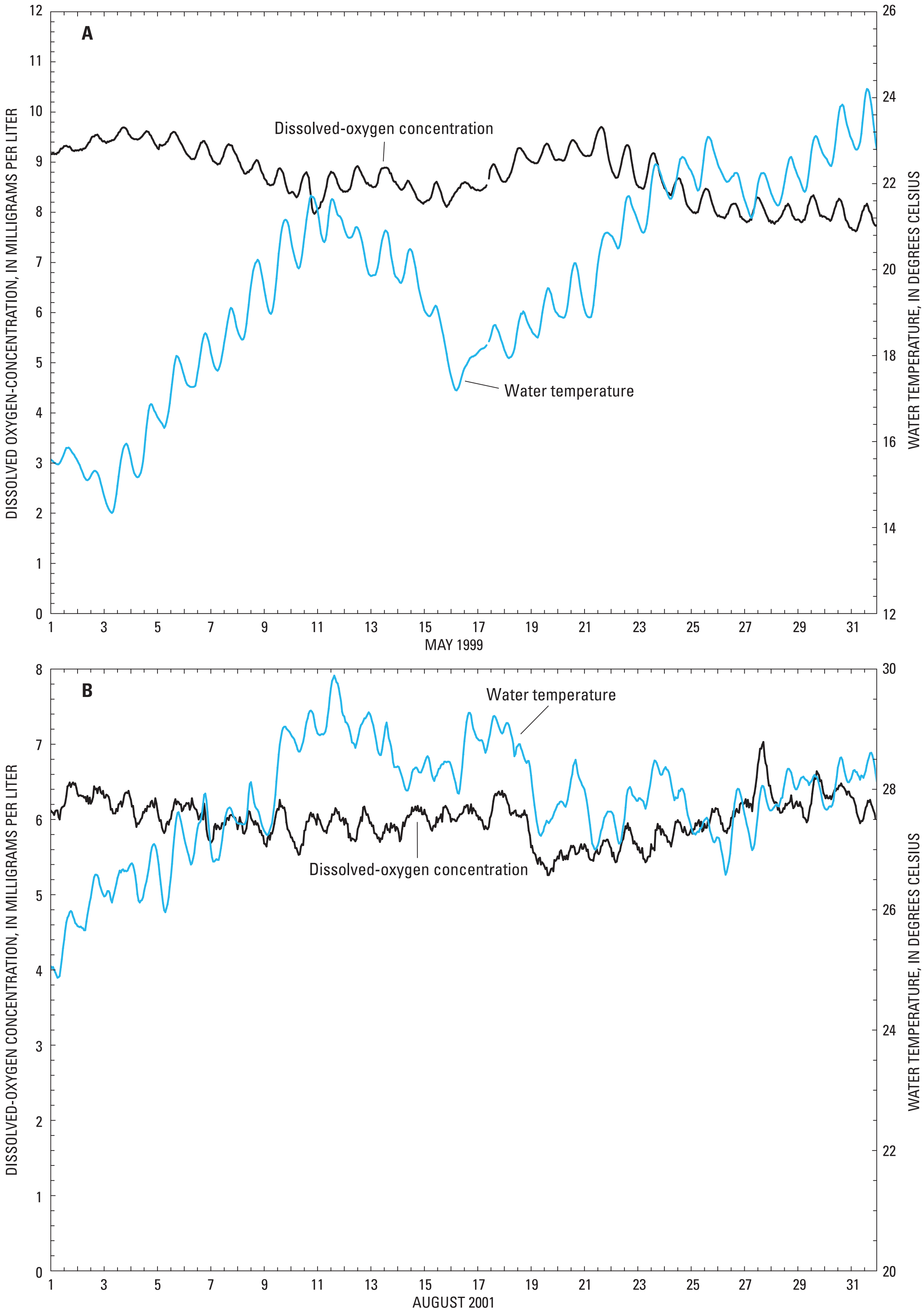


Figure 36. Hourly dissolved-oxygen concentration and water temperature at Roanoke River near Oak City (site 9), North Carolina, for (A) May 1999 and (B) August 2001.

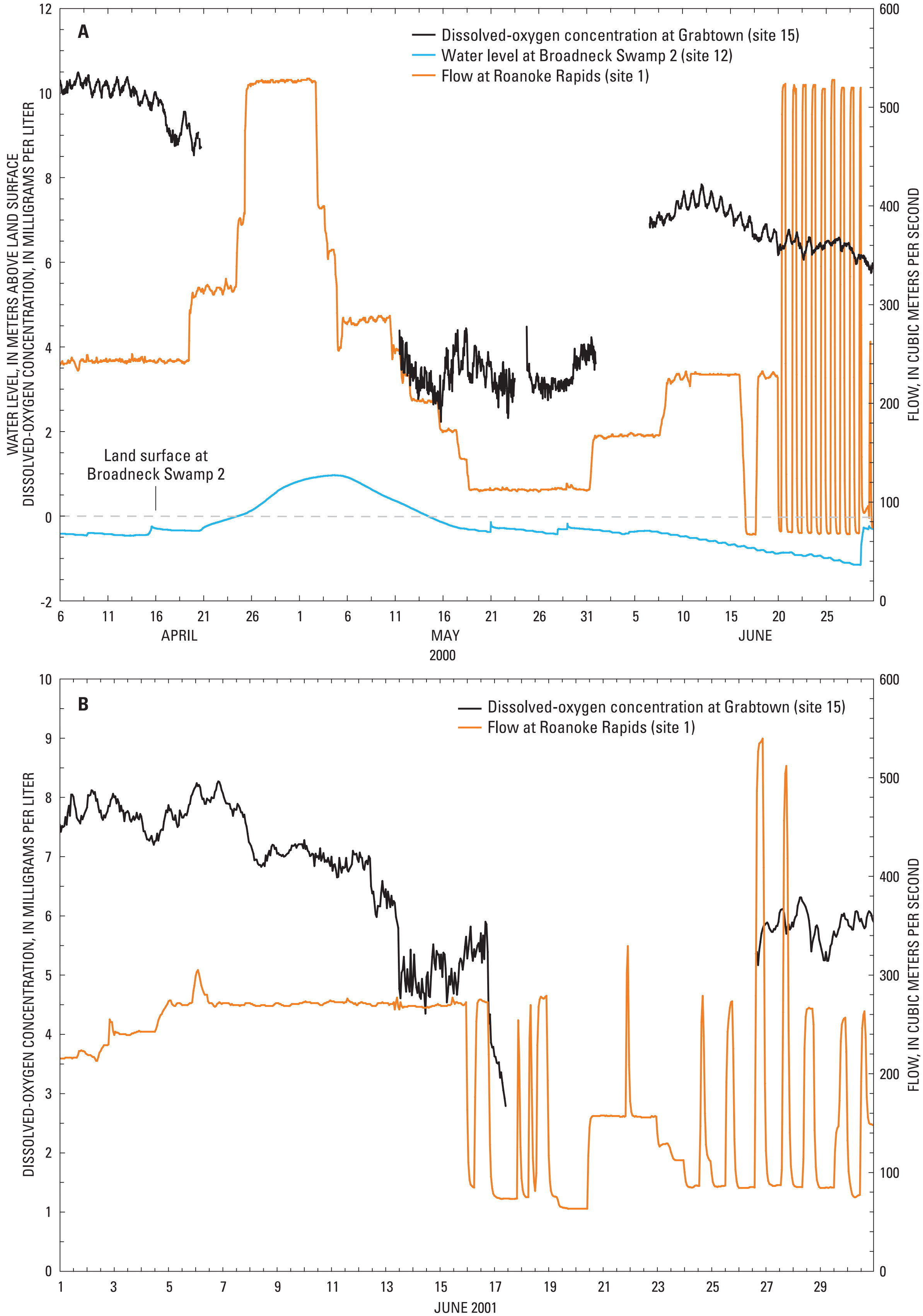


Figure 37. Hourly dissolved-oxygen concentration at Roanoke River near Grabtown (site 15), and hourly flow at Roanoke River at Roanoke Rapids (site 1), North Carolina, for (A) April–June 2000, including hourly water level at Broadneck Swamp 2 (site 12), and (B) June 2001.

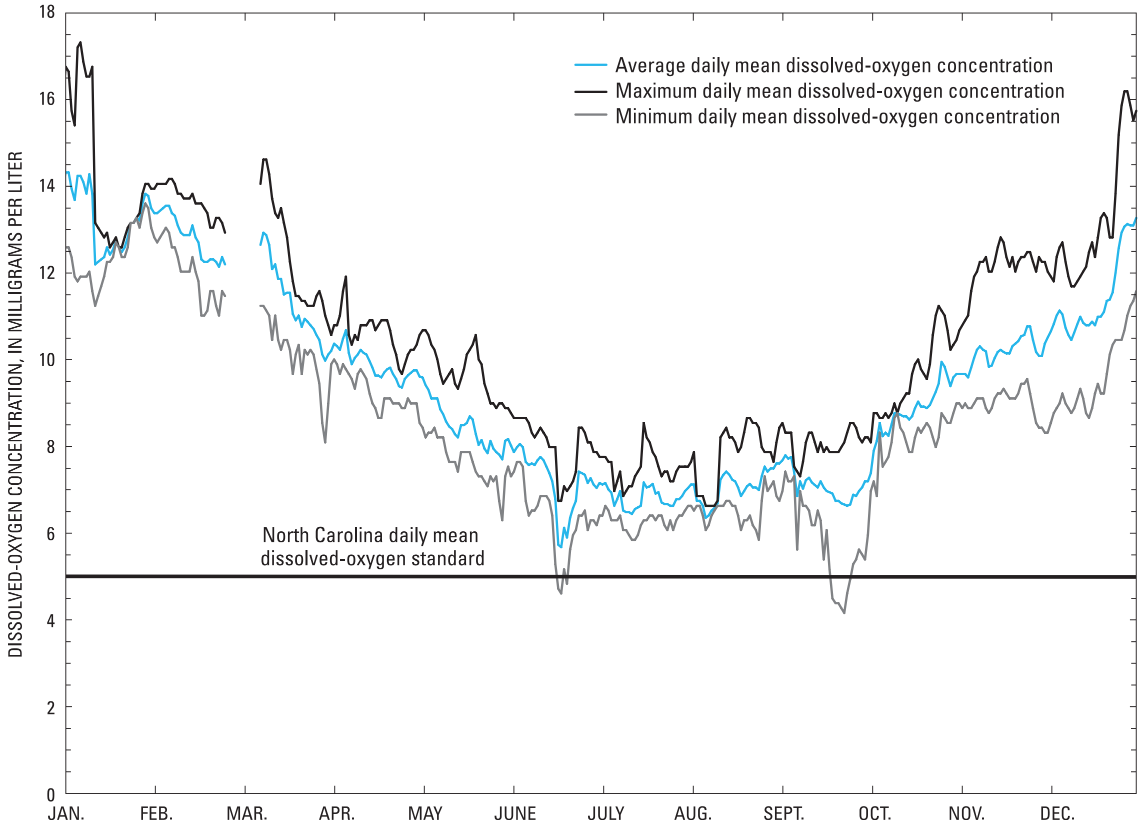


Figure 38. Average, maximum, and minimum daily mean dissolved-oxygen concentrations at Roanoke River near Oak City (site 9), North Carolina, 1998–2001.

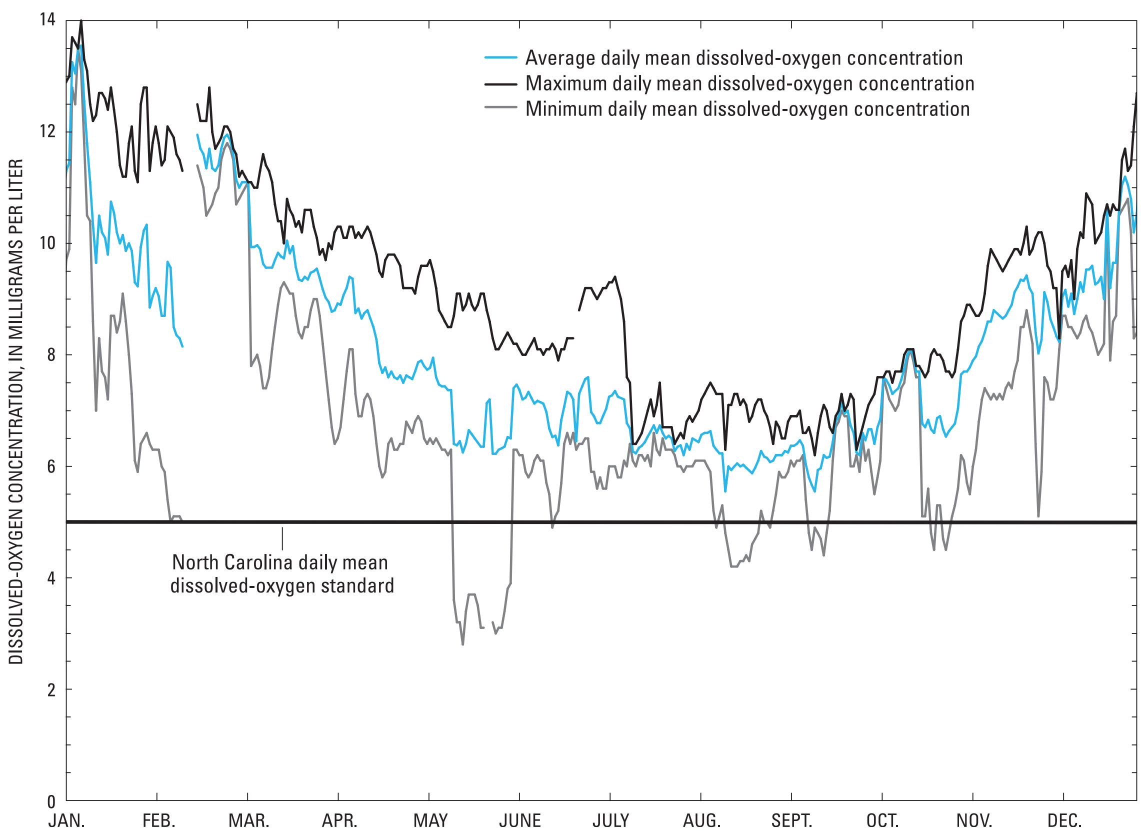


Figure 39. Average, maximum, and minimum daily mean dissolved-oxygen concentrations at Roanoke River near Grabtown (site 15), North Carolina, 1998–2001.

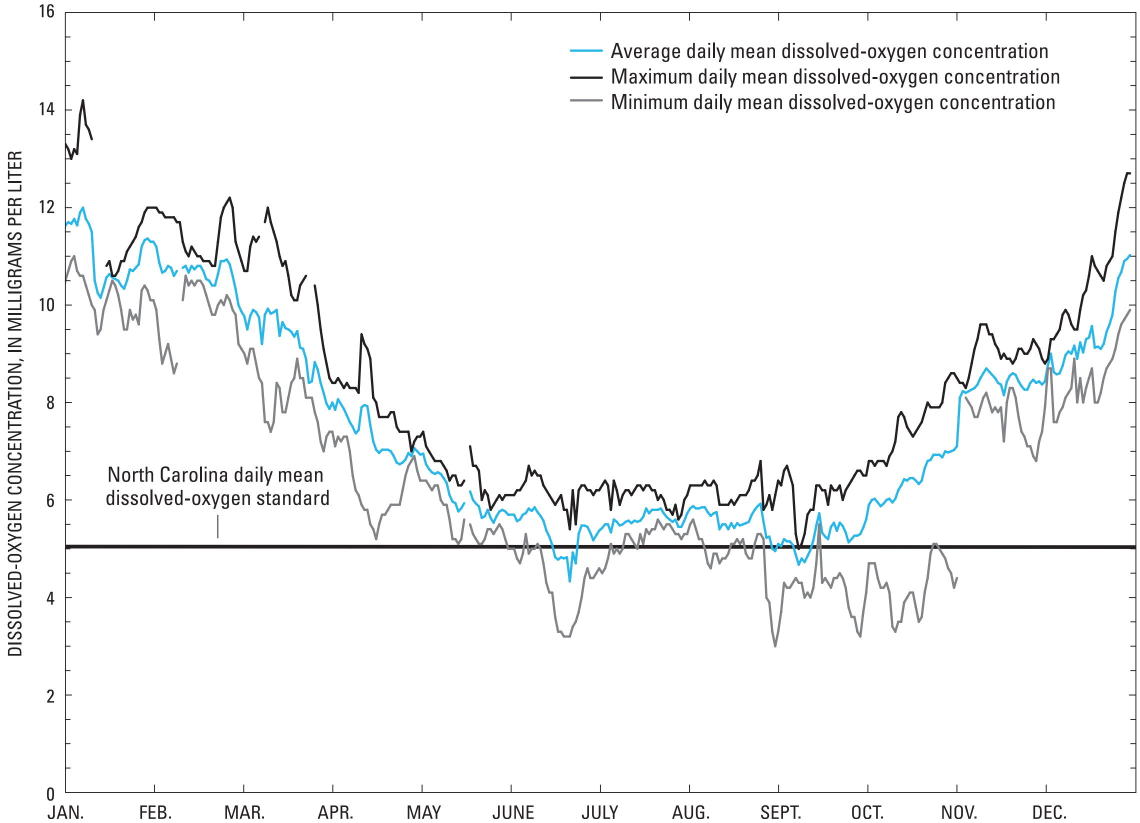


Figure 40. Average, maximum, and minimum daily mean dissolved-oxygen concentrations at Roanoke River at Jamesville (site 23), North Carolina, 1998–2001.

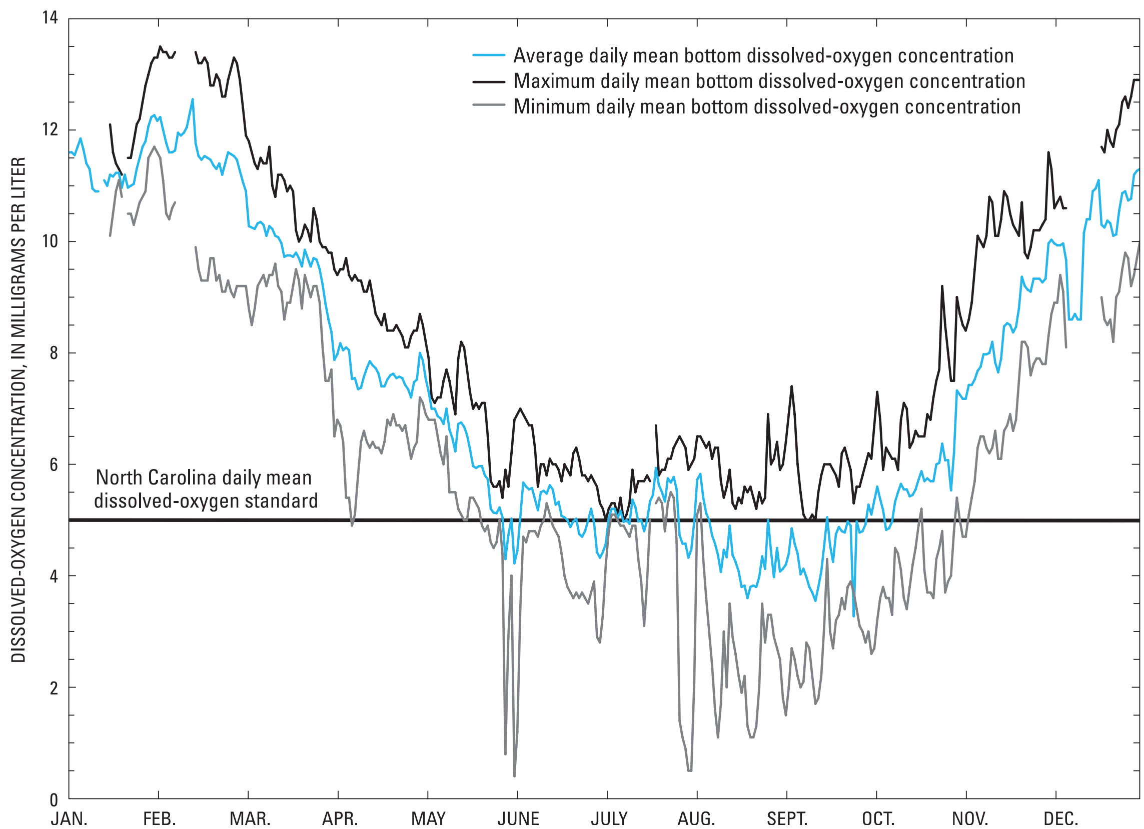


Figure 41. Average, maximum, and minimum daily mean bottom dissolved-oxygen concentrations at Roanoke River at NC-45 bridge (site 31), North Carolina, 1998–2001.

period, on every calendar day (in other words, at least once on May 15, at least once on May 16, and so on) from mid-May through October, the daily mean bottom DO concentration was less than 5 mg/L.

During the study, the largest vertical gradients in DO concentrations at the NC-45 site occurred in the summer (figs. 28, 29). It also was not unusual for the lowest DO concentration to be at some location other than near the bottom. For example, in March and September 2000, the minimum DO concentration was near mid-depth (fig. 29B). During fall and winter months, the maximum DO concentration typically was at the bottom (figs. 28, 29), but even during summer months, such as July and August 2000 and July 2001, the bottom DO often exceeded the mid-depth DO concentration (fig. 29).

Relation of Dissolved-Oxygen Concentration to River Flow and Floodplain Water-Level Conditions

Almost all (35 of 39) hourly occurrences of DO less than 5 mg/L at Halifax were at flows of 260 m^3/s or less. The 19 occurrences of daily mean DO concentrations less than 5 mg/L at Oak City all were at 10-day mean flows of between 180 and 280 m^3/s. DO concentrations less than 5 mg/L at Grabtown occurred only when the 10-day mean flow at Roanoke Rapids was less than 300 m^3/s. Similarly, DO concentrations less than 4 mg/L occurred only when the 10-day mean flow was less than 240 m^3/s. Flows below these thresholds did not, however, always coincide with low DO concentrations at Grabtown.

Median hourly DO concentrations at Grabtown typically were lowest during June—5.0 mg/L in 1998, 6.2 mg/L in 1999, 5.5 mg/L in 2000, and 4.9 mg/L in 2001. The change in flow regime from fairly high, steady flows for enhancement of striped bass spawning success to lower, load-following flows and the subsequent floodplain drainage that occurs with this change in flow regime are the most likely reasons for the typically lower DO concentrations in June.

All DO concentrations less than 5 mg/L at Jamesville occurred when the 10-day mean flow (and the 3-day lagged flow) at Roanoke Rapids was less than 570 m^3/s, although most occurred when the 10-day mean flow was less than 300 m^3/s. DO concentrations at less than 50 percent of saturation concentration occurred at flows less than 425 m^3/s. Flows below these thresholds did not, of course, always coincide with low DO concentrations at Jamesville.

Some generalizations can be made about 10-day mean flow at Roanoke Rapids and the minimum daily bottom DO concentration that might be expected to occur at NC-45 (fig. 42A). For example, at a 10-day mean flow greater than about 290 m^3/s and under current point- and nonpoint-source loading conditions, it is unlikely that the bottom daily mean DO concentration at NC-45 would be less than 5 mg/L. Likewise, at a 10-day mean flow of 200 m^3/s, daily mean bottom DO concentrations as low as but probably no lower than 3 mg/L could be expected (fig. 42A) for current loading conditions. Likewise, generalizations about the difference between mid-depth and bottom DO concentrations and flow can be made in somewhat the same manner as for daily mean DO concentrations (fig. 42B). At 10-day mean flows less than 200 m^3/s, the difference between mid-depth and bottom DO concentrations is likely to be greater than 1 mg/L, and at 10-day mean flows less than 100 m^3/s, the difference is likely to be 2 mg/L. For both flows, the difference is as likely to be positive (mid-depth greater than bottom) as negative (mid-depth less than bottom). As the 10-day mean flow increases from 200 m^3/s to about 300 m^3/s, the difference between mid-depth and bottom DO concentrations becomes less than 1 mg/L. For the few observations of 10-day mean flow greater than 300 m^3/s, bottom DO concentrations exceed mid-depth concentrations by about 1 mg/L.

Specific conductance at NC-45 was not well correlated with any measure of flow (hourly, daily mean, 7-day mean, 10-day mean, and others) in the Roanoke River at Roanoke Rapids. All daily mean bottom specific conductance readings greater than 230 µS/cm, however, occurred at 7-day mean flows less than 165 m^3/s, and all daily mean mid-depth readings greater than 320 µS/cm occurred at 7-day mean flows less than 85 m^3/s. Continuous measurements of flow near the mouth of the river could provide improved understanding of the relation of flow conditions to water-quality conditions in the river and provide data needed to calculate BOD and nutrient loadings to Albemarle Sound.

At Oak City (site 9), the September 1999 low DO concentrations were associated with the passages of Hurricanes Dennis and Floyd (fig. 24), which occurred on September 4–5, and September 15–16, respectively. Water level at the floodplain site (Big Swash 3, site 7), which is located upstream from the Oak City gage, increased from 1.5 m below land surface on September 5 to 0.2 m above land surface on September 7. At the time DO concentrations were falling on September 16, the water level at Big Swash 3 was increasing from 0.5 to 1.4 m above land surface. The high land-surface runoff from these storms is the likely reason for the low DO concentrations at Oak City. When flows were increased at Roanoke Rapids Dam on September 23, DO concentrations began to recover within a couple of days, suggesting that water with higher DO concentrations from Roanoke Rapids Lake had a diluting effect on water from land-surface runoff. It also is likely that runoff had decreased or stabilized by this time, as indicated by the stable water level at Big Swash 3.

The September 2000 low DO concentrations followed a period when flows were somewhat higher than normal at the time as well as during the previous 4 months (fig. 6) and were associated with experimental, high-volume load-following flow releases from Roanoke Rapids Dam that resulted in flooding and drainage of the backswamps adjacent to Coniott Creek (Graham and Cannon, 2001). Flow in the river was declining when DO fell below 5 mg/L on September 16 (fig. 33B), although the minimum DO concentration occurred a day before the minimum water level at Big Swash 3. Water levels at the Big Swash sites were below land surface during this time.

Likewise, the June 2001 flows were part of a study to evaluate the effects of load-following releases on floodplain

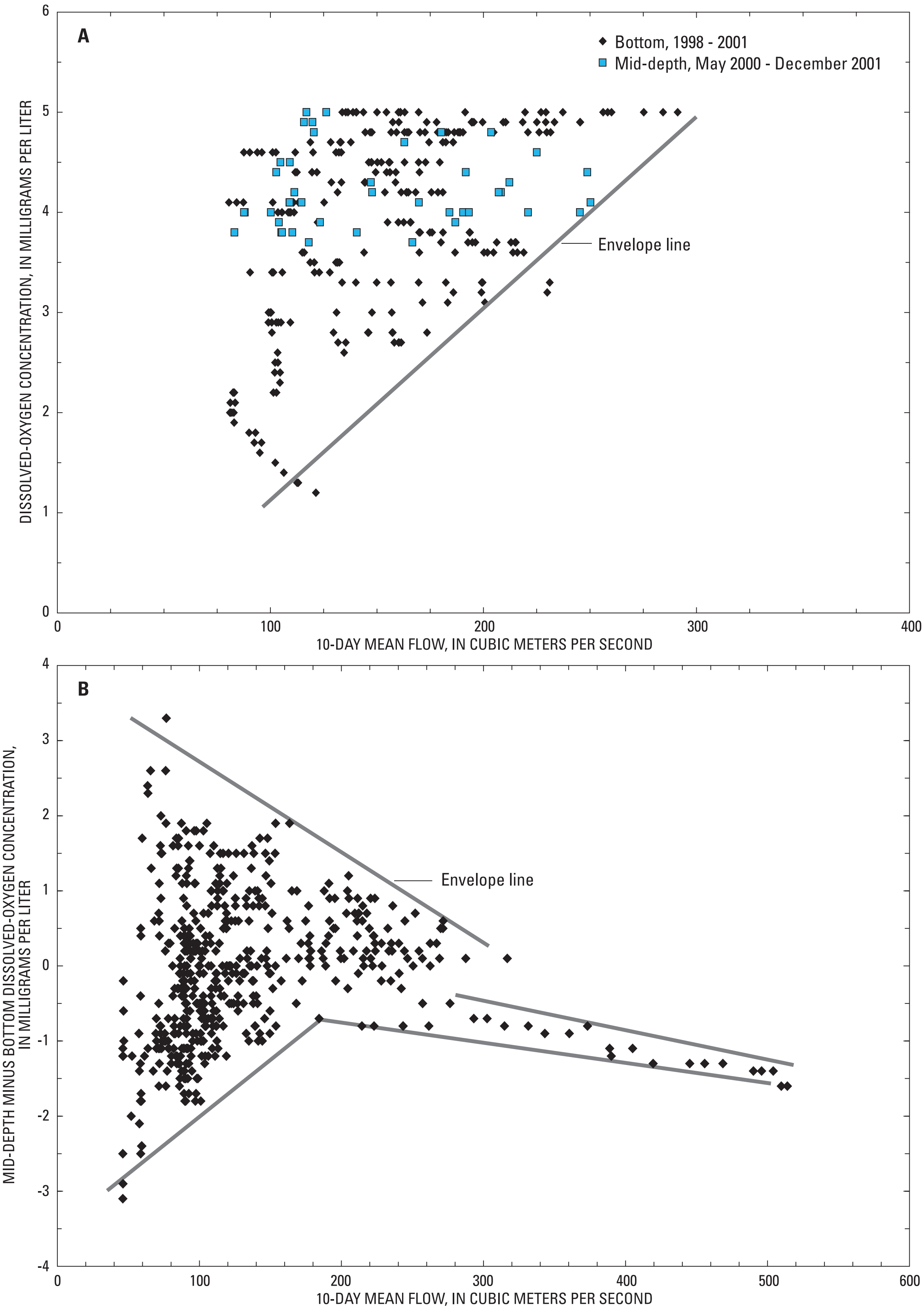


Figure 42. Relation of 10-day mean flow at Roanoke River at Roanoke Rapids (site 1) to (A) daily mean dissolved-oxygen concentration, 1998–2001, and (B) difference between mid-depth and bottom dissolved-oxygen concentration, 2000–2001, at Roanoke River at the NC-45 bridge (site 31), North Carolina.

inundation and water quality (Cannon and Graham, 2002). Flows during the study included 5 consecutive days of near-maximum load following (releases of approximately 540 m^3/s for 14 hours followed by releases of approximately 76 m^3/s for 10 hours each day), preceded by 2 days of typical minimal weekend discharges (about 76 m^3/s). Low DO concentrations followed a 10-day period of sustained flows at about 280 m^3/s, but floodplain water-level data were not available to assess backswamp drainage during this time (fig. 33C). During the study, hourly DO concentrations less than 5 mg/L at Oak City all occurred at flows between 60 and 410 m^3/s.

The May 2000 low DO event at Grabtown, when hourly DO concentrations were less than 3 mg/L, was associated with a stepdown in flow at Roanoke Rapids Dam (fig. 37A). Flows were greater than 500 m^3/s for about a week at the end of April, and then were reduced to about 285 m^3/s the first week of May. Because the DO record is incomplete, the exact time when DO dropped below 5 mg/L cannot be determined in relation to changes in flows. Prior to April 21, however, when the water levels at Broadneck Swamp 2 and 3 were below land surface (fig. 37A), the DO concentration at Grabtown was between 9 and 10 mg/L. The increase in flow resulted in inundation at Broadneck Swamp 2 and 3 (recall that Broadneck Swamp 2 and 3 were always inundated at 10-day mean flows greater than 350 m^3/s). With the subsequent reduction in flows, Broadneck 2 and 3 began to drain, and DO concentrations at Grabtown became less than 4 mg/L. DO concentration at Grabtown reached a minimum on May 15, at about the time the Broadneck 2 water level dropped below land surface (fig. 37A), and surface drainage likely was greatly reduced.

Although the water temperature increased from about 15 °C on April 21 to about 22 °C on May 11, the drop in DO concentration during this period was not the result of the increase in water temperature. The DO saturation was about 85 percent on April 21, remained at about 40 percent from May 11 to May 31 when DO concentrations were low (fig. 37A), and was about 80 percent on June 6 when DO concentrations were again greater than 5 mg/L but water temperature was in excess of 22 °C. If the low DO concentrations in May were due solely to an increase in water temperature, then the DO saturation percentage would have remained relatively constant rather than decreasing and then increasing again as observed.

The low DO event in June 2001 (fig. 37B) also appears to be associated with a decrease in flows, when conditions changed from a steady flow of about 270 m^3/s to load-following releases. According to eq. 1 and information in table 8, the Broadneck 2 and 3 sites would have been inundated to a depth of about 0.3 m following 10 days of flow at 270 m^3/s. With the reduction in mean flows on June 16, it is likely that Broadneck Swamp began to drain to the river. The passage of Tropical Storm Allison on June 15–17, when 265 mm of rainfall was recorded at Williamston, and subsequent backswamp flooding undoubtedly affected instream DO conditions. The absence of floodplain water-level gages and missing DO record during this period, however, make this event more difficult to interpret.

The U.S. Fish and Wildlife Service monitored DO concentration in Coniott Creek during 1996 and 1997 (J. Richter, written commun., November 2002). Between May and September 30, 1996, DO was measured 35 times near the mouth of the creek, and 83 percent of the concentrations were less than 4 mg/L. During the same period in 1997, however, 38 percent of the DO concentrations were less than 4 mg/L. Broadneck Swamp water-level data were not available for 1996, but in 1997, there was little drainage from the swamp during May–September (fig. 13). Monthly mean flow in May 1997 was greater than in May 1996, but during June–September, monthly mean flows were higher in 1996 than in 1997. The higher flows in 1996, with the increased potential for backswamp inundation and subsequent drainage, perhaps explains the reason for the lower DO concentrations in 1996 compared to 1997. These data also demonstrate that low (less than 4 mg/L) DO conditions occur much more frequently in Coniott Creek, and by implication in other similar tributaries, than in the Roanoke River.

One notable exception when DO concentrations at Grabtown were less than at Jamesville was during May 2000 (fig. 43). As previously shown, the low DO at Grabtown was associated with drainage from Broadneck Creek as a result of a decrease in flow. It is possible that the very low DO concentrations measured at Grabtown in May 2000 were from Coniott Creek water that had not uniformly mixed with Roanoke River water, or it is possible that there was some recovery in DO concentrations in the 43 km between Grabtown and Jamesville. Water also was draining from the Devils Gut transect during this period (fig. 43)

The very low DO concentrations measured at Jamesville in late August and early September 1998 were associated with a period of drainage from Devils Gut (fig. 44). The DO concentration at Jamesville dropped from about 7 mg/L on August 27 to about 2.5 mg/L on September 1. During the same time, water level at Devils Gut 2 fell about 0.5 m. The largest change in DO occurred during August 27–29, when water level at Devils Gut 1 fell from above land surface to below land surface (fig. 44). Streamflow at Roanoke Rapids was fairly steady at about 80 m^3/s during August 7–24, but then load-following releases occurred during August 24–26, 28, 31, and September 1–2, including a flow of about 380 m^3/s that persisted for about 12 hours on August 25. This increase in flow did not inundate the Broadneck sites (fig. 13) but did inundate Devils Gut 1 and 2. Consequently, DO concentrations at Grabtown did not exhibit the sharp decline observed at Jamesville, most likely as a result of the floodplain drainage. As suggested in the discussion of the Grabtown DO data, it also is likely that the low DO concentrations observed in June 2001 at Jamesville were the result of a change in flow conditions—a flow-regime change from steady at 270 m^3/s to load following and runoff from Tropical Storm Allison.

Rulifson and others (1990) collected weekly samples at four sites in the Roanoke River near Plymouth during April–June 1988. Flows during the period were moderate (generally 55–140 m^3/s) and fairly steady, with little hydropower peaking. DO, total organic carbon (TOC), and BOD appeared to be

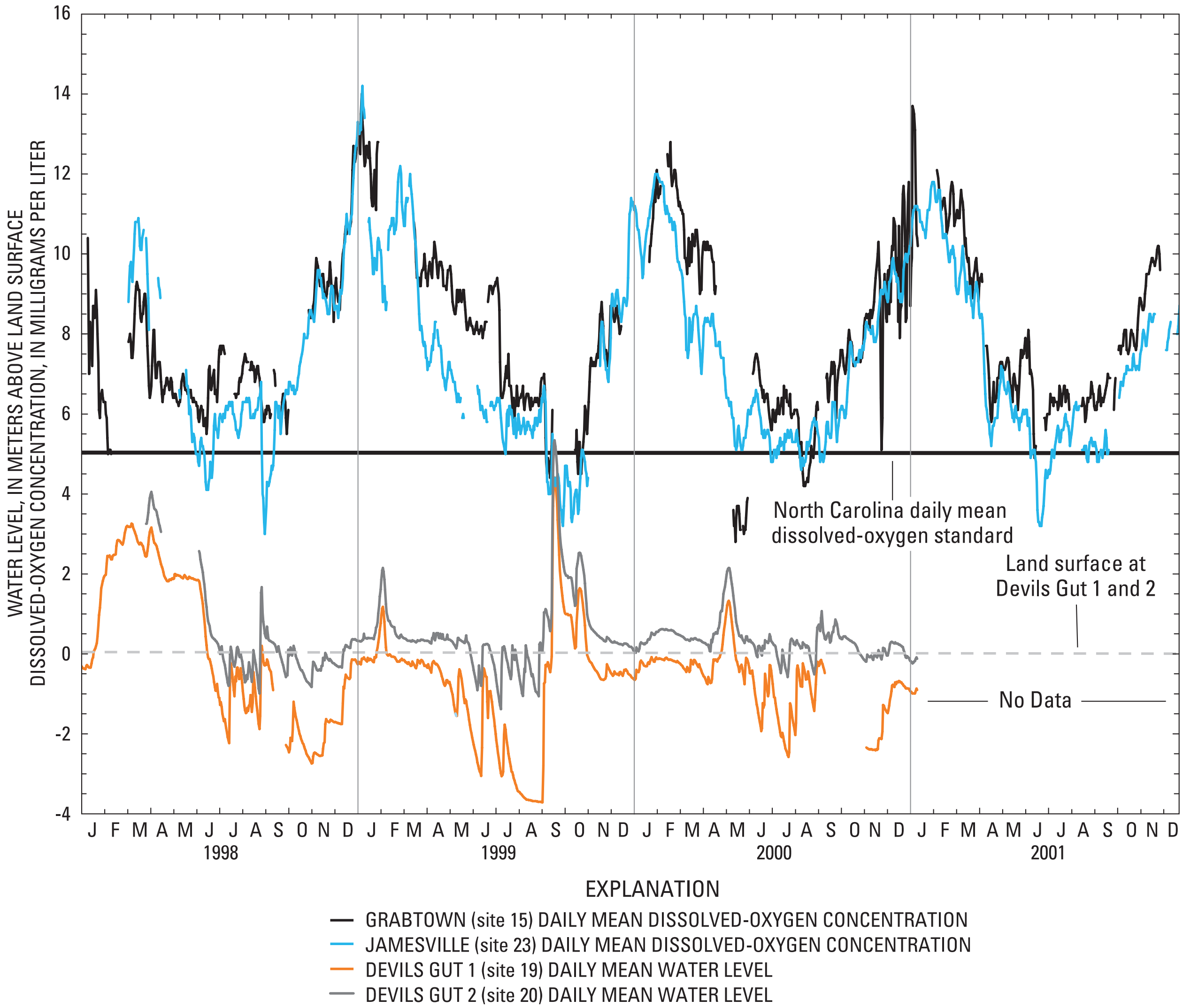


Figure 43. Daily mean dissolved-oxygen concentrations at Roanoke River near Grabtown (site 15) and Roanoke River at Jamesville (site 23), North Carolina, 1998–2001, and daily mean water levels at Devils Gut 1 (site 19) and Devils Gut 2 (site 20), 1998–2000.

negatively correlated to river flow, although the correlations were weak (correlation coefficients of 0.6 or less). TOC and BOD concentrations were higher near Plymouth than at an upstream sampling station. Most of the organic carbon near Plymouth was in the soluble form, and Rulifson and others (1990) attributed the higher TOC concentrations at Plymouth to swamp drainage.

Lebo (1998) also observed that DO at river kilometer 20 (between Jamesville and Plymouth) decreased in association with increased flow at Roanoke Rapids Dam. Lebo concluded that when flows at Roanoke Rapids increase from baseflow conditions (about 55 m^3/s) to more than 225 m^3/s, the DO at river kilometer 20 decreases. This decrease in DO was attributed to the increased swamp drainage at higher flows and the associated increased organic matter loading. Lebo also noted, however, that additional data and analyses were needed to confirm this conclusion and to more quantitatively assess the relation between upstream flow and downstream DO concentration.

Lebo (1998) concluded that flow at river kilometer 20 increased about 2 days after the release of short-term peak discharges (load-following operations). It is important to remember that waves (changes in water level and flow) travel at a velocity approximately equal to the square root of the product of the depth of flow and the gravitational constant. Hence, the speed of a wave in 4.5 m of water is about 6.7 m/s (meters per second) or about 24 km/hr (kilometers per hour). Water and waterborne materials, however, travel at speeds much slower than the wave. Consequently, the time difference between the occurrence of peak water levels at two locations on the river cannot be used to infer the travel time of a mass of water. The results reported by Hermann (1993) demonstrate that water mass movement is substantially slower than the wave velocity. Hermann (1993) conducted a series of dye studies in the

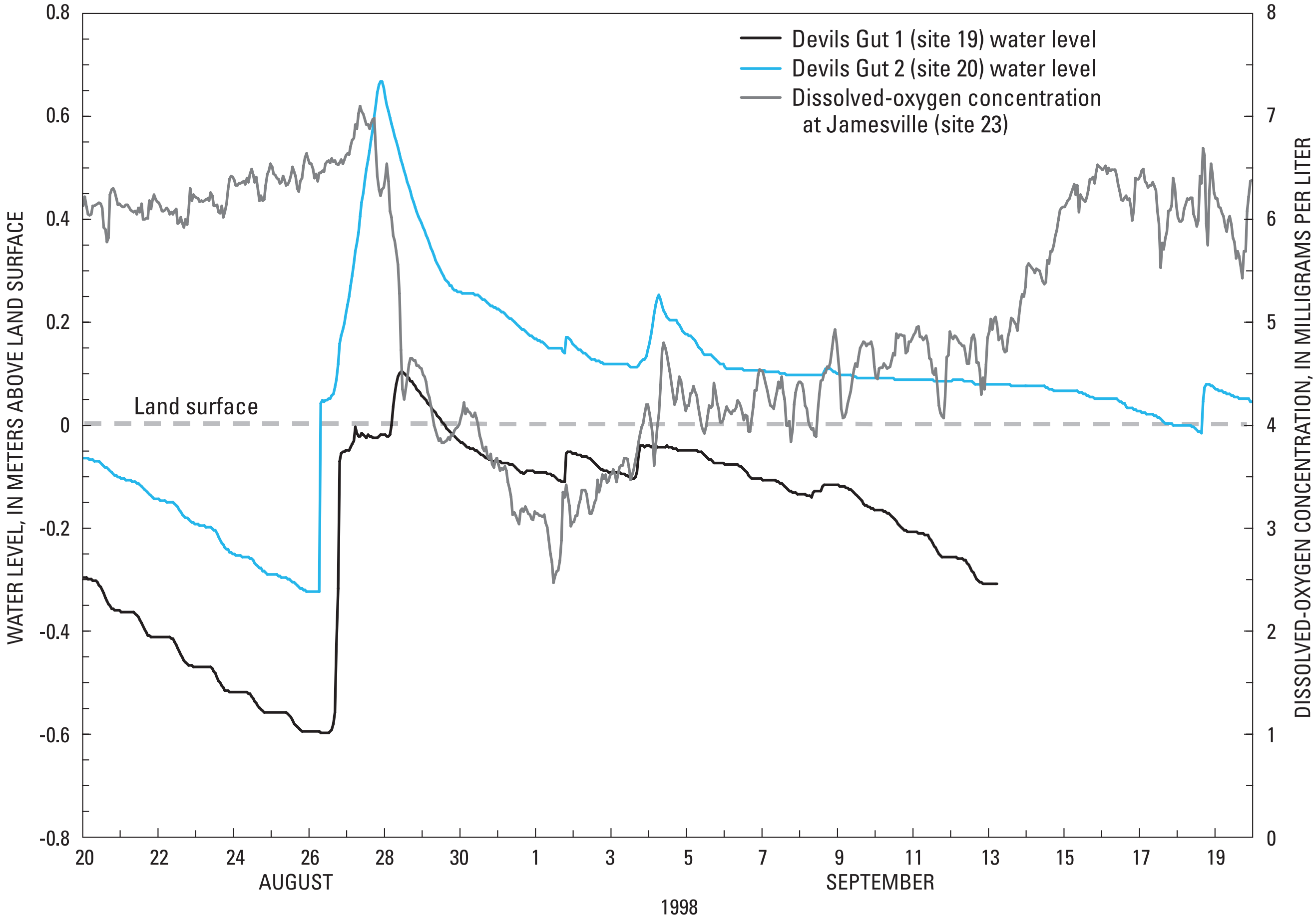


Figure 44. Hourly dissolved-oxygen concentrations at Roanoke River at Jamesville (site 23), North Carolina, and hourly water levels at Devils Gut 1 (site 19) and 2 (site 20), August 20–September 19, 1998.

Roanoke River for steady flows of approximately 270, 160, and 74 m^3/s. Estimated water-mass travel times between the Roanoke River at Roanoke Rapids (site 1, river kilometer 208) and river kilometer 13 were 4.3 days at 270 m^3/s, 8.4 days at 160 m^3/s, and between 9 and 10 days at 74 m^3/s. Hermann (1993) noted that transport rates estimated during steady-flow conditions would be modified under conditions of hydropower peaking.

Longitudinal Distribution of Dissolved Oxygen Along the Roanoke River

Flow conditions differed for each set of synoptic measurements of DO concentration made in the Roanoke River by the USGS (fig. 45). The daily mean flow at Roanoke Rapids on June 3, 1998, was 448 m^3/s, and the mean flow for the 7 days preceding June 3 was 531 m^3/s. The June 3, 1998, measurements were made as flow was being stepped down from an approximately 1-month period of steady flow at about 540 m^3/s. The September 3, 1998, measurements were made during a low-flow period. The daily mean flow on September 3, 1998, was 75 m^3/s, and the mean flow for the preceding week was 93 m^3/s. Some hydropower peaking occurred during the 7 days prior to September 3, 1998. The daily mean flow on May 8, 2000, was 283 m^3/s, and mean flow for the previous 7 days was 372 m^3/s. Flow was being stepped down from a fairly steady flow of about 540 m^3/s, which occurred during April 25–May 2, 2000.

Fromm and Lebo (1997) reported the results of DO measurements in the Roanoke River following Hurricane Fran in 1996. Data were collected downstream from river kilometer 157 during 7 days in October–November 1996, as flows at Roanoke Rapids were gradually reduced from about 570 to about 55 m^3/s following the Roanoke River Betterment Plan. DO concentrations in tributaries draining to the river generally were less than 4 mg/L, and the lowest concentrations were in tributaries upstream from Williamston (river kilometer 56). Longitudinal distributions of DO in the river reported by Fromm and Lebo (1997) were similar to the June and September 1998 USGS results. Concentrations upstream from about river kilometer 130 generally were high (greater than 6 mg/L) and stable (little change with distance along the river) for the seven sets of measurements. As with the USGS results, however, DO concentrations decreased with distance downstream, and the average DO-concentration decrease between

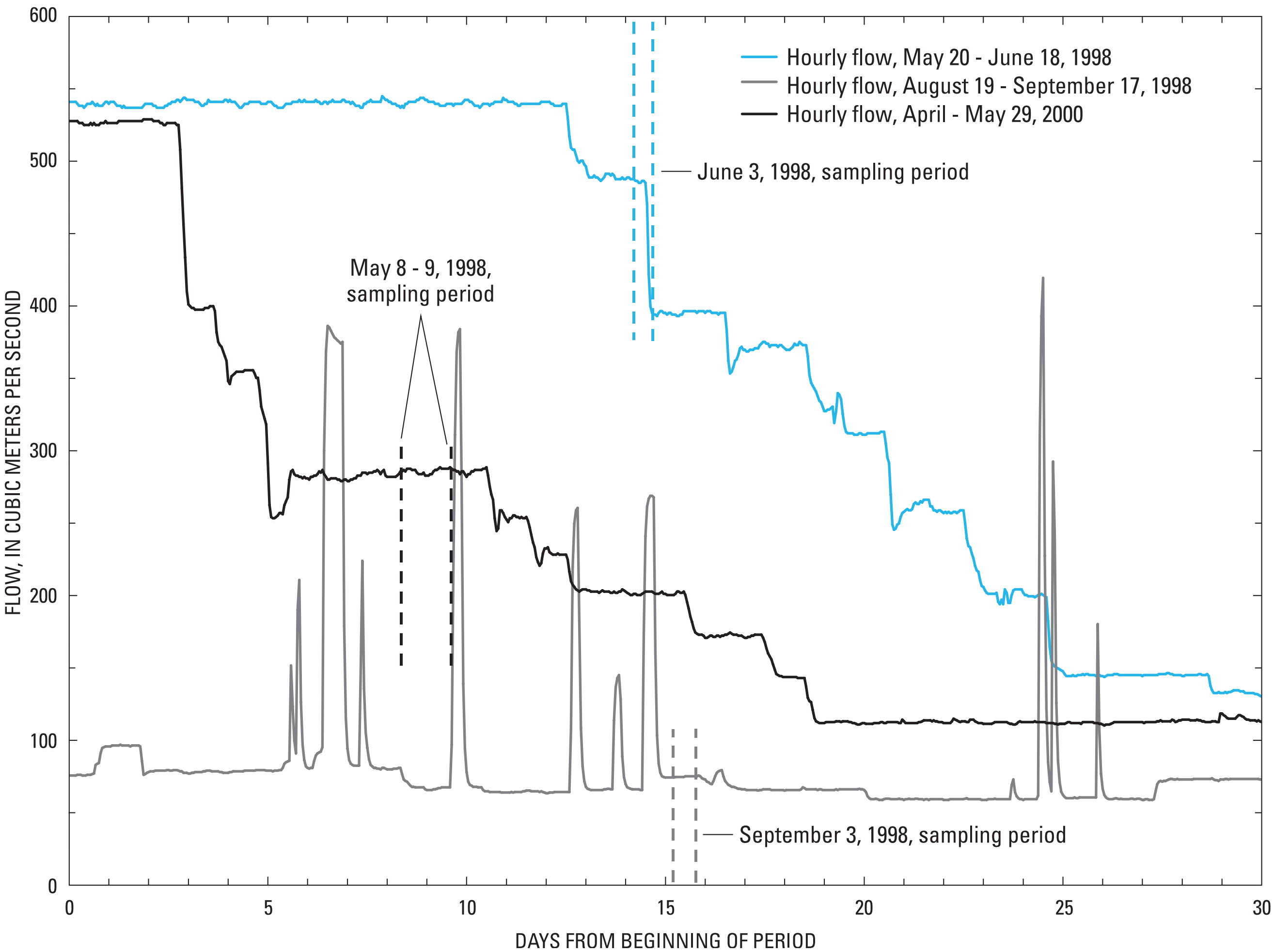


Figure 45. Hourly flow at Roanoke Rapids (site 1), North Carolina, for periods that included synoptic measurements of dissolved oxygen in the Roanoke River.

river kilometer 130 and the NC-45 bridge (site 31, river kilometer 3) for the seven measurements was 3.1 mg/L.

Results from the USGS and the Fromm and Lebo (1997) studies were combined to show the range of longitudinal DO profiles for the 10 different sets of conditions measured (fig. 46). The profiles represent a wide range of flow conditions but a somewhat limited set of seasonal conditions, as eight of the profiles were measured during the fall. The primary features of all profiles, however, are the local minimum near Halifax and the increase in the rate of DO change with distance downstream from about Hamilton compared to upstream from Hamilton (fig. 46). The maximum values downstream from Williamston were measured during May 8–9, 2000. The minimum values between Williamston and Jamesville were measured by Fromm and Lebo (1997) on October 16, 1996, and the minimum values downstream from Jamesville were measured on September 3, 1998 (fig. 46).

The North Carolina Department of Environment, Health, and Natural Resources (1996) developed a steady-state, low-flow, water-quality model for the reach of the Roanoke River between Roanoke Rapids Dam and Hamilton (site 10), at about river kilometer 97. The model included only loading from point sources. According to model simulations for 1995 conditions at a flow of 40 m^3/s, the longitudinal DO profile for the reach has two "sag" points, or minimums—one at Halifax (site 2, river kilometer 187) and one at river kilometer 103, about 3 km upstream from Oak City (site 9). Predicted minimum DO concentrations at both of these points for 1995 conditions was about 6 mg/L compared to about 7 mg/L for the case of no point-source discharges or withdrawals in the modeled reach; the minimum DO value measured during this study in the modeled reach was 5.4 mg/L (fig. 46). Downstream from the sag point near Oak City, the simulated DO concentrations increased slightly to Hamilton. The location and magnitude of the DO minimums depend on, among other things, the flow. Results from the NCDWQ model agree qualitatively with the synoptic DO measurements made during this study in that there is a clear sag in the vicinity of Halifax for all measurements and a sag or decrease in DO concentration between Scotland Neck and Oak City.

The longitudinal distribution of DO in the Roanoke River varies seasonally (fig. 47). During the study, the longitudinal

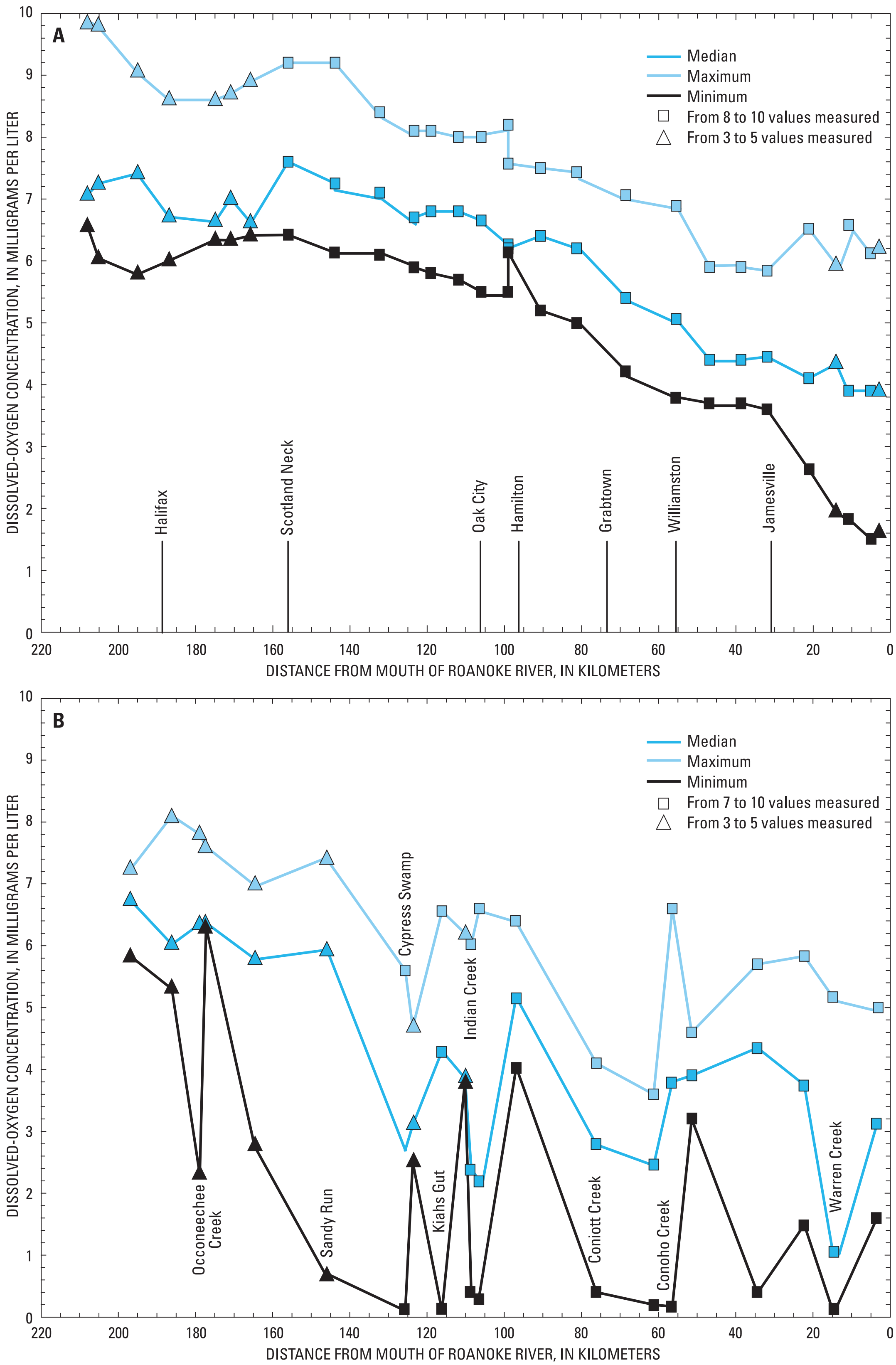


Figure 46. Median, maximum, and minimum dissolved-oxygen concentrations from three sets of U.S. Geological Survey synoptic measurements and seven sets of synoptic measurements by Fromm and Lebo (1997) at (A) selected locations along the Roanoke River, and (B) the mouths of selected tributaries to the Roanoke River, North Carolina.

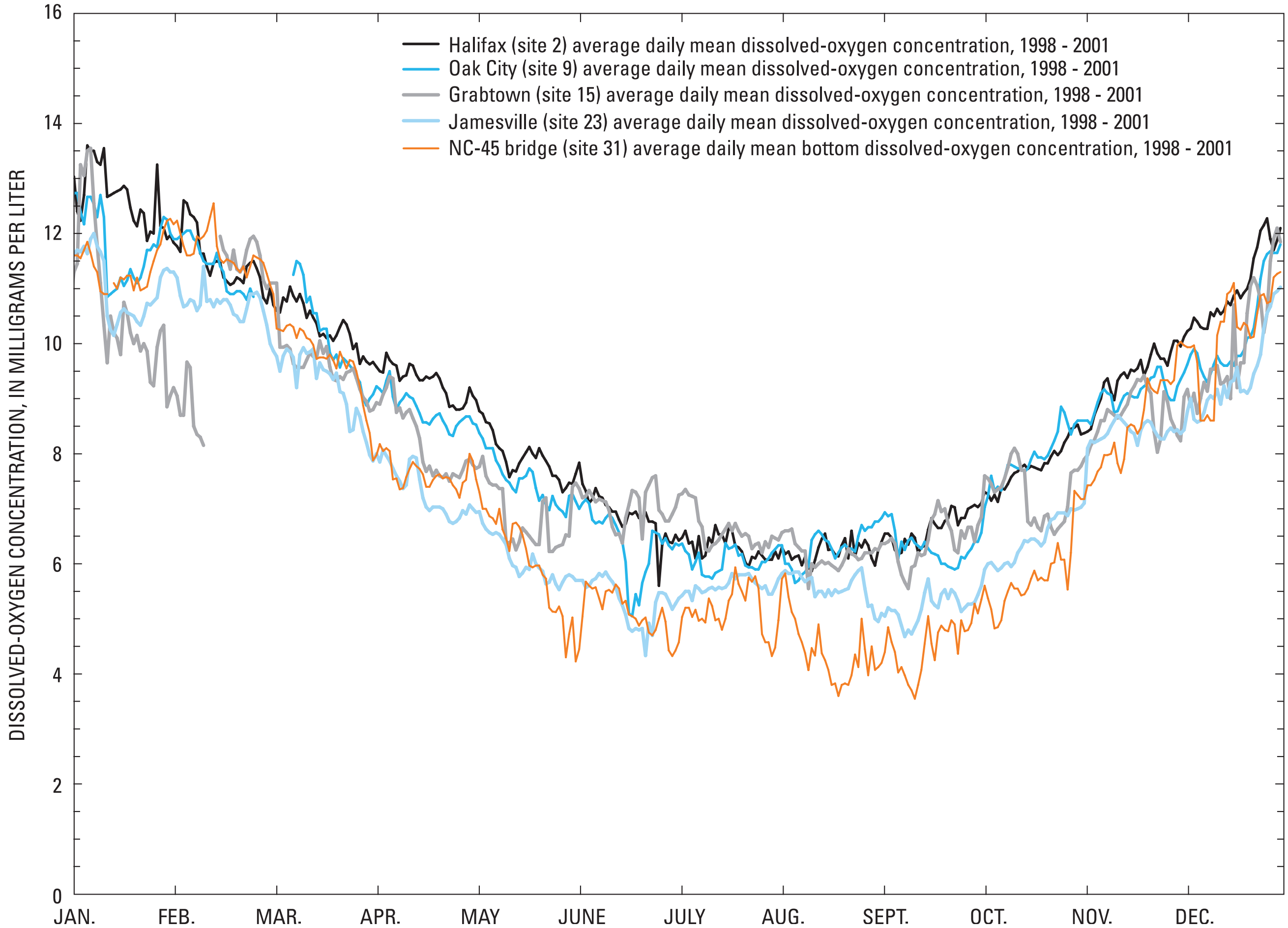


Figure 47. Average daily mean dissolved-oxygen concentration at five continuous monitoring locations in the Roanoke River, North Carolina, 1998–2001.

gradient was largest during June and August–October and smallest in March. During January–April, the DO concentration at the NC-45 gage (bottom sensor), on average, is likely to be greater than upstream at Jamesville, if the 1998–2001 data are representative of long-term conditions. Moreover, there were times in the fall when the DO concentration at Grabtown was less than at NC-45. During warm-weather months, however, DO at NC-45 typically was less than at upstream sensors. As seen in the longitudinal profiles (fig. 47), there is little DO concentration difference between Halifax and Oak City during most of the year, although the longitudinal profiles indicate that the DO concentrations are not uniform in the reach.

Biochemical oxygen demand in the tributaries generally was less than 1 mg/L on June 3, 1998. On September 3, 1998, BOD in the tributaries downstream from and including Indian Creek (river kilometer 106.5) ranged from 1.1 to 6.9 mg/L with a mean concentration of 3.3 mg/L, but tributary BOD concentrations upstream from Indian Creek were less than 1 mg/L. In contrast, Coniott Creek and other tributaries downstream all had BOD concentrations less than 2 mg/L, but 12 measured tributaries upstream from Coniott Creek had a mean BOD concentration of 3.2 mg/L with the highest concentration of 8.3 mg/L in Cypress Swamp. With two exceptions, all of the main-stem BOD concentrations during the three sets of measurements were less than or equal to 1.2 mg/L. Fromm and Lebo (1997) reported higher main-stem BOD concentrations at higher river flows following the passage of Hurricane Fran. All of the BOD concentrations in excess of 2 mg/L occurred at flows greater than 540 m^3/s. Tributary BOD concentrations generally increased with decreasing river flows. At a flow of 57 m^3/s, the mean BOD concentration in six tributaries downstream from and including Indian Creek was 2.7 mg/L. At a moderate flow of 240 m^3/s, the highest BOD concentrations were in tributaries upstream from and including Indian Creek. Cannon and Graham (2002) did not, however, detect any differences in BOD at four river locations between Hamilton and Jamesville during July 2001 at flows ranging from about 70 to 530 m^3/s. The samples were collected during a period of floodplain inundation and drainage induced by experimental high-volume load following at Roanoke Rapids. Samples concurrently collected from two floodplain stations—one near Coniott Creek and one from the Devils Gut swamp near Speller's Creek—yielded much higher BOD concentrations.

Summary and Conclusions: Instream Dissolved-Oxygen Conditions

Dissolved-oxygen concentrations typically decrease with increasing distance from Roanoke Rapids Dam. During the study period 1998–2001, the median DO concentration at Halifax, the upstream-most station, was 8.4 mg/L, and the median concentration at the downstream-most station (NC-45, bottom sensor) was 6.6 mg/L. Several synoptic measurements of DO concentration down the river identified the presence of a DO sag in the vicinity of Halifax (river kilometer 187), with some recovery of concentrations between Halifax and about Scotland Neck at river kilometer 156. The DO sag was predicted by a low-flow, steady-state, water-quality model developed by the NCDWQ (North Carolina Department of Environment, Health, and Natural Resources, 1996). Data from the synoptic measurements also indicated that the greatest rate of change in DO concentrations with distance along the river was downstream from Hamilton (river kilometer 97), which is downstream from the NCDWQ model domain.

The frequency with which the North Carolina water-quality standards for DO were exceeded also increased with distance from Roanoke Rapids Dam, and many of the low DO events were concurrent with backswamp drainage. The number of days during the study period in which the daily mean DO concentration was less than 5 mg/L are 2 days at Halifax, 18 days at Oak City, 45 days at Grabtown, 136 days at Jamesville, and 235 days at the NC-45 bottom sensor. Most of the occurrences of daily mean DO concentration less than 5 mg/L occurred during May–October, with the most occurring in September. If the low DO concentrations associated with Hurricane Floyd flooding are not considered, then June is the month during which daily mean DO concentrations were most likely to be less than 5 mg/L. June typically is the month during which the higher, spawning-enhancement flows are stepped down to the lower, summer load-following flows (fig. 6), and it is likely that this change in flow regime and the associated draining of the backswamps is at least partially responsible for the relatively large number of occurrences of low DO concentrations in June. It also is worth noting that during the study period, monthly point-source BOD loads in the summer were typically one-third of the loads during the winter (fig. 4B).

The downstream-most 29 km of the Roanoke River are classified as swamp waters, so DO values may be less than 5 mg/L due to "natural conditions." For designated swamp waters, standard water-quality models may not accurately simulate existing or future conditions. For this reason, applications for wastewater discharge into swamp waters are handled on a case-by-case basis in North Carolina. Other States also recognize the effect of natural conditions on DO concentrations and choose to protect water quality in various ways.

The effect of swamp drainage on instream DO concentration is difficult to determine quantitatively. A general sense of the relative magnitude of BOD loading from floodplain waters can be estimated, however, in the following manner. At a 10-day mean flow of 200 m^3/s, the relations of Townsend and Foster (2002) estimate that about 135 km^2 will be inundated in the lower Roanoke River corridor. With an assumed uniform inundation depth of 0.1 m (eqs. 1 and 2) and a uniform BOD concentration of 2 mg/L (based on sampling results), the total BOD content of the swamp waters would be 27,000 kg. At a 10-day mean flow of 500 m^3/s, an assumed uniform inundation depth of 0.4 m, and a uniform BOD concentration of 2 mg/L, the BOD content of the floodplain water would be 340,000 kg. In comparison, the BOD load from point sources in the lower Roanoke River basin during the summer is about 120,000 kg and about 300,000 kg during the winter (fig. 4B). These calculations of floodplain BOD load are based on a number of simplifying assumptions and empirical relations. Other assumptions could be made, but the assumptions used here are reasonable.

These calculations indicate that BOD load from the Roanoke River floodplain is about the same order of magnitude as the point-source BOD load. The rate at which the floodplain load is delivered to the river will certainly have some control on the effect of this loading on river water-quality conditions. Unlike the point-source loads, however, floodplain loads are delivered occasionally rather than continuously. Floodplain drainage, however, often occurs in the late spring or early summer after the end of spawning-season flows; BOD load from point sources typically is at or near the annual minimum during this time (fig. 4B).

Dissolved-oxygen concentrations are qualitatively related to flow conditions. Daily mean DO concentrations less than 5 mg/L occurred only at 10-day mean flows of 180–280 m^3/s at Oak City, only at 10-day mean flows less than 240 m^3/s at Grabtown, and primarily at 10-day mean flows less than 300 m^3/s at Jamesville. At NC-45, under current loading conditions, it is unlikely that the daily mean bottom DO concentration would be less than 5 mg/L for 10-day mean flows greater than about 290 m^3/s. Likewise, at a 10-day mean flow of 200 m^3/s, daily mean bottom DO concentrations could be as low as, but probably no lower than, 3 mg/L. The difference between mid-depth and bottom DO concentrations at NC-45 also is related to flow in somewhat the same manner as daily mean DO concentrations. At 10-day mean flows less than 200 m^3/s, the difference between mid-depth and bottom DO concentrations is likely to be greater than 1 mg/L, and at 10-day mean flows less than 100 m^3/s, the difference is likely to be 2 mg/L. For both flows, the difference is as likely to be positive (mid-depth greater than bottom) as negative (mid-depth less than bottom).

During May 11, 2000–December 31, 2001, when data from both the mid-depth and bottom sensors were available at NC-45, the median bottom DO concentration was 6.1 mg/L, and the median mid-depth concentration was 6.1 mg/L. Hourly DO concentrations less than 4 mg/L occurred about four times more often at the bottom sensor than at the top, but hourly DO concentrations greater than 8 mg/L occurred about 50 percent more frequently at the bottom than at mid-depth. DO concentrations were about as likely to be higher at the bottom sensor as at the mid-depth sensor. Data from vertical profiles of DO concentrations at NC-45 indicated that the minimum DO concentration could occur at mid-depth as well as at the bottom.

The daily variation in DO concentration was about 0.5 to 0.7 mg/L at all sites except Halifax; at the Halifax site, the daily variation was less than 1.5 mg/L. The small daily DO amplitudes qualitatively suggest that primary productivity in the Roanoke River is fairly low, but more detailed process studies are required to confirm this. The DO and temperature diurnal variations at Halifax were out of phase with expected conditions in that maximum water temperatures and DO concentrations occurred at night. Data on travel time between Roanoke Rapids Dam and Halifax, data on DO concentrations at Roanoke Rapids Dam, and the presence of daytime secondary daily peaks in some of the Halifax DO and temperature records suggest that the natural diurnal DO variations at Halifax are overwhelmed by releases from Roanoke Rapids Dam, which reflect conditions in Roanoke Rapids Lake and possibly Lake Gaston rather than instream processes. Downstream from Halifax, daily DO-concentration and water-temperature peaks typically occur in the afternoon, as expected.

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