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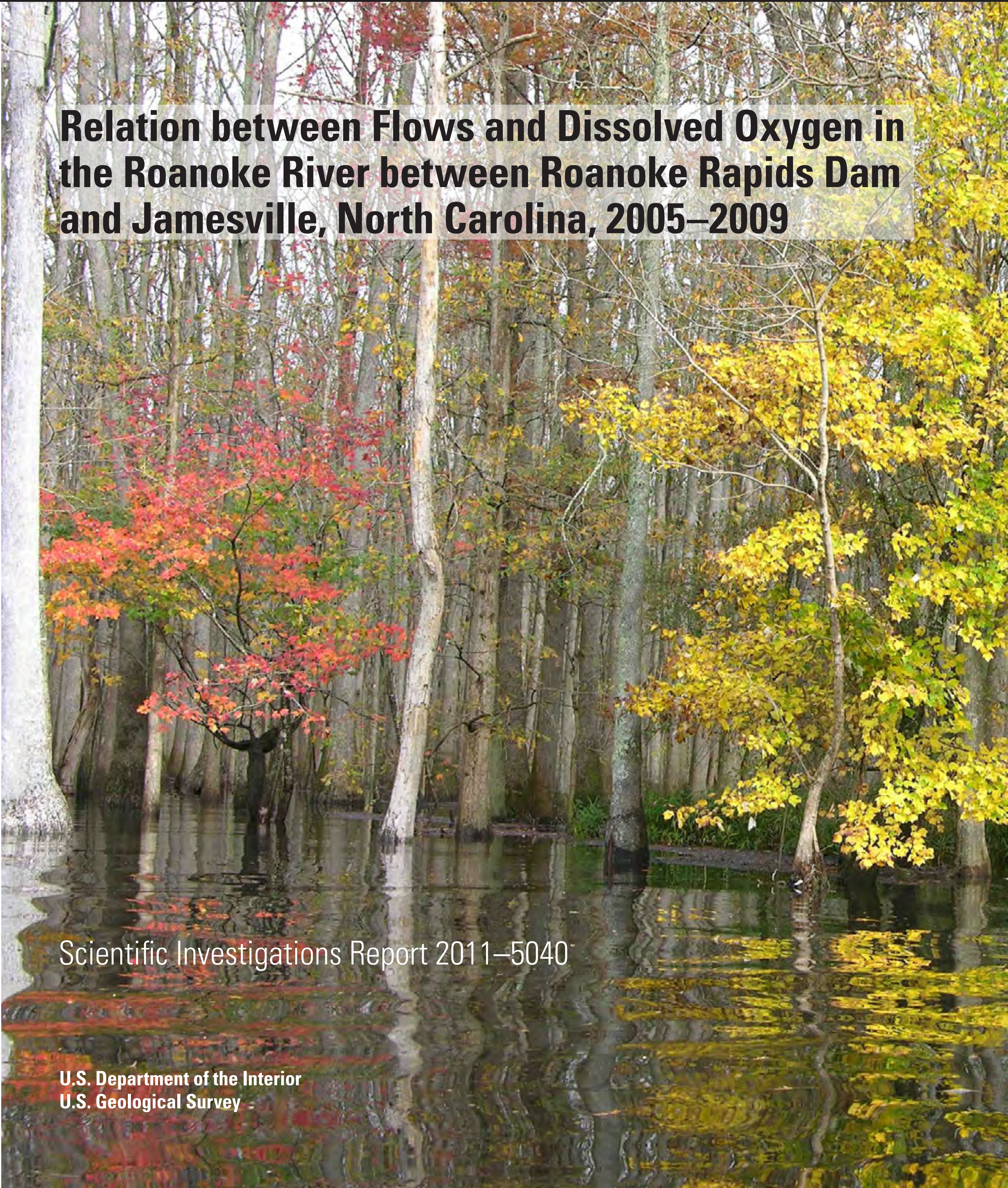

Relation between Flows and Dissolved Oxygen in the Roanoke River between Roanoke Rapids Dam and Jamesville, North Carolina, 2005–2009

Scientific Investigations Report 2011–5040

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

Cover Photographs: *Front cover*—Devil's Gut flood plain near Jamesville, North Carolina. *Back cover*—Roanoke River near Hamilton, North Carolina. Photographs taken by Jean Richter, U.S. Fish and Wildlife Service.

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By Loren L. Wehmeyer and Chad R. Wagner

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Conversion Factors

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
cubic foot per day (ft^3/d)	0.02832	cubic meter per day (m^3/d)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:
$°F=(1.8\times°C)+32$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29) or North American Vertical Datum of 1988 (NAVD 1988), as indicated in the text.

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

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

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

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

Relation between Flows and Dissolved Oxygen in the Roanoke River between Roanoke Rapids Dam and Jamesville, North Carolina, 2005–2009

By Loren L. Wehmeyer and Chad R. Wagner

Abstract

The relation between dam releases and dissolved-oxygen concentration, saturation and deficit, downstream from Roanoke Rapids Dam in North Carolina was evaluated from 2005 to 2009. Dissolved-oxygen data collected at four water-quality monitoring stations downstream from Roanoke Rapids Dam were used to determine if any statistical relations or discernible quantitative or qualitative patterns linked Roanoke River in-stream dissolved-oxygen levels to hydropower peaking at Roanoke Rapids Dam.

Unregulated tributaries that inundate and drain portions of the Roanoke River flood plain are crucial in relation to in-stream dissolved oxygen. Hydropower peaking from 2005 to 2009 both inundated and drained portions of the flood plain independently of large storms. The effects of these changes in flow on dissolved-oxygen dynamics are difficult to isolate, however, because of (1) the variable travel time for water to move down the 112-mile reach of the Roanoke River from Roanoke Rapids Dam to Jamesville, North Carolina, and (2) the range of in-situ conditions, particularly inundation history and water temperature, in the flood plain.

Statistical testing was conducted on the travel-time-adjusted hourly data measured at each of the four water-quality stations between May and November 2005–2009 when the weekly mean flow was 5,000–12,000 cubic feet per second (a range when Roanoke Rapids Dam operations likely affect tributary and flood-plain water levels). Results of this statistical testing indicate that at the 99-percent confidence interval dissolved-oxygen levels downstream from Roanoke Rapids Dam were lower during peaking weeks than during non-peaking weeks in three of the five years and higher in one of the five years; no data were available for weeks with peaking in 2007. For the four years of statistically significant differences in dissolved oxygen between peaking and non-peaking weeks, three of the years had statistically signficant differences in water temperature. Years with higher water temperature during peaking had lower dissolved oxygen during peaking. Only 2009 had no constistent statistically significant water-temperature difference at all sites, and dissolved-oxygen levels downstream from Roanoke Rapids Dam during peaking weeks that year were lower than during non-peaking weeks.

Between 2005 and 2009, daily mean dissolved-oxygen concentrations below the State standard occurred during only 1 of the 17 (6 percent) peaking weeks, with no occurrence of instantaneous dissolved-oxygen concentrations below the State standard. This occurrence was during a 9-day period in July 2005 when the daily maximum air temperatures approached or exceeded 100 degrees Fahrenheit, and the draining of the flood plains from peaking operations was followed by consecutive days of low flows.

Introduction

Virginia Electric and Power Company, which operates as Dominion Virginia Power and Dominion North Carolina Power (hereafter called Dominion), is required by the Federal Energy Regulatory Commission (FERC) to monitor dissolved oxygen (DO) and water temperature in the Roanoke Rapids Dam tailrace (at Roanoke River mile 137). Dominion also is required to support continuous monitoring of DO and water temperature in the Roanoke River (figs. 1, 2) downstream from the dam at the U.S. Geological Survey (USGS) streamgaging stations at Halifax (station number 0208062765 at river mile 119), Oak City (station number 02081022 at river mile 66), and Jamesville (station number 02081094 at river mile 19). In addition, the FERC requires the data to be evaluated for at least one 5-year cycle to determine if an association occurs between hydropower peaking and reduced water quality to below the State standard in the mainstem of the Roanoke River (Virginia Electric and Power Company, 2005). Flow rescheduling involves changing the timing of flow releases out of Dominion's lakes from the timing of water arriving from the U.S. Army Corps of Engineers' (USACOE) upstream lake. Rescheduling flows allows for hydropower peaking, which is the release of water through the dam turbines to generate electricity during periods of high demand, typically in the late afternoon and evening during weekdays.

The USACOE manages flow releases from Kerr Lake, and Dominion manages downstream flow releases from Lake Gaston and Roanoke Rapids Lake (fig. 1). The two downstream reservoirs have much less storage capacity than Kerr Lake, so releases from Kerr Lake generally control the

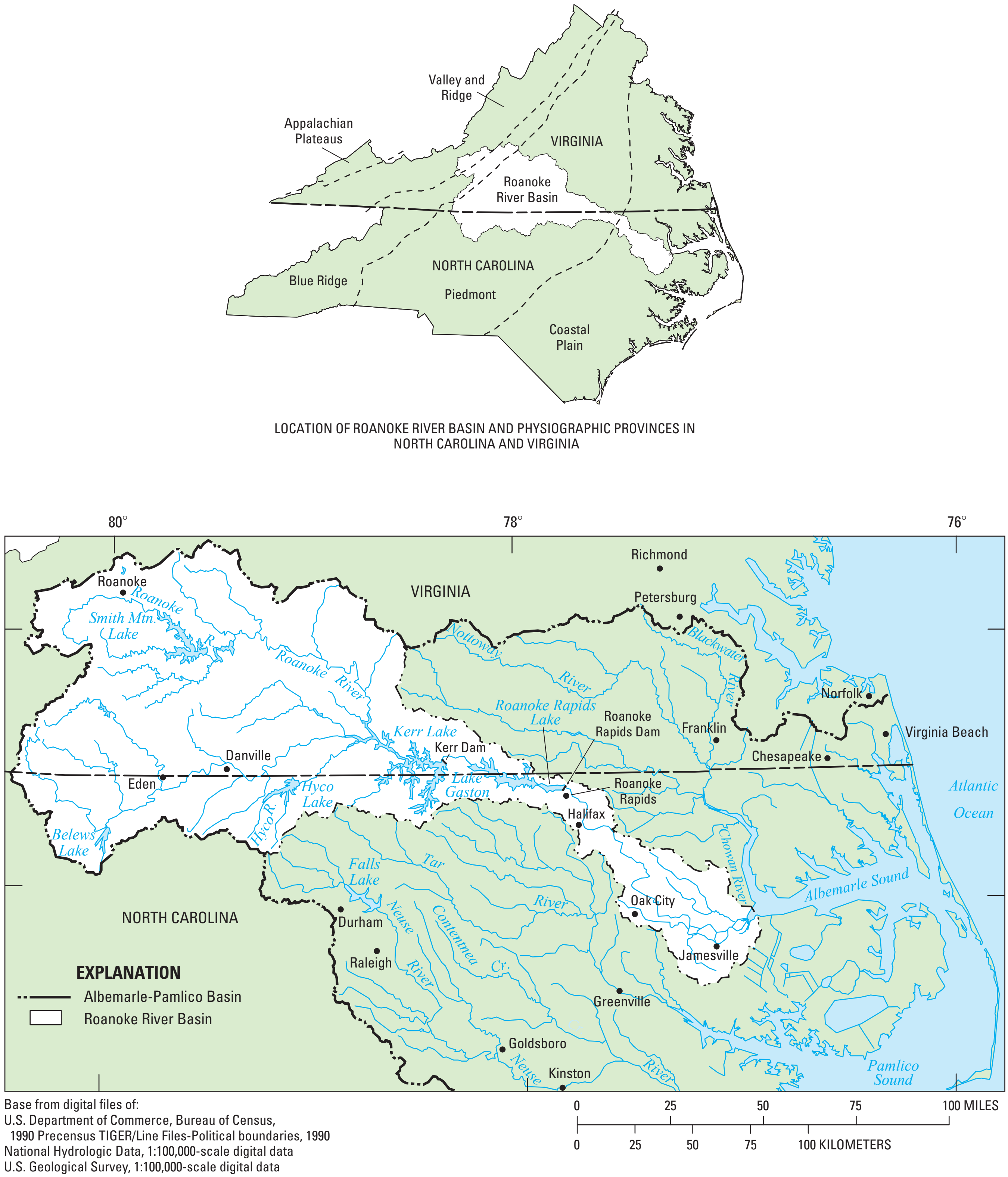
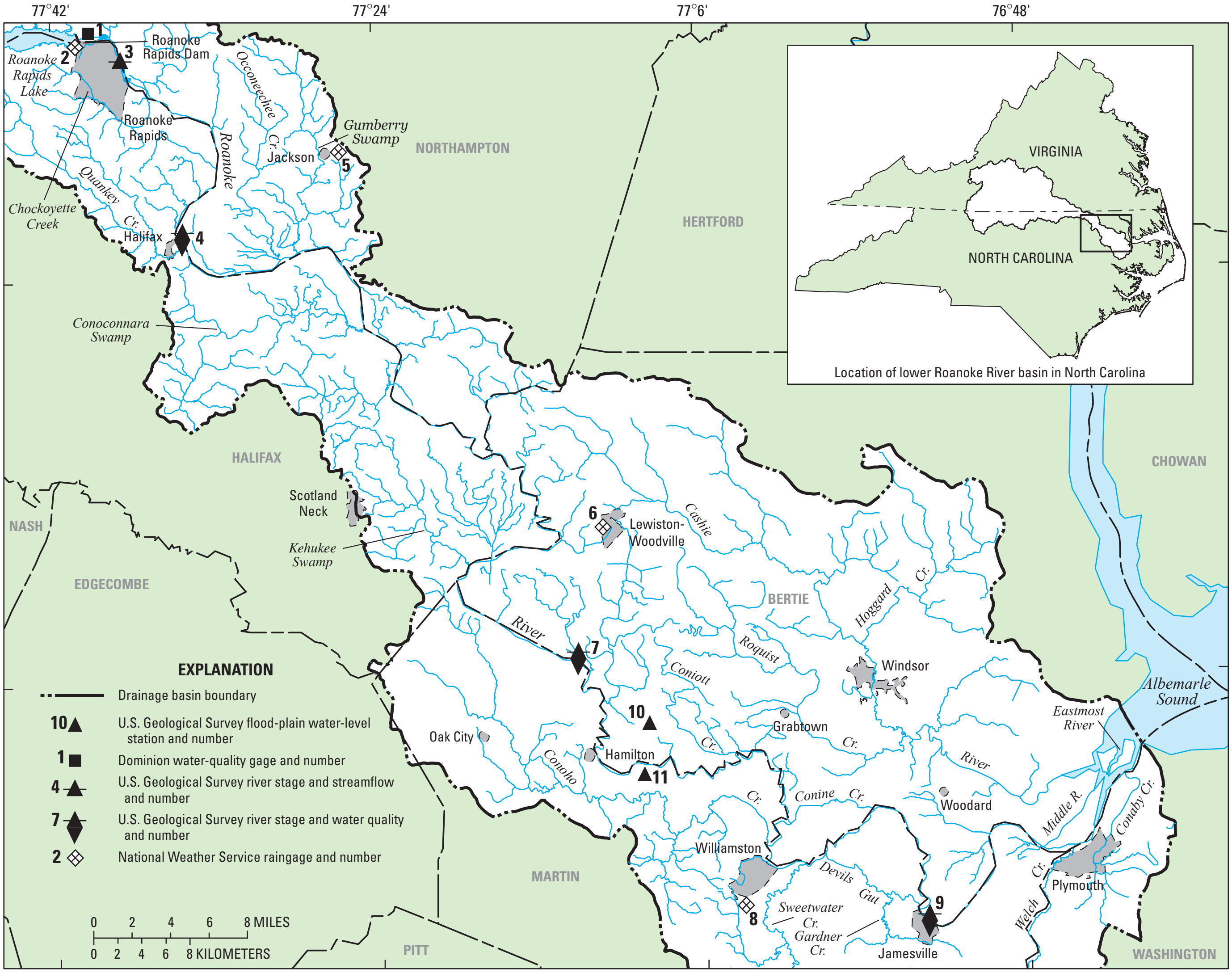


Figure 1. The Roanoke River basin in Virginia and North Carolina.



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-scale digital data
U.S. Geological Survey, 1:100,000-scale digital data

Figure 2. U.S. Geological Survey, Dominion, and National Weather Service data-collection sites in the Roanoke River basin between Roanoke Rapids Dam and Jamesville, North Carolina.

operation of Lake Gaston and Roanoke Rapids Lake. The USACOE provides Dominion with a weekly flow declaration, which is the amount of weekly mean flow that is expected to be released from Kerr Lake. Dominion can reschedule weekly mean flows within the constraints of license requirements and the storage capacities of the reservoirs to optimize power generation during times of peak energy demand.

Dominion requested that the USGS evaluate Roanoke River in-stream DO data collected from 2005 to 2009 from Roanoke Rapids Dam to Jamesville, North Carolina. The analysis emphasized periods when the weekly (beginning Saturday at 12:00 midnight) mean flows from Roanoke Rapids Dam were between 5,000 and 12,000 cubic feet per second (ft^3/s), herein called the critical range. At weekly mean flows in the critical range, hydropower peaking from Roanoke Rapids Dam potentially affects in-stream DO concentrations as a result of backswamp flooding and drainage (Virginia Electric and Power Company, 2005). At lower weekly mean flows, little backswamp flooding occurs, but at higher weekly mean flows, flood-control releases by the USACOE at Kerr Lake generally dominate Dominion operations, and backswamp flooding is beyond the control of Dominion.

In a USGS report by Bales and Walters (2003), the relations among Roanoke River flood-plain water levels, in-stream DO, and streamflow from 1997 to 2001 were discussed. Key findings from that report include: (1) flood-plain drainage on in-stream DO is difficult to determine quantitatively, (2) the biochemical oxygen demand (BOD) loading from point sources is about the same order of magnitude as the BOD loading from flood-plain waters, (3) DO is qualitatively related to flow conditions, (4) small daily DO amplitudes qualitatively indicate that primary production in the Roanoke River is fairly low, and (5) the natural diurnal DO variations at Halifax were out of phase with expected conditions, which indicates that the natural diurnal DO variations were overwhelmed by releases from Roanoke Rapids Dam.

The current study addresses one of the six USGS science strategy goals, “Understanding ecosystems and predicting ecosystem change” (U.S. Geological Survey, 2007). The study also addresses at least three priority issues of the USGS 2007 Federal-State Water Cooperative Program: water quality, water availability and use, and water resources in the coastal zone (U.S. Geological Survey, 2008). Finally, the study meets the science plan goal of the USGS North Carolina Water Science Center to support Federal and State water-resources programs through support for FERC-licensing requirements by collecting, interpreting, and disseminating quality-assured hydrologic data.

Purpose and Scope

This report describes the effects of flow releases from Roanoke Rapids Dam on DO concentrations, including percentages of saturation and deficit levels, in the Roanoke River between Roanoke Rapids and Jamesville, North Carolina, during May–November from 2005 to 2009. The focus of the analysis is on periods when weekly (beginning Saturday at 12:00 midnight) mean flows were between 5,000 and 12,000 ft^3/s, which is the flow range in which hydropower peaking potentially affects in-stream DO. Streamflow data from one station; rainfall data from four stations; and water temperature, DO concentration, and DO percentage-of-saturation data from four stations (table 1; fig. 1) were used in the analysis to determine if statistical relations or qualitative patterns linked Roanoke River in-stream DO levels to water releases at Roanoke Rapids Dam.

Description of the Study Area

The study area is an approximately 112-mile (mi) reach of the Roanoke River between Roanoke Rapids Dam and Jamesville, North Carolina (fig. 1). The drainage area at Jamesville is 9,250 square miles (mi^2), which is about 10 percent larger than the drainage area at Roanoke Rapids Dam.

Flow monitoring by the USGS in the Roanoke River at Roanoke Rapids began in 1911 (U.S. Geological Survey, 2011). The Roanoke River has been regulated by Kerr Dam since 1950 and by Roanoke Rapids Dam since 1955. Prior to regulation in 1950, the maximum recorded flow was 261,000 ft^3/s on August 18, 1940, and the minimum discharge was about 250 ft^3/s on December 16, 1955. Under the current configuration, since October 1963 when Smith Mountain Lake (fig. 1) was completed in the headwaters of the Roanoke River, the highest recorded instantaneous flow was 37,700 ft^3/s in 1993, and the lowest recorded instantaneous flow was

Table 1. Streamflow, water-quality, and precipitation monitoring stations in the Roanoke River Basin, North Carolina, that were used in this study.

[River mile, the distance from the mouth of the Roanoke River to the station; mi^2, square mile; NAD 83, North American Datum of 1983; WQ, continuous water-quality data, including pH, water temperature, specific conductance, and dissolved-oxygen concentration; NWS, National Weather Service; —, not applicable; RF, rainfall data; USGS, U.S. Geological Survey; Q, streamflow data]

Station name (site number) shown in figure 2	Station number	Data collected by	Station type	River mile	Drainage area (mi^2)	Latitude (NAD 83)	Longitude (NAD 83)	Data	Period of record[a]
Roanoke Rapids Dam tailrace (site1)	—	Dominion	Streamgage	137	8,369	36°28'48"	77°40'09"	WQ	July 2003–Dec. 2009
Roanoke Rapids (site 2)	317319	NWS	Raingage	—	—	36°29'	77°40'	RF	Unknown–Dec. 2009
Roanoke River at Roanoke Rapids (site 3)	02080500	USGS	Streamgage	134	8,384	36°27'38"	77°38'03"	Q	Dec. 1911–Dec. 2009
Roanoke River at Halifax (site 4)	0208062765	USGS	Streamgage	119	8,450	36°19'59"	77°34'58"	WQ	Mar. 1998–Dec. 2009
Jackson (site 5)	314456	NWS	Raingage	—	—	36°27'38"	77°38'03"	RF	Sept. 1948–Dec. 2009
Lewiston (site 6)	314962	NWS	Raingage	—	—	36°08'	77°10'	RF	Mar. 1954–Dec. 2009
Roanoke River near Oak City (site 7)	02081022	USGS	Streamgage	66	8,810	36°00'51"	77°12'54"	WQ	Mar. 1998–Dec. 2009
Williamston (site 8)	319440	NWS	Raingage	—	—	35°51'	77°02'	RF	Aug. 1948–Dec. 2009
Roanoke River at Jamesville (site 9)	02081094	USGS	Streamgage	19	9,250	35°48'49"	76°53'37"	WQ	Mar. 1998–Dec. 2009
Broadneck Swamp 1 (site 10)	355812077082301	USGS	Flood plain	—	—	35°58'10"	77°08'27"	WL	Apr. 1997–Jan. 2001
Broadneck Swamp 3 (site 11)	355540077083401	USGS	Flood plain	—	—	35°55'41"	77°08'35"	WL	Aug. 1996–Jan. 2001

[a] The period of record for all stations extends beyond December 2009, but only the period of record to the end of the data analysis in this investigation is shown.

760 ft^3/s in 1970. Because of the upstream regulation, flooding and flood-plain 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). The timing, duration, and extent of flood-plain inundation can have either positive or negative effects on vegetation, wildlife, and fisheries in the Roanoke River between Roanoke Rapids Dam and Jamesville depending on inundation characteristics (Rulifson and Manooch, 1993). Total permitted wastewater discharge between Roanoke Rapids Dam and Jamesville is about 5,814,600 cubic feet per day (43.5 million gallons per day), or about 67 ft^3/s, although most facilities do not operate at permitted capacity (North Carolina Department of Environment and Natural Resources, 2006).

Methods

Data from one streamflow station, four water-level and water-quality stations, and four weather stations were compiled. Continuous streamflow data were collected at Roanoke Rapids, North Carolina (site 3), about 2.8 mi downstream from Roanoke Rapids Dam. Water-quality data (table 1; fig. 1) were collected from 1998 through 2009 at the USGS stations at Roanoke River at Halifax (site 4), Roanoke River near Oak City (site 7), and Roanoke River at Jamesville (site 9), and by Dominion (site 1) in the tailrace 900 feet (ft) downstream from the Roanoke Rapids Dam. Water-level and water-quality data were collected at the USGS sites. Water-quality data, including specific conductance, pH, water temperature, and DO concentrations, were measured at 15-minute intervals using multiparameter water-quality sondes connected to a data logger. USGS sondes were serviced and replaced with cleaned and calibrated units at approximately 4-week intervals. Maintenance, operation, calibration, and records computation were conducted using methods described by Wagner and others (2006). The Dominion sonde was used to measure DO concentration and water temperature; the sonde was cleaned and calibrated quarterly or as needed. If measurements were questionable, a second probe was deployed for verification. Records were maintained in paper and electronic formats.

The percentage of DO saturation and DO deficit (the difference between the saturated DO concentration and the measured DO concentration) at all sites were computed according to methods described by Bales and Nardi (2007), which require measurements (or estimates) of specific conductance, water temperature, DO concentration, and ambient barometric pressure. Ambient barometric pressure data were not collected during the period of study, so these data were approximated by computing the ambient barometric pressure based on the water-surface elevation altitude at the nearby USGS streamgage at Roanoke River at Roanoke Rapids. The ambient barometric pressure at each USGS streamgage was derived from the water-surface elevation referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29). At the Roanoke Rapids Dam tailrace, only water temperature and DO concentration were measured. Specific conductance at the Roanoke Rapids Dam tailrace was estimated by using measured specific conductance at the USGS station at Roanoke River at Halifax, which was adjusted for the main channel travel time between the USGS stations at Roanoke River at Roanoke Rapids and Roanoke River at Halifax. The travel time between the Roanoke Rapids Dam tailrace and the USGS station at Roanoke River at Roanoke Rapids (approximately 2.8 mi) was neglected because the domain of the hydraulic model that was used for estimating in-stream travel times did not extend upstream from this USGS station. However, the distance between Roanoke Rapids Dam and the USGS station at Roanoke River at Roanoke Rapids represents less than 3 percent of the distance from Roanoke Rapids Dam to the USGS station at Roanoke River at Jamesville. A record of specific conductance, in units of microsiemens per centimeter at 25 degrees Celsius (°C), was estimated at the Roanoke Rapids Dam tailrace using travel-time-adjusted specific conductance data at the USGS station Roanoke River at Halifax, the closest downstream station with specific conductance data.

A one-dimensional hydraulic model of the Roanoke River for the 110-mi reach from Roanoke Rapids to Jamesville was created by using HEC-RAS (Hydrologic Engineering Centers River Analysis System) version 4.0 to simulate travel times (U.S. Army Corps of Engineers, 2008). HEC-RAS simulates time-varying, cross section average flows and water levels in a network of open channels, including flows at hydraulic structures (bridges, culverts, etc.); levee breaching and overtopping also can be simulated. The geometry for the Roanoke model was developed from 101 surveyed cross sections of the main channel and flood plain, Light Detection and Ranging (LiDAR) data (20-ft by 20-ft pixels; 0.66-ft root mean square vertical accuracy) were used to delineate the entire flood plain, including along the 101 model cross sections. The model was forced using measured hourly streamflow at the upstream end of the model domain and measured hourly water levels at the downstream end. Intervening flows were small (drainage area increased 860 mi^2, or less than 10 percent) in the model domain. These flows were estimated at a daily time step by computing a combined average daily flow per square mile from USGS stations at Potecasi Creek near Union, NC (02053200), Ahoskie Creek at Ahoskie, NC (02053500), and Fishing Creek near Enfield, NC (02083000), and by multiplying this average unit flow value by the intervening drainages to the Roanoke River in the study area. No major withdrawals or dischargers are in the modeled reach. Streamflow during the simulation period of 1998–2009 ranged from about 1,700 ft^3/s to 35,000 ft^3/s. The highest releases (35,000 ft^3/s) during the study period, the greatest flood-plain inundations, occurred during 1998 and 2003. As a result, data from these 2 years were used primarily for model calibration and testing and included continuous water level at six locations for 1998 and 2003 and continuous discharge at two locations from September 1, 2006, to August 30, 2007. A summary of the model calibration is presented in table 2.

Table 2. Summary of the Roanoke River model calibration and testing results, 1998, 2003 and 2006–2007.

[USGS, U.S. Geological Survey; ft, feet; ft³/s, cubic feet per second; NC, North Carolina; —, not applicable]

USGS station number	Station name	1998		2003		2006–2007	
		Mean error in stage (ft)	Standard deviation of the mean error (ft)	Mean error in stage (ft)	Standard deviation of the mean error (ft)	Mean error in flow (ft^3/s)	Standard deviation of the mean error (ft^3/s)
0208062765	Roanoke River at Halifax, NC	0.16	1.10	–0.18	0.75	—	—
02081000	Roanoke River near Scotland Neck, NC	0.33	1.10	–0.23	0.85	—	—
0208102115	Roanoke River near Hills Ferry, NC	0.51	0.59	—	—	—	—
02081022	Roanoke River near Oak City, NC	0.37	0.71	0.03	1.17	78	1,163
02081054	Roanoke River at Williamston, NC	0.02	0.45	–0.02	0.74	141	1,857
020810860	Roanoke River near Woodard, NC	0.16	0.33	—	—	—	—

Daily rainfall totals (National Climatic Data Center, 2010) and 1971–2000 daily climate normals (National Climatic Data Center, 2008) were obtained for four National Weather Service (NWS) climatic index stations in the general vicinity of the study area (table 1; fig. 2). The 1971–2000 daily climate normals dataset provides the average daily value for each calendar day for several climate variables at individual stations and is often used as a reference point to indicate average climatic conditions. These index stations were at Roanoke Rapids (site 2), Jackson (site 5), Lewiston (site 6), and Williamston, North Carolina (site 8; fig. 2).

Precipitation in the Roanoke River basin downstream from Roanoke Rapids Dam can cause flood-plain inundation and subsequent flood-plain drainage into the Roanoke River independently from dam releases. During warm months, water in the flood plain can become deplete of oxygen and return to the Roanoke River as surface water or groundwater, thereby decreasing in-stream DO. It is important, therefore, to distinguish the effects of local runoff, including tributary inflow and flood-plain drainage, from the effects of upstream dam releases. Discharge data were not available downstream from the USGS station at Roanoke River at Roanoke Rapids; therefore, rainfall data were used as a surrogate to identify periods of potentially elevated tributary inflows or flood-plain drainage to the river. The relations between interannual precipitation and mean DO, precipitation and in-stream DO for the months of May through November of each year, and individual storm precipitation events and associated DO were investigated to identify the effects of tributary inflows on in-stream DO in the Roanoke River.

Decreases in in-stream DO resulting from tributary runoff from large precipitation events were quantified by comparing the daily mean precipitation (averaging the two closest raingage daily precipitation totals) to changes in the percentage of DO saturation measured every hour. Storm systems producing rainfall in the Roanoke River basin often are slow moving. A storm was defined in this study as an event with a duration of up to 7 days initiated by a minimum of 1.5 inches of measured daily precipitation averaged between the two upstream or two downstream raingages and continuing on subsequent days if there was greater than 0.15 inch of rainfall per day.

Hourly and daily mean streamflow and DO data were evaluated during this study. Although the period of record for daily mean streamflow at the USGS streamgage at Roanoke Rapids began in 1911, hourly streamflow data are only available beginning in 1986 and through 2009 except for water years (October 1–September 30) 1989 and 1993. A striped bass flow regime was established in 1989, so the long-term period of record for flow at Roanoke Rapids Dam for this analysis was defined as 1989–2009. All years during the long-term period, except for water years 1989 and 1993, have at least 98.7 percent complete record for hourly flows and 100 percent complete record for daily flows. These data were separated into two additional data sets with all weeks that met the weekly specified-flow criteria (5,000 to 12,000 ft^3/s) and weeks that met both the specified-flow criteria and in which hydropower peaking occurred (table 3). A total of only 17 weeks of peaking operations occurred between 2005 and 2009 that met the weekly specified-flow criteria. Data for May through November were the focus of the analysis, as these are the months in which low DO values typically occur (Bales and Walters, 2003).

Streamflow at the USGS station at Roanoke River at Roanoke Rapids was characterized statistically for the study period (2005–2009) in order to identify interannual or intraannual variations that could be related to in-stream DO. The 2005–2009 period was the focus of this analysis because the license agreement for the operation of Roanoke Rapids Dam specifies report updates in each 5-year study cycle to document whether there is a causal link between rescheduling of flows and a reduction in water quality to below the State standard. This report represents the first 5-year analysis.

Table 3. Number of weeks per year that weekly mean flow was within the specified flow range from May 1 to November 30 at the U.S. Geological Survey streamgaging station at Roanoke River at Roanoke Rapids, North Carolina.

[ft^3/s, cubic foot per second]

Year	Number of weeks within the specified weekly mean flow range	
	5,000–12,000 ft^3/s	5,000–12,000 ft^3/s and hydropower peaking
2005	11	5
2006	9	9
2007	5	0
2008	6	1
2009	9	2

Streamflow statistics were summarized for periods during May through November when the weekly mean flow was 5,000 to 12,000 ft^3/s, and for periods when the weekly mean flow was 5,000 to 12,000 ft^3/s while hydropower peaking operations were occurring (defined as weeks with at least 1 day with a daily flow range of at least 5,000 ft^3/s). Separate May–November annual flow duration curves were developed for the study period and for the long-term period (1998–2009) using the entire flow record and the portion of the flow record when weekly mean flows were between 5,000 and 12,000 ft^3/s. Frequency, duration, and the magnitude-of-flow changes in the 5,000 to 12,000 ft^3/s range were characterized for the study period and compared to the long-term period (1989–2009).

Oxygen solubility in water decreases as water temperature increases. To investigate the potential effects of peaking at Roanoke Rapids Dam on downstream flow and water quality, the periods of the warmest water temperature (May through October) when weekly mean flows were between 5,000 ft^3/s and 12,000 ft^3/s were isolated for analysis. The periods from May through October were extended through November 30 to encompass the entire hurricane season. The periods of June 16–November 30, which are the periods within May to November when peaking is allowed, when weekly mean flows were between 5,000 ft^3/s and 12,000 ft^3/s were also analyzed separately. Dissolved-oxygen characteristics were summarized for the four water-quality stations for the period of available record. The change in DO longitudinally for a given parcel of water was estimated by comparing concurrent DO measurements adjusted for travel time between water-quality stations. The distribution of DO change was categorized by stream reach (Roanoke Rapids Dam tailrace to the USGS station at Roanoke River at Halifax, the USGS station at Roanoke River at Halifax to the USGS station at Roanoke River near Oak City, and the USGS station at Roanoke River near Oak City to the USGS station at Roanoke River at Jamesville) and by flow range.

The effects of flow rescheduling on in-stream DO were evaluated by examining DO concentration, percentage of saturation, and DO deficit time-series data for each stream reach separated into datasets of weeks with and without hydropower peaking. Median hourly DO concentrations for peaking and nonpeaking flows were compared statistically using the Fisher exact probability test (Fisher, 1922) for a 2-tailed p-test (Agresti, 1992), accessible as an online calculator (Langsrud, 2004). These statistical tests were used to determine if the median hourly value of annual DO in the critical range, adjusted for travel time, was different during weeks with hydropower peaking compared to DO during weeks without hydropower peaking.

A key question is how rescheduling changes the duration and frequency of flood-plain inundation. A measure of this change is the number of consecutive days when the daily mean flow is greater than the weekly mean flow because of rescheduling. The daily mean flows for 1989 through 2009 were compared to the weekly mean flows between June 16 and November 30 when the weekly mean flow was between 5,000 and 12,000 ft^3/s.

Relation between Flows and Dissolved Oxygen in the Roanoke River

An analysis of the interannual and intraanuual relations of tributary inflows (precipitation), streamflow and in-stream DO is presented in this section. The measured and travel-time adjusted DO record at the four water quality stations (table 1; fig. 2) are related to measured precipitation and streamflow to document any causal link between rescheduling of flows and a reduction in water quality to below the State standard.

Effects of Tributary Inflows on In-stream Dissolved Oxygen

Annual precipitation in the study area during 2005–2009 varied temporally and spatially (table 4). At two of the four stations with raingages, the 2005–2009 May–November mean measured precipitation was less than the May–November annual mean precipitation during the NWS reference period of 1971–2000 (National Climate Data Center, 2008). The wettest year of the study period was 2006 when all four raingages recorded more than 42 inches of precipitation; 2007 was the driest year when three of the four stations recorded less than 22 inches of precipitation (table 4).

A consistent relation was not apparent between annual May through November mean DO concentrations and annual May through November precipitation amounts. At Jamesville, the station most affected by tributary inflows and flood-plain runoff, the annual May through November period (2006) with the highest rainfall total corresponded with the lowest annual mean May through November DO concentration and DO percentage of saturation and highest DO deficit (table 5).

Table 4. Annual precipitation, in inches, during May through November 2005–2009 in the Roanoke River Basin, North Carolina.

Station name	1971–2000 average	2005–2009 average	2005	2006	2007	2008	2009
Roanoke Rapids	28.00	27.76	23.55	44.80	20.88[a]	21.54	28.03
Jackson	27.70	33.60	27.02	49.63	25.52	29.30	36.54[b]
Lewiston	29.20	27.88	25.99[c]	44.64	18.15	22.81	27.81
Williamston	31.00	31.09	31.98	42.60	21.87	25.50	33.51
Average	28.98	30.08	27.14	45.42	21.61	24.79	31.47

[a] Data estimated using 1971–2000 monthly average for November.

[b] Data estimated using 1971–2000 monthly average for October.

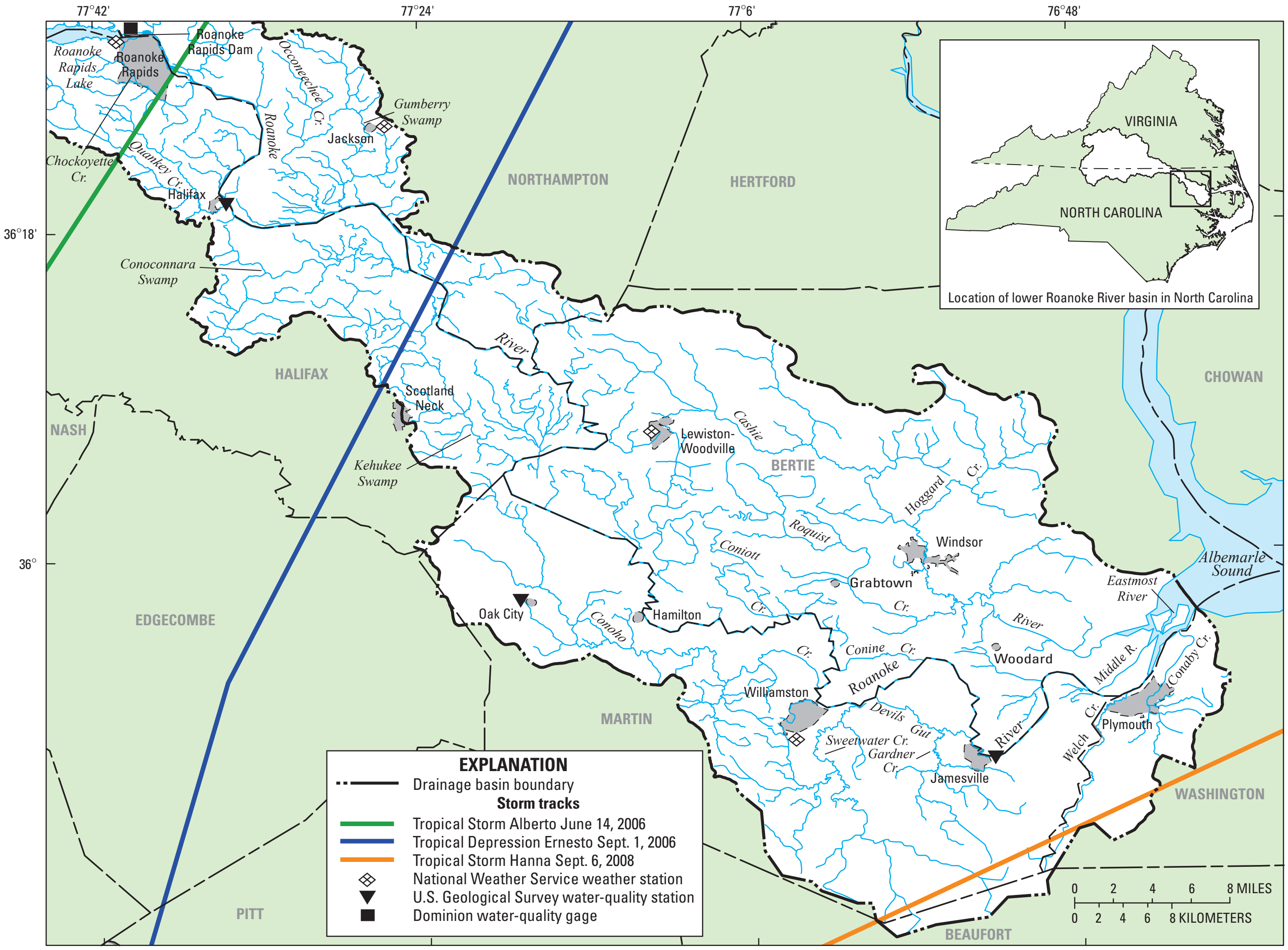
[c] Data estimated using 1971–2000 monthly average for June.

Table 5. Annual May through November 2005–2009 precipitation and dissolved-oxygen concentration, percentage of dissolved-oxygen saturation, and dissolved-oxygen deficit in the Roanoke River Basin, North Carolina.

Station name	2005–2009 average	2005	2006	2007	2008	2009
May–November precipitation (inches)	30.08	27.14	45.42	21.61	24.79	31.47
Dissolved-oxygen concentration (milligrams per liter)						
Roanoke River at Roanoke Rapids	7.9	6.9	7.7	6.7	9.7	8.5
Roanoke River at Halifax	7.5	7.2	7.1	7.6	7.9	7.7
Roanoke River near Oak City	7.1	6.9	6.8	7.0	7.4	7.6
Roanoke River at Jamesville	6.5	5.9	5.8	6.9	7.0	6.6
Dissolved oxygen (percent saturation)						
Roanoke River at Roanoke Rapids	90.7	79.1	88.2	78.0	110.9	97.0
Roanoke River at Halifax	86.9	82.5	83.1	88.2	90.2	89.5
Roanoke River near Oak City	82.1	78.9	77.9	81.9	84.6	88.3
Roanoke River at Jamesville	75.7	70.6	67.3	81.1	80.7	77.2
Dissolved oxygen deficit (milligrams per liter)						
Roanoke River at Roanoke Rapids	0.8	1.8	1.0	1.9	–1.1	0.2
Roanoke River at Halifax	1.1	1.5	1.4	1.0	0.8	0.9
Roanoke River near Oak City	1.5	1.8	1.9	1.5	1.3	1.0
Roanoke River at Jamesville	2.1	2.4	2.8	1.6	1.6	2.0

However, the year with the lowest rainfall total (2007) did not correspond with the highest DO concentration and deficit or the lowest DO deficit at Jamesville (table 5).

Precipitation and DO data during 2005–2009 were analyzed at the daily time scale to look at storm-specific responses. The largest measured daily precipitation totals at the four raingages occurred as the result of rainfall from tropical cyclones. Rainfall from three named storms passed through the Roanoke River basin during 2006–2008 (fig. 3; National Oceanic and Atmospheric Administration, 2009). Precipitation associated with tropical depression Ernesto (August 31–September 2, 2006) resulted in the maximum daily precipitation measured at Lewiston (site 6, 5.32 inches in 1 day and 6.54 inches total for the storm) and at Williamston (site 8, 6.60 inches in 1 day and 8.69 inches total for the storm; fig. 2; National Climatic Data Center, 2010). Measured precipitation at Roanoke Rapids (site 2) and Jackson (site 5, fig. 2) was 3.00 and 3.79 inches within a single day, and 7.02 inches and 7.43 inches total for the storm, respectively. Rainfall from Tropical Storm Alberto (June 14–15, 2006) resulted in the maximum daily precipitation measurements recorded during 2005–2009 at Roanoke Rapids (3.90 inches in 1 day and 4.11 inches total for the storm) and Jackson (4.82 inches in 1 day and 5.56 inches total for the storm). Measured precipitation associated with Tropical Storm Alberto was 3.44 inches at Lewiston and 2.49 inches at Williamston. During the 3-day period of rainfall from Tropical Storm Hanna passing the region (September 5–7, 2008), the maximum recorded precipitation was 2.10 inches at Williamston (2.00 inches in a single day).



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-scale digital data
U.S. Geological Survey, 1:100,000-scale digital data

Figure 3. National Weather Service cooperative observer weather stations, water-quality stations, and named storm tracks (National Oceanic and Atmospheric Administration, 2009) for 2005 to 2009 in the Roanoke River basin, North Carolina.

Precipitation from storms was compared to changes in the percentage of hourly DO saturation. For the USGS station at Roanoke River at Halifax (site 4, fig. 2), the mean measured precipitation at the two upstream-most raingages—Roanoke Rapids (site 2) and Jackson (site 5)—was used in the comparison. For the USGS station at Roanoke River near Oak City (site 7, fig. 2) and the USGS station at Roanoke River at Jamesville (site 9), the mean measured precipitation at the two downstream-most stations—Lewiston (site 6) and Williamston (site 8)—was used in the comparison. Daily precipitation events were categorized into groups of 1.5 inches or more of precipitation per day (table 6). The numbers of storms during 2005–2009 that resulted in precipitation events ranging from 1.5 to 5.5 inches or greater also were categorized into groups (table 7).

The precipitation events listed in tables 6 and 7 were compared to in-stream DO saturation during and following the precipitation events. Occurrences when DO saturation decreased by at least 10 percent within 7 days including the day precipitation began are shown in tables 8 and 9, which indicate that most large precipitation events result in low in-stream DO conditions. From May through November 2005–2009, the average of the two upstream raingages recordings was at least 1.5 inches of precipitation per day on 20 days, and on 12 days for the two downstream raingages (table 6). The 20 days in the upstream portion of the watershed occurred during 16 separate storms, and the 11 days in the downstream portion of the watershed occurred during 11 separate storms (table 7). All days with precipitation greater than 4.5 inches resulted in at least a 10 percent decrease in DO saturation, likely because of tributary inflow (table 8).

Table 6. Number of daily precipitation measurements between 1.5 and 5.5 inches or greater during May through November 2005–2009 in the Roanoke River Basin, North Carolina.

[Upstream, the average of the Roanoke Rapids and Jackson raingages; Downstream, the average of the Lewiston and Williamston raingages]

Station	1.5–2.0 inches	2.01–2.5 inches	2.51–3.0 inches	3.01–3.5 inches	3.51–4.0 inches	4.01–4.5 inches	4.51–5.0 inches	5.01–5.5 inches	Greater than 5.5 inches
Upstream	10	2	7	0	0	1	0	0	0
Downstream	5	3	2	0	0	0	1	0	1

Table 7. Number of storms that occurred during May through November 2005–2009 with measured precipitation between 1.5 and 5.5 inches or greater in the Roanoke River Basin, North Carolina.

[Upstream, the average of the Roanoke Rapids and Jackson raingages; Downstream, the average of the Lewiston and Williamston raingages]

Station	1.5–2.0 inches	2.01–2.5 inches	2.51–3.0 inches	3.01–3.5 inches	3.51–4.0 inches	4.01–4.5 inches	4.51–5.0 inches	5.51–5.5 inches	Greater than 5.5 inches
Upstream	6	2	1	2	0	3	0	0	2
Downstream	3	1	3	0	1	0	0	1	2

Table 8. Fraction of occurrences of measured hourly dissolved-oxygen saturation that decreased by at least 10 percent within 7 days of rainfall events with measured daily precipitation within the spcified range during May through November 2005–2009 in the Roanoke River Basin, North Carolina.

[Upstream, the average of the Roanoke Rapids and Jackson raingages; Downstream, the average of the Lewiston and Williamston raingages]

Station	1.5–2.0 inches	2.01–2.5 inches	2.5–3.0 inches	3.01–3.5 inches	3.5–4.0 inches	4.01–4.5 inches	4.5–5.0 inches	5.01–5.5 inches	Greater than 5.5 inches
Upstream									
Halifax	4/10	1/2	4/7	0/0	0/0	0/1	0/0	0/0	0/0
Downstream									
Oak City	1/5	1/3	2/2	0/0	0/0	0/0	1/1	0/0	1/1
Jamesville	2/5	2/2	2/2	0/0	0/0	0/0	1/1	0/0	1/1

Table 9. Fraction of occurrences of measured hourly dissolved-oxygen saturation that decreased at least 10 percent within 7 days of storms with measured precipitation within the specified range during May through November 2005–2009 in the Roanoke River Basin, North Carolina.

[Upstream, the average of the Roanoke Rapids and Jackson raingages; Downstream, the average of the Lewiston and Williamston raingages]

Station	1.5–2.0 inches	2.0–2.5 inches	2.5–3.0 inches	3.0–3.5 inches	3.5–4.0 inches	4.0–5.0 inches	5.0–6.0 inches	6.0–7.0 inches	7.0–8.0 inches
Upstream									
Halifax	3/6	1/2	0/2	2/2	0/0	2/3	0/0	0/1	1/1
Downstream									
Oak City	0/3	1/1	1/3	0/0	0/1	0/0	1/1	2/2	0/0
Jamesville	1/3	1/1	2/2	0/0	0/1	0/0	1/1	2/2	0/0

Storm precipitation total is a better measure of the magnitude of tributary inflow than daily precipitation. Flood-plain tributaries drain slowly and the longer the residence time of water in the flood plain, the greater the opportunity for DO to become hypoxic or anoxic. The percentage of DO saturation at Oak City and Jamesville decreased by at least 10 percent, likely at least partially because of tributary inflows, during all storms with greater than 5 inches of measured precipitation (table 9). Storms with measured precipitation greater than 3 inches in the upstream area were followed by DO saturation decreases of at least 10 percent for five of the seven storms, likely at least partially because of tributary inflows (table 9).

Characterization of Streamflow

The May through November flow regime from Kerr Lake changed substantially in 1989 when operational modifications were made to improve juvenile striped bass recruitment by shifting to a flow regime during spring spawning that more closely resembled pre-impoundment conditions (Rulifson and Manooch, 1990). Consequently, the period 1989–2009 was defined as the long-term period of streamflow for comparison with 2005–2009 flows. Daily mean streamflow at Roanoke River at Roanoke Rapids (site 3) during 2005–2009 (6,170 ft^3/s) was nearly 25 percent less than during 1989–2009 (8,150 ft^3/s). No single year between 2005 and 2009 had an annual mean streamflow that exceeded the 1989–2009 mean, and only the 2005 median of the annual daily mean flow (6,610 ft^3/s) exceeded the 1989–2009 median (6,090 ft^3/s; fig. 4). The maximum daily discharge from 2005 to 2009 at Roanoke River at Roanoke Rapids was 22,300 ft^3/s. The median value of all Roanoke River at Roanoke Rapids daily mean flows during 2005–2009 (3,880 ft^3/s) was greater than the median of the instantaneous hourly flow data for the same period (2,960 ft^3/s).

During 1989–2009, the median hourly flow at the Roanoke River at Roanoke Rapids (site 3) was 4,260 ft^3/s. The fraction of time flows (less than 3,000 ft^3/s) was within 10 percent for the 2005–2009 and 1989–2009 data (fig. 5). During 2005–2009, 34 percent of flows were between 4,000 ft^3/s and 20,000 ft^3/s; however, 43 percent of flows during 1989–2009 were within this range. The difference in the distribution of long-term (1989–2009) flows between 2,000 and 8,000 ft^3/s and flows within the 5,000–12,000 ft^3/s critical range (2005–2009) was greater than 10 percent for May through November (fig. 6).

The probability of exceedance was within 10 percent for flow-restricted duration curves and the full range of flows for May–November 1989–2009 and May–November 2005–2009, but flows during 2005–2009 were consistently lower (fig. 6). During May–November 2005–2009, hourly flows of at least 20,000 ft^3/s (the approximate discharge at

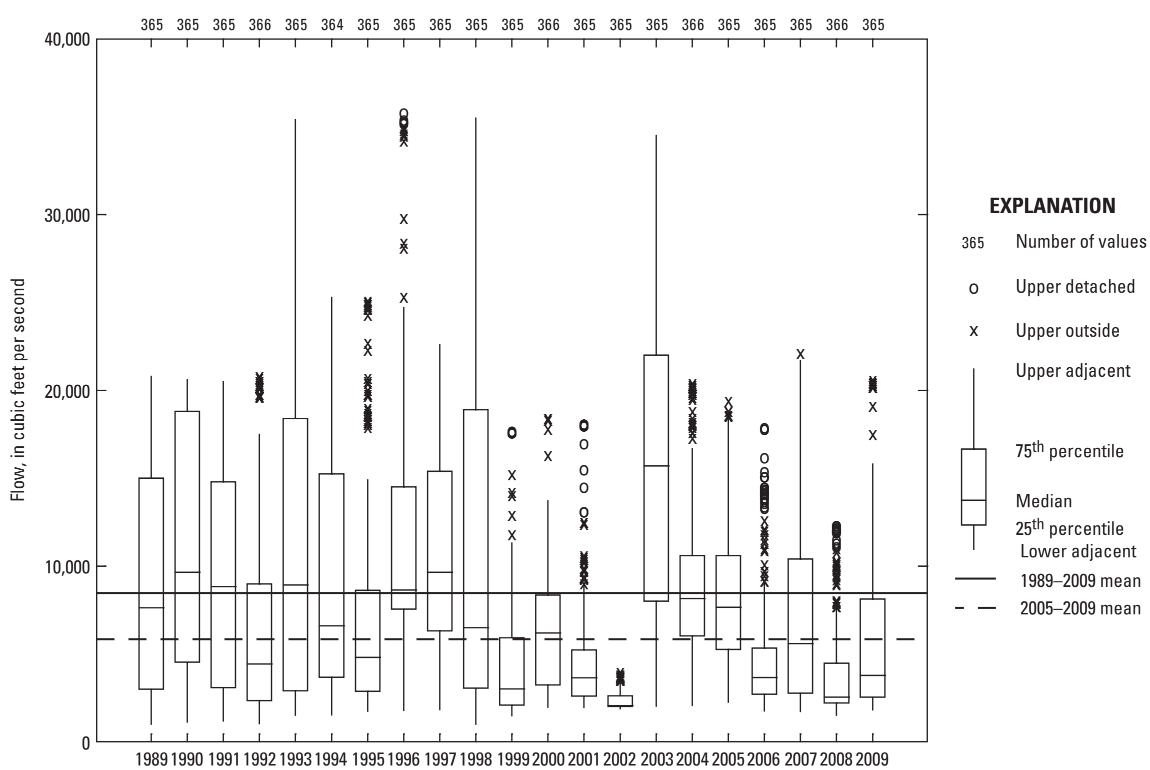


Figure 4. Distribution of daily mean discharge data by year for the long-term period 1989–2009 at the USGS streamgage at Roanoke River at Roanoke Rapids, North Carolina.

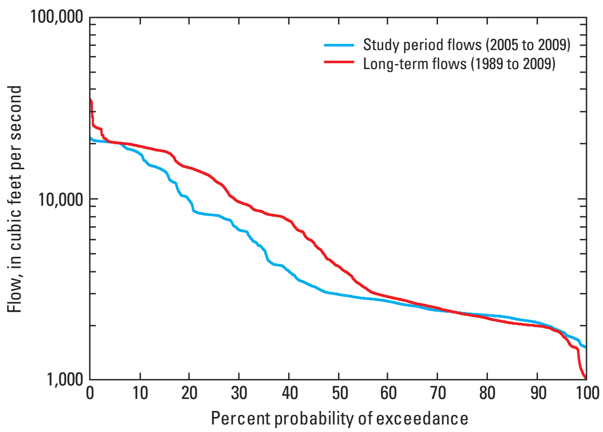


Figure 5. Long-term (1989 to 2009) and 2005 to 2009 hourly flow duration curves for the Roanoke River at Roanoke Rapids, North Carolina.

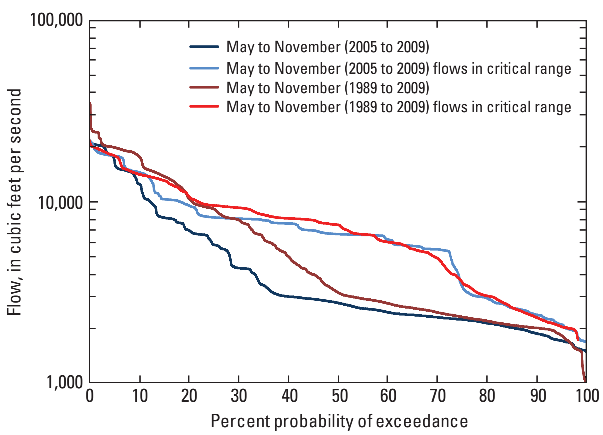


Figure 6. Long-term (1989–2009) and 2005–2009 hourly flow-duration curves with and without weekly mean flows within the critical range of 5,000–12,000 cubic feet per second for May through November at the Roanoke River at Roanoke Rapids, North Carolina.

Table 10. May to November minimum flow requirements for operating the Roanoke Rapids Dam (Federal Energy Regulatory Commission, 2005).

[ft³/s, cubic foot per second]

Time period	Flow (ft³/s)
May 1–June 15	Same as weekly declaration
June 16–30	2,800
July 1–September 15	2,000
September 16–November 16	1,500
November 16–30	2,000

full power-generation capacity of Roanoke Rapids Dam) occurred 0.8 percent of the time during weeks in which flows were restricted to the critical flow range of 5,000–12,000 ft^3/s. For the same time period, hourly flows of at least 20,000 ft^3/s occurred 3.0 percent of the time for the full range of weekly specified flows. Flows greater than 15,000 ft^3/s (another typical power generation discharge level) during 2005–2009 occurred 8.1 percent of the time within the critical flow range compared to 6.5 percent of the time outside of the critical flow range.

Flow operation restrictions for Roanoke Rapids Dam, as defined in Article 409 of Dominion's license (Federal Energy Regulatory Commission, 2005), specify that during the May through November period, the minimum flows listed in table 10 must be maintained except during drought conditions as determined by the USACOE. During drought conditions, the minimum flow requirement is 1,500 ft^3/s from September 1 to November 30 and 2,000 ft^3/s for all other months. Because of these minimum flow requirements, the right tail (lower discharges) of the flow duration curves for 2005–2009 and 1989–2009, both with and without flow restrictions, are almost identical (fig. 6).

To maximize hydropower generation during periods of high energy demand with the limited storage in Roanoke Rapids Lake, a hydropower-peaking scenario for a typical weekday includes a sustained peak discharge during the afternoon followed by minimum flows during the remainder of the day. If the weekly mean flow is reduced, the quantity of water discharged during the afternoon peaking also is reduced, but the number of hours the flow is at the minimum level remains the same. Therefore, the flow-restricted probabilities of exceedance increased sharply at 5,000 ft^3/s (fig. 6) because weekly mean flows were below 5,000 ft^3/s more often than above 12,000 ft^3/s (fig. 7).

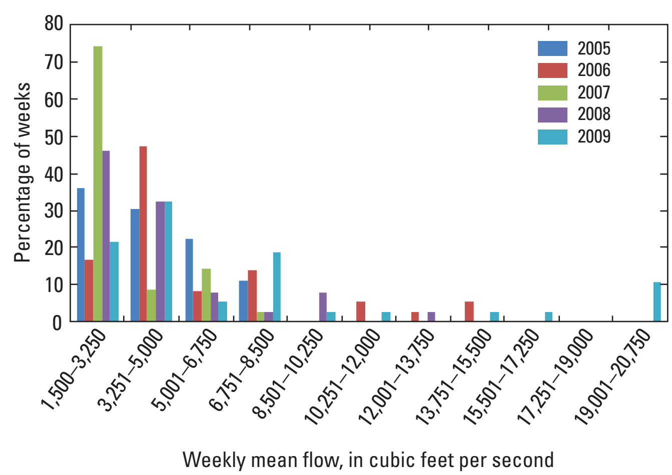


Figure 7. Annual distribution of weekly mean flows within the specified range at Roanoke River at Roanoke Rapids May through November, 2005–2009.

Examining the 2005–2009 hourly discharges for each month during May through November revealed differences in the flow distribution at times when hydropower peaking at Roanoke Rapids Dam was allowed and when it was not (fig. 8). The minimum flow during May 2005–2009, when hydropower peaking was not permitted, was greater than 4,000 ft^3/s, and the maximum flow was less than 13,000 ft^3/s. May flows, when peaking was not allowed, were in the 6,000–8,000 ft^3/s range 28 percent of the time as compared to 2 percent of the time in the same range during July, when peaking was allowed. In June, when hydropower peaking was permitted during the latter half of the month, flows were in the 6,000–8,000 ft^3/s range 19 percent of the time. Hydropower peaking at Roanoke Rapids Dam occurred most frequently in November, which resulted in flows of at least 14,000 ft^3/s occurring 25 percent of the time. The lowest volumes of water entered Roanoke Rapids Lake during August and September; consequently, the smallest fraction of peaking flows from Roanoke Rapids Dam also occurred during this time.

The monthly flow data were subdivided into only the weeks when the weekly mean flow was in the critical flow range (fig. 9). September was excluded from the graph in fig. 9 because no weekly mean flows were above 5,000 ft^3/s during September. In October, flows were above 14,000 ft^3/s 25 percent of the time when the weekly mean flow was 5,000–12,000 ft^3/s (fig. 9), but when the full range of weekly mean flows were considered, flows were above 14,000 ft^3/s only 7 percent of the time (fig. 8).

The opportunities for peaking between June 16 and November 30 during 2005–2009 when the weekly mean flow was in the critical flow range varied depending on water availability. The year 2007 was too dry to produce a single day of peaking (daily flow range greater than 5,000 ft^3/s), and 2008 only had 4 days of peaking (1 peaking week) within the critical flow range (table 3). During 2005–2009, 82 peaking days (17 peaking weeks) were within this range. Within the critical flow range, the daily flow range generally was either small (less than 1,000 ft^3/s) or rather large (greater than 11,000 ft^3/s; fig. 10). The spike at 12,000–13,000 ft^3/s is approximately the difference between the required minimum flow and a peak discharge of 15,000 ft^3/s. Likewise, the 16,000–17,000 ft^3/s daily range in flow is approximately the difference between the required minimum flow and a peak discharge of 20,000 ft^3/s, the approximate maximum operational capacity of Roanoke Rapids Dam.

The duration of consecutive days with at least a 2,000 ft^3/s difference between the daily mean flow and the weekly mean flow identifies periods when hydropower peaking likely altered the interaction of the flood plain with the river (table 11). The likelihood of having consecutive days with both high and low flows is minimal when hydropower peaking is not occurring. The largest difference for the longest duration occurred during the week of July 8–14, 2006. The weekly mean flow was 11,322 ft^3/s, and the daily mean flows for the week were at least 2,000 ft^3/s greater than the weekly mean for 3 days, all of which had daily mean flows more than 6,000 ft^3/s greater than the weekly mean flow.

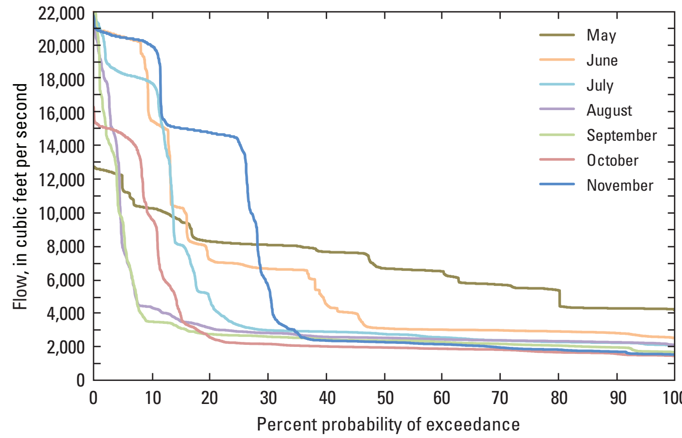


Figure 8. Monthly (May–November) 2005–2009 hourly flow-duration curves for the Roanoke Rapids Dam.

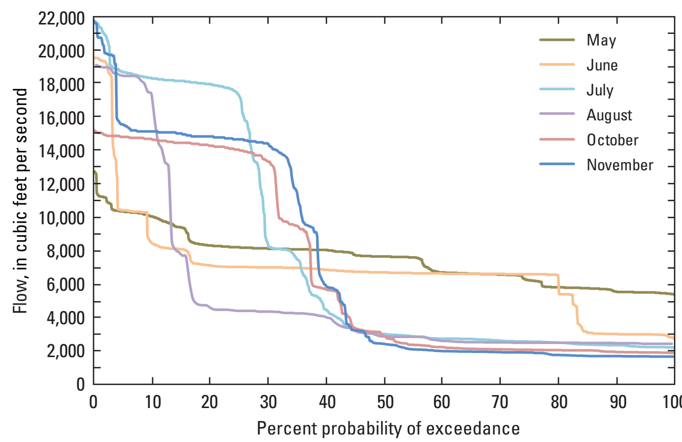


Figure 9. Monthly (May–August, October, November) 2005–2009 hourly flow-duration curves for the Roanoke River at Roanoke Rapids when the weekly mean flow was in the critical range of 5,000–12,000 cubic feet per second.

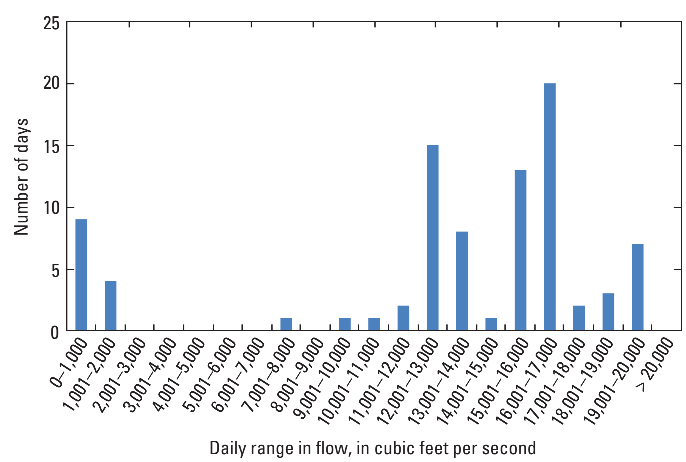


Figure 10. Daily range in flow for weekdays between June 16 and November 30, 2005–2009, when the weekly mean flow was between 5,000 and 12,000 cubic feet per second at the Roanoke River at Roanoke Rapids.

Table 11. Number of consecutive days between May 1 and November 30 with differences greater than 2,000 cubic feet per second between the daily mean flow and the weekly mean flow in the Roanoke River, North Carolina, 2005–2009.

[>, greater than]

Duration	Difference, in cubic feet per second			
	>2,000	>4,000	>6,000	>8,000
2 days	7	1	0	0
3 days	1	2	1	0
4 days	1	0	0	0
5 days	2	0	0	0
>5 days	0	0	0	0

In summary, the annual mean flows at the Roanoke Rapids streamgage (site 3) indicated nearly 25 percent less streamflow during 2005–2009 than during 1989–2009. The distribution of flow was similar in the two periods at low flows, but much different at moderate to high flows, primarily because 2005–2009 was abnormally dry. The daily range in flow, within the critical flow range from June 16 to November 30, generally was either small (less than 1,000 ft^3/s) or large (greater than 11,000 ft^3/s). For days when flows were in the critical flow range, a daily flow range between 1,000 and 11,000 ft^3/s occurred 6 out of 87 days (6.9 percent) and a daily flow range greater than 11,000 ft^3/s occurred 72 out of 87 days (82.8 percent) during 2005–2009 (fig. 10). During the wettest year (2006) the number of peaking weeks (9) was comparable to other periods in the 1998–2009 long-term period when 8 peaking weeks occurred in 1999 and 2003.

In-Stream Dissolved-Oxygen Conditions

The North Carolina water-quality standard for DO is as follows:

> "Dissolved oxygen: not less than 6.0 mg/L [milligrams per liter (L)] 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, 2007)

The Roanoke River from Roanoke Rapids Dam to Jamesville is classified as non-trout waters. The area downstream from Jamesville to Albemarle Sound is classified as swamp waters.

Most of the measured occurrences of DO levels below 5.0 mg/L in the Roanoke River between 1997 and 2009 occurred during the warm months of May through October (Bales and Walters, 2003). However, the Atlantic hurricane season lasts through November and provides the potential for low DO levels following large storms. A warm November also can lead to low DO levels, such as in 2009 when DO at Jamesville was 5.2 mg/L as late as November 26, possibly a result of the passage of Hurricane Ida late in the season.

In order to interpret the causal relation between peaking and in-stream DO levels, DO data from each station for 2005–2009 were travel-time adjusted on the basis of a one-dimensional hydraulic model from the USGS station at Roanoke River at Roanoke Rapids (site 3) to the USGS station at Roanoke River at Jamesville (site 9, fig. 2). The DO data were not simulated; measured DO data from the USGS stations at Halifax (site 4), Oak City (site 7), and Jamesville that corresponded to the modeled travel-time estimates from Roanoke Rapids were used in the following analysis to only interpret causal relation between peaking and in-stream DO levels. The reach between the Roanoke Rapids Dam tailrace and the USGS station at Roanoke River at Roanoke Rapids was outside the model domain; therefore, the time for water to travel the 2.8 mi from the tailrace to the Roanoke Rapids station was omitted. The median travel time from May to November each year during 2005–2009 is listed in table 12; however, travel-time-adjusted time series data in the analysis were generated from continuously simulated travel time rather than May–November averages.

Mean annual May through November DO concentrations decreased from Halifax to Oak City and from Oak City to Jamesville during 2005–2009. When water was supersaturated with oxygen in the Roanoke Rapids Dam tailrace, DO concentrations decreased from the dam all the way to Jamesville. When the water was not supersaturated in the Roanoke Rapids Dam tailrace, concentrations of DO often increased between the Roanoke Rapids Dam tailrace and Halifax before decreasing to Jamesville. The variability of DO in the tailrace is much greater than at the stations downstream. For May through November 2005–2009, the standard deviation of the hourly measurements of DO concentration in the Roanoke Rapids Dam tailrace was 2.2 mg/L compared to 1.3 mg/L or less for the other three stations.

As previously stated, peaking at Roanoke Rapids Dam from 2005 to 2009 was permitted between June 16 and November 30. Using data in the critical flow range from June 16–November 30 isolates the period when peaking was allowed and, thus, the effect of rescheduling flows on longitudinal changes in DO. Adding the period of May 1–June 15 potentially could mask the effects of peaking because it includes the period without peaking. However, not including the May 1–June 15 period for comparisons of peaking and non-peaking DO levels resulted in less than 5 non-peaking weeks between 2005 and 2009 in the 5,000–12,000 ft^3/s weekly mean flow range. Therefore, the May 1–June 15 period when no peaking occurred provided several additional weeks for comparison with predominantly peaking weeks from June 16 to November 30. All comparisons of peaking and non-peaking DO levels were based on the May–November period.

During the June 16–November 30 period, no instantaneous hourly DO concentrations at any station were recorded below the State standard of 4.0 mg/L during weekly mean flows greater than 12,000 ft^3/s (table 13). At weekly mean

Table 12. Median number of days each year for water to travel from the U.S. Geological Survey station at Roanoke River at Roanoke Rapids to each listed station from May through November 2005–2009.

Station name	2005–2009 average	2005	2006	2007	2008	2009
Roanoke River at Halifax	0.6	0.5	0.5	0.6	0.6	0.6
Roanoke River near Oak City	2.8	2.7	2.5	3.1	3.0	2.7
Roanoke River at Jamesville	5.8	5.6	4.7	6.7	6.3	5.6

Table 13. Summary of travel-time-adjusted hourly dissolved-oxygen concentrations from June 16 through November 30, 2005–2009, for weekly mean flows less than 5,000 cubic feet per second, between 5,000 and 12,000 cubic feet per second, and greater than 12,000 cubic feet per second in the Roanoke River, North Carolina.

[ft^3/s, cubic foot per second; mg/L, milligram per liter; <, less than; —, not applicable; >, greater than]

Statistic	Weekly mean flow (in ft^3/s)	Year				
		2005	2006	2007	2008	2009
Roanoke Rapids Dam tailrace						
Median hourly concentration (mg/L)	<5,000	6.5	7.1	6.7	7.6	7.6
	5,000–12,000	5.9	7.9	—	6.1	7.0
	>12,000	—	8.8	—	—	10.0
Percent of hourly measurements less than 4 mg/L (State standard)	<5,000	3.4%	1.2%	1.0%	0.0%	0.0%
	5,000–12,000	7.6%	0.0%	—	0.0%	0.0%
	>12,000	—	0.0%	—	—	0.0%
Percent of hourly measurements less than 5 mg/L	<5,000	12.3%	4.3%	12.4%	1.8%	0.0%
	5,000–12,000	24.2%	3.2%	—	0.6%	0.0%
	>12,000	—	0.0%	—	—	0.0%
Halifax						
Median hourly concentration (mg/L)	<5,000	6.7	6.6	7.4	7.7	7.1
	5,000–12,000	5.8	7.8	—	6.2	7.1
	>12,000	—	8.8	—	—	8.8
Percent of hourly measurements less than 4 mg/L (State standard)	<5,000	0.0%	0.0%	0.0%	0.0%	0.0%
	5,000–12,000	0.0%	0.0%	—	0.0%	0.0%
	>12,000	—	0.0%	—	—	0.0%
Percent of hourly measurements less than 5 mg/L	<5,000	3.2%	0.6%	0.0%	0.0%	0.0%
	5,000–12,000	4.5%	4.6%	—	0.0%	0.0%
	>12,000	—	0.0%	—	—	0.0%
Oak City						
Median hourly concentration (mg/L)	<5,000	6.5	6.1	6.7	6.8	7.3
	5,000–12,000	5.7	6.8	—	5.6	6.8
	>12,000	—	8.6	—	—	8.5
Percent of hourly measurements less than 4 mg/L (State standard)	<5,000	0.0%	0.0%	0.0%	0.0%	0.0%
	5,000–12,000	0.0%	0.7%	—	0.0%	0.0%
	>12,000	—	0.0%	—	—	0.0%
Percent of hourly measurements less than 5 mg/L	<5,000	0.0%	1.4%	0.2%	0.0%	0.0%
	5,000–12,000	0.0%	2.8%	—	0.0%	0.0%
	>12,000	—	0.0%	—	—	0.0%
Jamesville						
Median hourly concentration (mg/L)	<5,000	5.7	5.2	6.5	6.5	6.6
	5,000–12,000	5.5	6.1	—	5.4	5.8
	>12,000	—	6.2	—	—	5.8
Percent of hourly measurements less than 4 mg/L (State standard)	<5,000	0.0%	9.8	0.0%	0.0%	0.0%
	5,000–12,000	0.0%	3.7%	—	0.0%	0.0%
	>12,000	—	0.0%	—	—	0.0%
Percent of hourly measurements less than 5 mg/L	<5,000	17.3%	36.7%	0.0%	0.0%	3.9%
	5,000–12,000	9.6%	22.2%	—	1.2%	26.6%
	>12,000	—	0.0%	—	—	0.0%

flows below 5,000 ft^3/s, instantaneous measurements below the State standard of 4.0 mg/L at the Roanoke Rapids Dam tailrace were recorded in 2005, 2006, and 2007 and at the USGS station at Roanoke River at Jamesville (table 13). Between June 16 and November 30, 2005–2009, when the weekly mean flow was between 5,000 ft^3/s and 12,000 ft^3/s, instantaneous measurements of DO concentration below the 4.0-mg/L State standard were recorded in the Roanoke Rapids Dam tailrace in 2005 during 7.6 percent or 55 hours (table 13) of 719 hourly measurements (table 14). DO concentrations below Kerr Dam may fall below the Virginia State standards, which are identical to North Carolina State standards. When releases of water with DO below the State standard occur at Kerr Dam, Dominion must meet or exceed the instantaneous DO concentrations measured below Kerr Dam in the Roanoke Rapids tailrace. The 55 hours of instantaneous DO measurements below the State standard in the Roanoke Rapids Dam tailrace occurred during September 2005 when the daily mean DO data at USGS station 02079500 at Roanoke River at Buggs Island, Virginia, were either missing or below 2.3 mg/L (*http://waterdata.usgs.gov/va/nwis/uv/?site_no=02079500&PARAmeter_cd=00065,00060,62620,00062*).

No instantaneous hourly measurements of DO concentration below the State standard of 4.0 mg/L were recorded for any flow conditions between 2005 and 2009 at the USGS station at Roanoke River at Halifax. Only in 2006 were there any instantaneous hourly measurements below the instantaneous State standard of 4.0 mg/L—5 out of 1,512 hourly measurements, or 0.3 percent of June 16–November 30, 2006, measurements at the USGS station at Roanoke River near Oak City, and 66 out of 1,512 hourly measurements, or 4.4 percent of June 16–November 30, 2006, measurements at the USGS station at Roanoke River at Jamesville station (tables 13 and 14).

Peaking was not allowed from May 1 through June 15, 2005–2009, so data in the critical flow range from June 16 through November 30, 2005–2009, were analyzed in order to isolate the period when hydropower peaking was allowed and likely to occur if conditions were appropriate. The station-by-station plot (fig. 11) of data measured from June 16 through November 30, 2005–2009, shows that the highest and lowest DO concentrations measured were in the Roanoke Rapids Dam tailrace. Dissolved-oxygen concentrations, however, consistently were lower at the USGS station at Roanoke River at Jamesville station. The Roanoke Rapids Dam tailrace and the USGS station at Roanoke River at Halifax had similar distributions, with DO concentrations between 5.5 and 8.5 mg/L more than 60 percent of the time.

Table 14. Number of hourly measurements of dissolved-oxygen concentrations from June 16 through November 30, 2005–2009, for weekly mean flows less than 5,000 cubic feet per second, between 5,000 and 12,000 cubic feet per second, and greater than 12,000 cubic feet per second in the Roanoke River, North Carolina.

[ft^3/s, cubic foot per second; Q, weekly mean flow; <, less than; —, not applicable; >, greater than]

Weekly mean flow (in ft^3/s)	Year				
	2005	2006	2007	2008	2009
Roanoke Rapids Dam tailrace					
Q<5,000	3,313	2,039	4,032	3,864	2,856
5,000<Q<12,000	719	1,512	—	168	504
Q>12,000	—	481	—	—	672
Halifax					
Q<5,000	2,866	1,942	4,032	3,801	2,488
5,000<Q<12,000	447	1,287	—	168	504
Q>12,000	—	133	—	—	672
Oak City					
Q<5,000	3,003	1,913	4,032	3,529	2,852
5,000<Q<12,000	719	1,512	—	168	463
Q>12,000	—	481	—	—	672
Jamesville					
Q<5,000	2,705	1,769	4,032	3,864	2,840
5,000<Q<12,000	470	1,512	—	168	459
Q>12,000	—	481	—	—	409

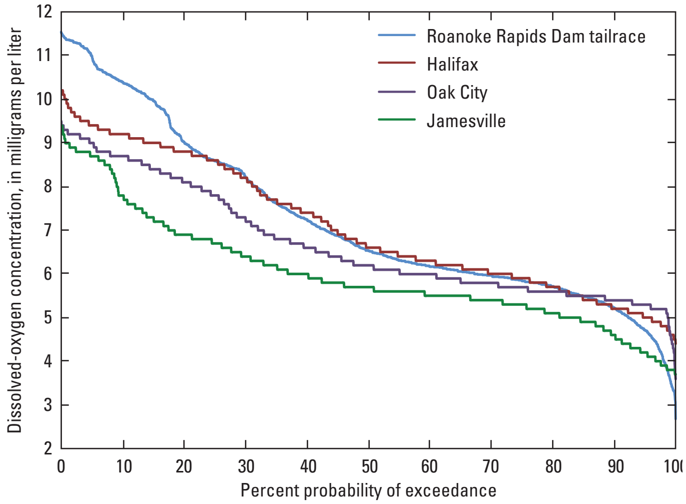


Figure 11. Dissolved-oxygen concentrations at water-quality sites in the Roanoke River basin downstream from Roanoke Rapids Dam from June 16 through November 30, 2005–2009, when the weekly mean flow was between 5,000 and 12,000 cubic feet per second.

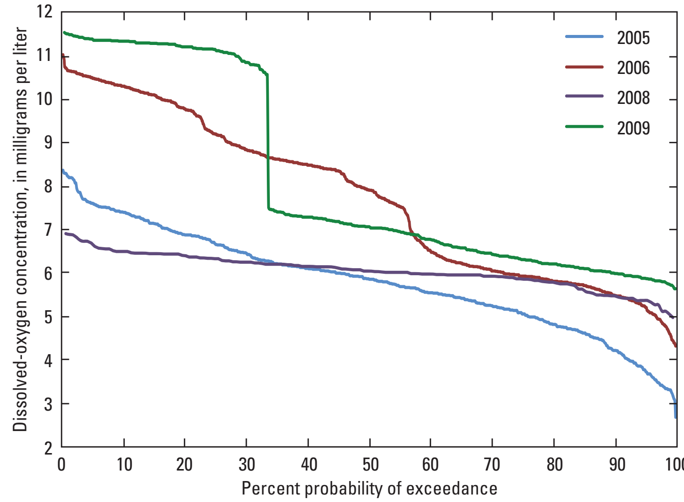


Figure 12. Hourly dissolved-oxygen concentration duration curves for weekly mean flows between 5,000 and 12,000 cubic feet per second for the period June 16–November 30, 2005–2009, at the Roanoke Rapids Dam tailrace, North Carolina.

Within-Year and Year-to-Year Dissolved-Oxygen Conditions

Hourly water-quality data available from 2005 to 2009 at the Roanoke Rapids Dam tailrace and at three USGS stations downstream on the Roanoke River at Halifax, near Oak City, and at Jamesville were used in the DO analysis for the Roanoke River basin. Available data for the period June 16–November 30, 2005–2009, when the weekly mean flow was 5,000–12,000 ft^3/s, were evaluated for each year individually.

Roanoke Rapids Dam Tailrace

The distribution of hourly measurements of DO concentration in the Roanoke Rapids Dam tailrace between June 16 and November 30, 2005–2009, when the weekly mean flow was between 5,000 and 12,000 ft^3/s ranged from 2.7 mg/L (2005) to 11.5 mg/L (2009). No weeks in 2007 met the criteria for the critical flow range between June 16 and November 30 (fig. 12).

Dissolved-oxygen concentrations in the Roanoke Rapids Dam tailrace during 2005 and 2008 generally were much lower than in 2006 and 2009 when the June 16–November 30 weekly mean flow was 5,000–12,000 ft^3/s (fig. 12). The 2008 data, however, represent only 1 week of data (July 19–25). The 2005 and 2008 DO duration curves (fig. 12) have a much different shape than the 2006 and 2009 curves. The large jump in 2009 at the 33-percent probability of exceedance was the result of (1) 1 week of data in November (cooler water temperature and higher DO), (2) several weeks between June 16 and July 31 (warmer temperatures and lower DO), and (3) no data from August to October (transition from warmer to cooler water temperatures) with weekly declarations between 5,000 and 12,000 ft^3/s. During 2005, DO concentrations remained low in the high probability of exceedance range because the weekly mean flow was not in the 5,000–12,000 ft^3/s range during the cooler months; in fact, no data were collected in the 5,000–12,000 ft^3/s weekly mean flow range after August 19. The 2006 curve represents a year with weekly mean flows in the 5,000–12,000 ft^3/s range distributed more evenly between June 16 and November 30, resulting in more even distributions of water temperature and, consequently, DO concentration. The distribution of weeks when the weekly mean flow was between 5,000 and 12,000 ft^3/s throughout the June 16–November 30 period is reflected in figure 12. In other words, if a greater proportion of weeks when the weekly mean flow is 5,000–12,000 ft^3/s occurs during the cooler months, the DO concentration for the year will be higher than if all of the weeks when the weekly declaration is 5,000–12,000 ft^3/s occur during the warmest part of the year, such as occurred in 2008.

Halifax

The 2005–2009 annual DO duration curves for the Roanoke River at Halifax are similar to the curves for the Roanoke Rapids Dam tailrace (figs. 12, 13). The lower end of the DO distribution at Halifax, however, was greater by about 1.8 mg/L than the Roanoke Rapids Dam tailrace in 2005, and lower by 1.5 mg/L than the Roanoke Rapids Dam tailrace at the upper end of the DO distribution in 2009 (fig. 13).

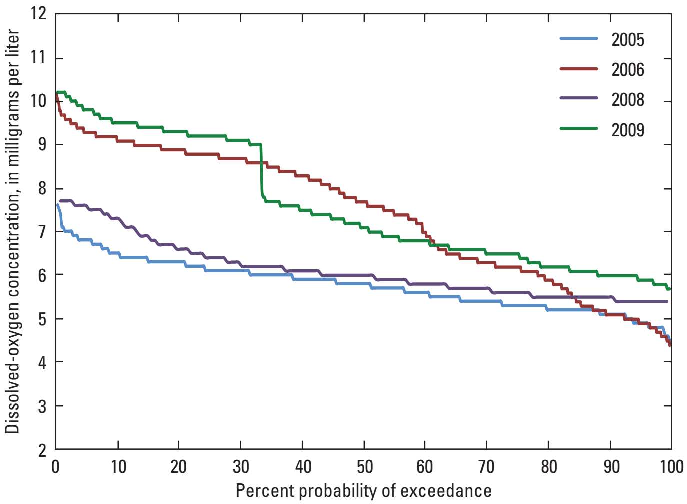


Figure 13. Hourly dissolved-oxygen concentration duration curves for weekly mean flows between 5,000 and 12,000 cubic feet per second for the period June 16–November 30, 2005–2009, for the Roanoke River at Halifax, North Carolina.

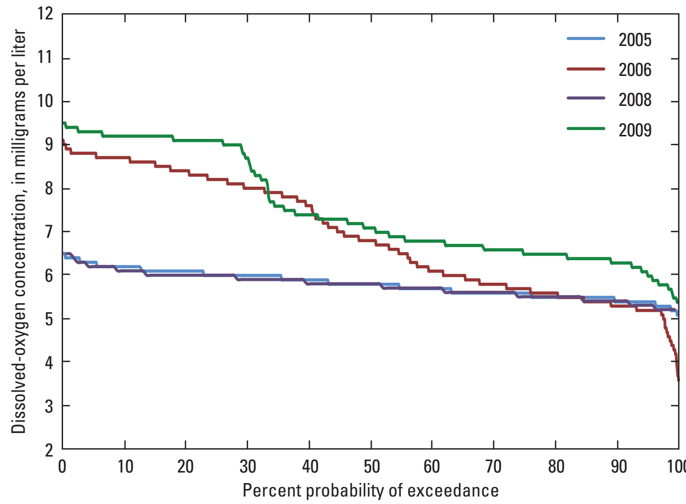


Figure 14. Hourly dissolved-oxygen concentration duration curves for weekly mean flows between 5,000 and 12,000 cubic feet per second for the period June 16–November 30, 2005–2009, for the Roanoke River near Oak City, North Carolina.

Oak City

The 2005–2009 annual DO duration curves for the Roanoke River near Oak City (fig. 14) are different at the lower DO concentrations from those at the upstream stations (fig. 13), but the shapes are similar for the upper 95 percent of the hourly DO measurements. The lowest hourly measured DO concentration (3.6 mg/L) in the critical flow range occurred early in the morning on July 6, 2006, following approximately 1.7 inches of rainfall. The daily mean DO concentration at Oak City was below 5.0 mg/L for 2 consecutive days (July 5–6, 2006) and instantaneous hourly DO concentrations were below 4.0 mg/L for 5 consecutive hours beginning at 1:00 a.m. on July 6, 2006, most likely associated with between 1.7 and 4.2 inches of rainfall that occurred during the preceding 10 days. The decrease in DO concentration below the State standard during this period began prior to the arrival of flow from hydropower peaking on July 3, 2006; therefore, the decrease was not initiated by peaking operations.

Jamesville

The June 16–November 30, 2005–2009, DO duration curves for the Roanoke River at Jamesville when the weekly mean flow was 5,000–12,000 ft^3/s show years when DO concentrations were both fairly consistent (2005 and 2008) and highly variable (2006 and 2009; fig. 16). The narrow distributions of DO concentrations in 2005 and 2008 were the result of narrow distributions of weeks with weekly mean flows between 5,000 and 12,000 ft^3/s during June 16–November 30. In 2005, no weekly flow declarations were in the critical flow range after August 18, and in 2008, all data were recorded during a single week in July. For all years between 2005 and 2009 (excluding 2007), the DO concentration at Jamesville had 50 percent exceedance of approximately 6 mg/L.

Travel-time adjusted daily mean DO concentrations remained at or below 5.0 mg/L at Jamesville for an extended period from June 11 to June 25, 2006, and from June 26 to July 1, 2006, which included a period of 17 hours with instantaneous DO concentrations below 4.0 mg/L (fig. 15*A*). This period of low DO concentrations likely was induced by between 2.5 and 5.6 inches of rainfall associated with Tropical Storm Alberto in the study area during June 11–15, 2006, followed by another event that produced up to 2.6 inches of rainfall in the area during June 24–28, 2006. The weekly flow declarations for this period of low DO concentration ranged from 3,045 to 4,378 ft^3/s. Hydropower peaking was initiated on June 27 and extended through June 30, 2006, with low flows of 3,000 ft^3/s and peak flows of approximately 18,500 ft^3/s on June 28 and 29. However, during this period, the mean daily DO concentration dropped below 5.0 mg/L prior to the onset of peaking operations.

Another example of travel-time adjusted daily mean DO concentrations remaining below the State standard for an extended period of time is shown in figure 15*B* for the period July 15–31, 2006, which included 56 hours between July 21 and 23 when instantaneous DO concentrations were below 4.0 mg/L. Peaking operations were on-going during this period, however, the decrease in DO concentrations below the State standard likely was initiated by a sustained discharge of approximately 18,000 ft^3/s from Roanoke Rapids Dam during July 11–14, 2006 (fig. 15*B*). The travel-time adjusted mean daily DO concentrations did not decrease below State standards until the sustained discharge concluded and peaking operations began; however, the flood plains were inundated by the sustained releases, and the subsequent low flows (associated with peaking operations) allowed potentially anoxic water in the inundated flood plains to drain back into the Roanoke River. It is noteworthy that the decline in DO concentration

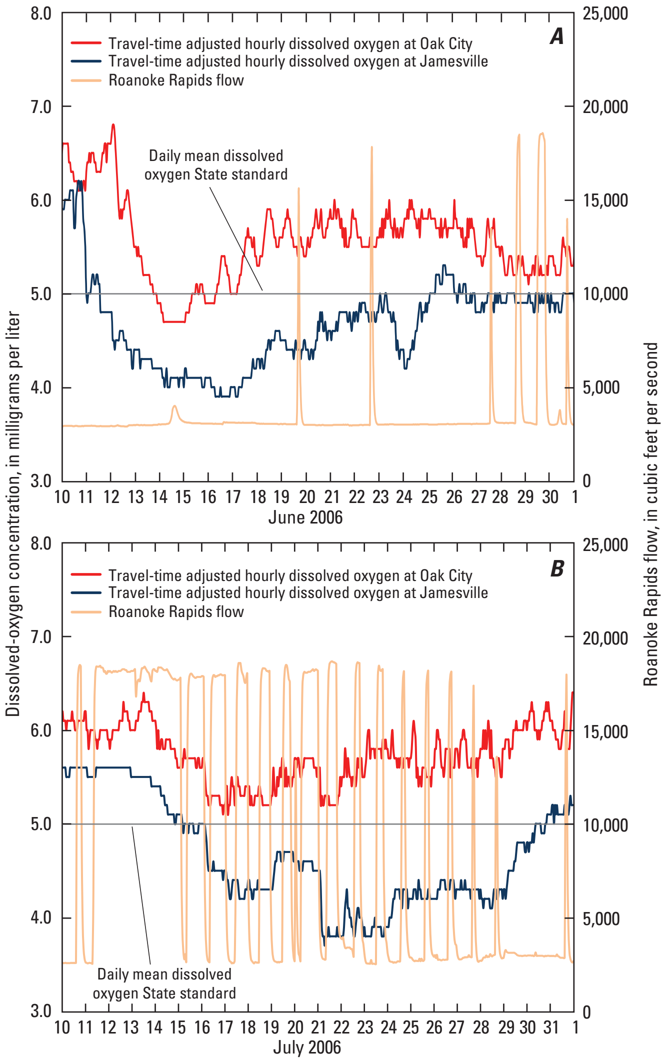


Figure 15. Examples of river conditions when daily mean and instantaneous dissolved-oxygen concentration were below the State standards in the Roanoke River near Oak City and at Jamesville, North Carolina, during *(A)* June 10–July 1, 2006, and *(B)* July 10–August 1, 2006.

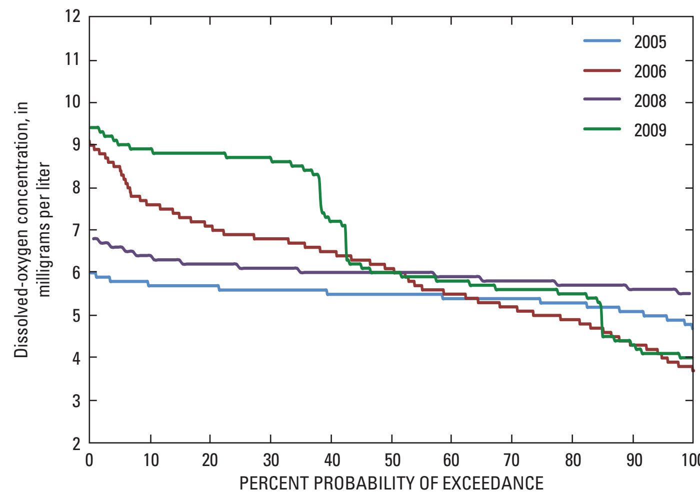


Figure 16. Hourly dissolved-oxygen concentration duration curves for weekly mean flows between 5,000 and 12,000 cubic feet per second for the period June 16–November 30, 2005–2009, for the Roanoke River at Jamesville, North Carolina.

actually began around July 13 (prior to the onset of peaking), indicating that the flood plains had been inundated by the sustained discharge of 18,000 ft^3/s and water was flowing through the flood plains and returning to the main channel in an anoxic condition.

The minimum mean daily DO concentration at Jamesville (2.9 mg/L) occurred on September 3, 2006, and was associated with precipitation from Tropical Storm Ernesto, which produced between 7.1 and 8.7 inches of rainfall in the watershed between August 30 and September 2, 2006. No peaking operations occurred during or leading up to this period, and weekly flow declarations for the entire month of August 2006 were less than 5,000 ft^3/s.

Dissolved Oxygen below the State Standard Resulting from Peaking Operations

At all sites, few daily mean DO concentrations less than 5 mg/L occurred when the mean weekly flow was between 5,000 and 12,000 ft^3/s and may have been caused by peaking operations rather than by large rainfall events. Between 2005 and 2009, no occurrences of daily mean DO concentrations below 5 mg/L were measured at the water-quality monitoring sites on the Roanoke River at Halifax or near Oak City that corresponded to (1) discharges when the weekly mean flow was 5,000–12,000 ft^3/s, (2) the occurrence of hydropower peaking, and (3) large storms that were not the likely source of low DO concentrations. In fact, only 3 days during the entire 5-year study period had recorded daily mean DO at Halifax less than 5 mg/L. This situation occurred only once between 2005 and 2009 at Jamesville and was confined to a travel-time adjusted 9-day period between July 21 and July 31, 2005, when the daily maximum air temperatures approached or exceeded 100 degrees Fahrenheit (fig. 17). This occurrence at Jamesville corresponded to discharge from Roanoke Rapids Dam on July 21–22, 2005, during a weekly flow declaration of 7,425 ft^3/s, and on July 26–27, 2005, during a weekly flow declaration of 3,822 ft^3/s, with peaking of 16,500–18,900 ft^3/s for up to 6 consecutive hours. These peak releases were followed by minimal peaking in the next several days, possibly allowing the flood plain to drain more than it would have if peaks were not absent for 3 consecutive days following the peaking.

The DO concentration at Jamesville ranged from 4.4 to 5.5 mg/L during a period between occurrences of peaking (July 24–25, 2005), which indicates the influence of some factor other than peaking on the variability in DO concentration.

The graph of travel-time adjusted stage and DO concentration at the Jamesville site (fig. 17*B*) indicates that fluctuations in stage are similar during periods of peaking and non-peaking. The large non-peaking stage fluctuations may be attributed to tidal effects in the reach. During this period from July 19 to August 1, 2005, the trend of DO concentrations tended to correspond with the fluctuations of stage at Jamesville (fig. 17*B*). As the stage at Jamesville decreased, flood-plain drainage of anoxic water was induced, which corresponds to a decrease of in-stream DO concentrations.

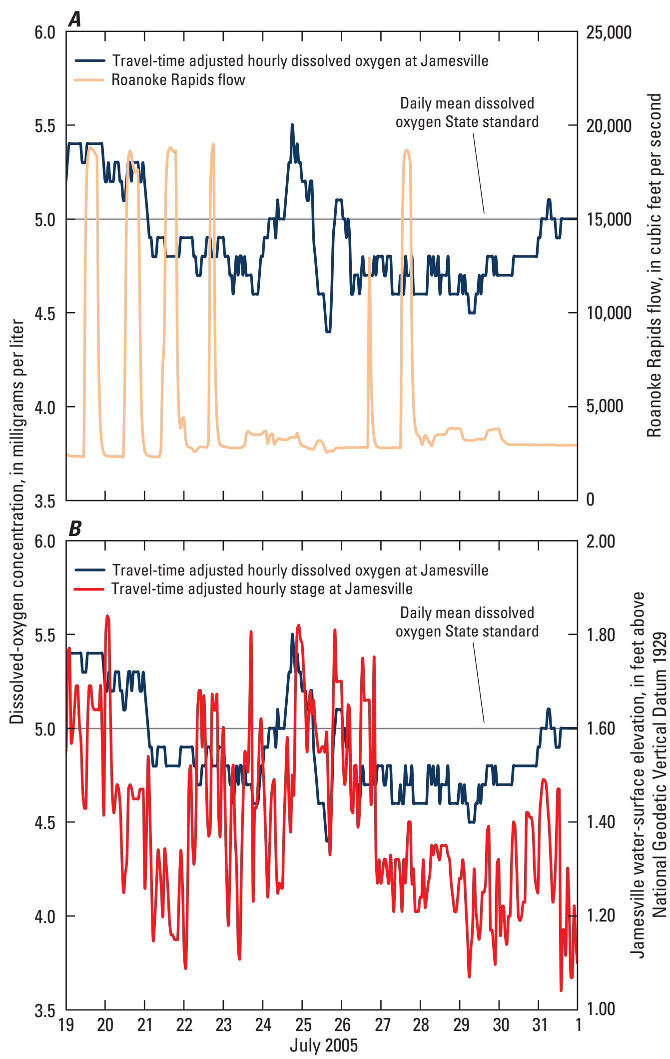


Figure 17. The only occurrence during 2005–2009 when the daily mean dissolved-oxygen concentration below the State standard (5 milligrams per liter) was linked to hydropower peaking and was independent of large rainfall events occurred during July 2005 on the Roanoke River at Jamesville when the weekly mean flow was between 5,000–12,000 cubic feet per second for travel-time adjusted dissolved-oxygen concentration plotted with *(A)* Roanoke River at Roanoke Rapids flow and *(B)* stage at Jamesville.

Between 2005 and 2009, when the weekly mean flow was 5,000–12,000 ft^3/s, peaking operations resulted in daily mean DO concentrations below the State standard (5 mg/L) for only 1 of the 17 (6 percent) peaking weeks, and no occurrences of instantaneous DO concentrations were recorded below the State standard (4 mg/L).

Downstream Changes in Dissolved Oxygen

The time it takes for water to travel from the Roanoke Rapids Dam tailrace to Jamesville and the water-quality monitoring stations between is important because longitudinal changes in DO are crucial to understanding how hydropower peaking affects water quality. Hourly DO concentration data were evaluated when the weekly mean flow at the USGS station at Roanoke River at Roanoke Rapids was between 5,000 and 12,000 ft^3/s (table 3). The distributions of DO concentration changes during travel-time adjusted peaking and non-peaking during May to November 2005–2009 were computed for the Roanoke Rapids Dam tailrace to Halifax (site 4, figs. 2 and 18), Halifax to near Oak City (site 7, figs. 2 and 19), and near Oak City to Jamesville (site 9, figs. 2 and 20). The negative values on the y-axis indicate a decrease in DO concentration from upstream to downstream. Negative values between Roanoke Rapids Dam tailrace and the USGS station at Roanoke River at Halifax were generally only seen when water in the tailrace was supersaturated.

The change in DO concentration between the Roanoke Rapids Dam tailrace and the USGS station at Roanoke River at Halifax (fig. 18) varied more than changes in the downstream reaches (from Halifax to near Oak City and from near Oak City to Jamesville). In the reach from the tailrace to Halifax, 75 percent of all changes in downstream DO concentration were within –2.4 and 0.4 mg/L for non-peaking and –1.2 and 0.4 mg/L for peaking periods. The median decrease in DO concentration from the Roanoke Rapids Dam tailrace to the USGS station at the Roanoke River at Halifax was smaller during peaking than during non-peaking periods.

The change in DO concentration between the USGS stations at Roanoke River at Halifax and Roanoke River near Oak City (fig. 19) shows a greater median decline in DO concentration during non-peaking. In the reach from Halifax to near Oak City, 75 percent of all changes in downstream DO concentration were within –0.9 and –0.2 for non-peaking and –0.6 and 0.2 for peaking periods. The largest negative changes in this reach likely indicate when the flood plain was interacting with the river and causing DO to decrease the most. Overall, the distribution of the large negative changes in this reach are similar for peaking and non-peaking periods, although fewer large negative values are outside the inner quartile range for the peaking periods (fig. 19).

The change in DO concentrations between the USGS stations at Roanoke River near Oak City and Roanoke River at Jamesville (figure 20) had a wider distribution and a slightly higher median during peaking. In the reach from near Oak City to Jamesville, 75 percent of all changes in downstream DO concentration were within –1.1 and –0.4 for non-peaking and –1.4 and –0.1 for peaking periods.

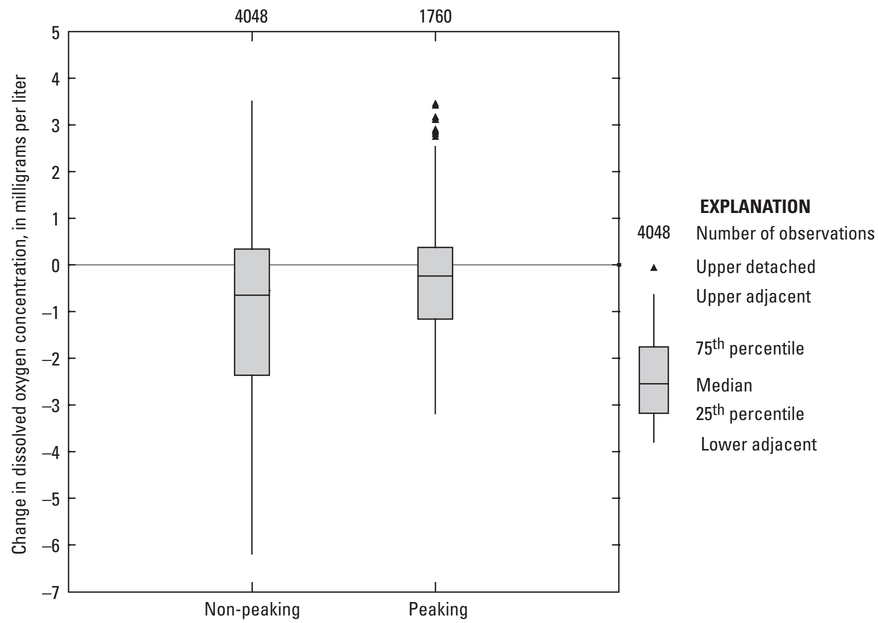


Figure 18. Change in hourly dissolved-oxygen concentration in the Roanoke River from Roanoke Rapids Dam tailrace to Halifax during travel-time adjusted non-peaking and peaking, when the weekly mean flow was between 5,000 and 12,000 cubic feet per second, 2005–2009.

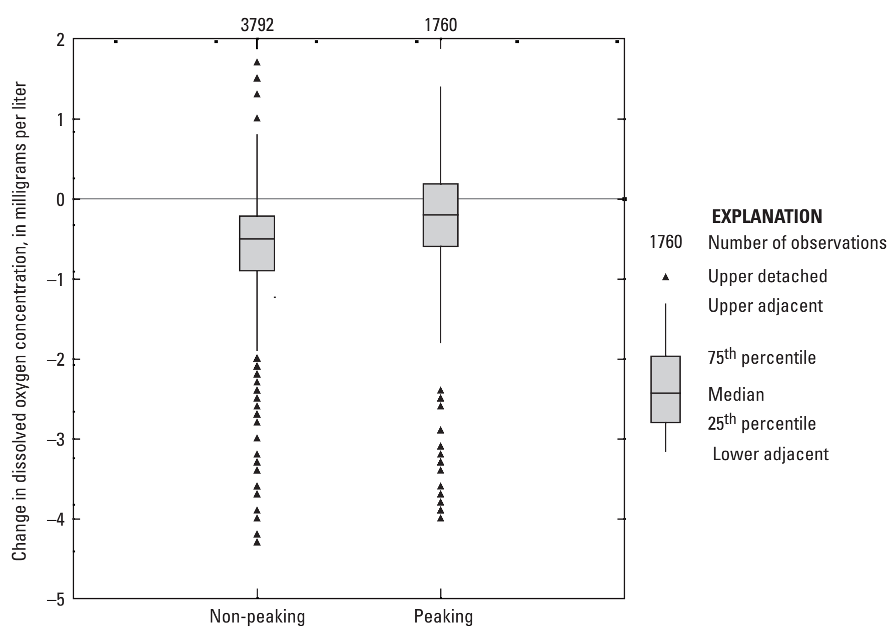


Figure 19. Change in hourly dissolved-oxygen concentration in the Roanoke River from Halifax to near Oak City during travel-time adjusted non-peaking and peaking, when the weekly mean flow was between 5,000 and 12,000 cubic feet per second, 2005–2009.

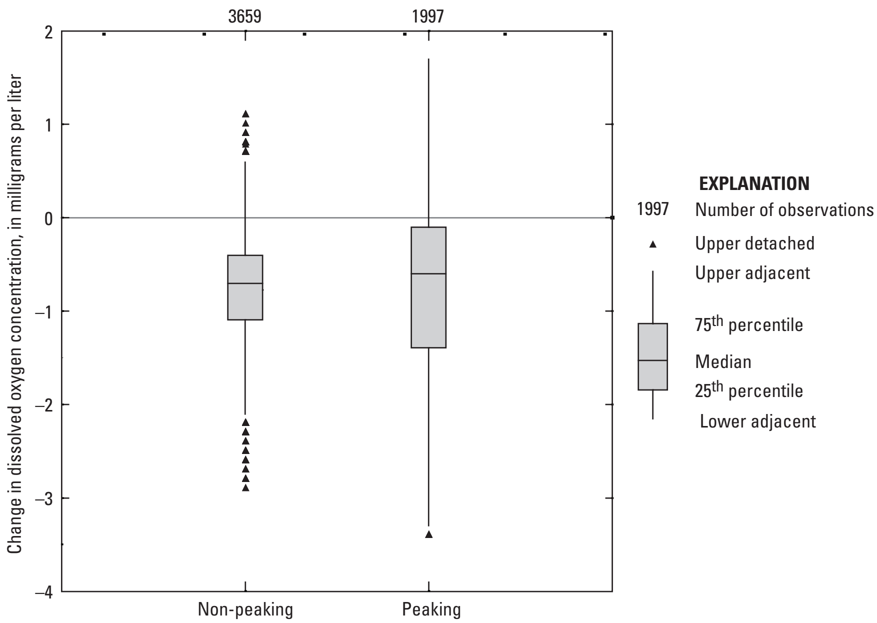


Figure 20. Change in hourly dissolved-oxygen concentration in the Roanoke River from near Oak City to Jamesville during travel-time adjusted non-peaking and peaking, when the weekly mean flow was between 5,000 and 12,000 cubic feet per second, 2005–2009.

At a weekly mean flow of 12,000 ft^3/s and a minimum flow requirement of 3,000 ft^3/s, Roanoke Rapids Dam could operate at full capacity (approximately 20,000 ft^3/s) 53 percent of the week. Sustained periods of high flows in 2000, for example, increased water levels in Broadneck Swamp just downstream from Oak City, whereas similar peak-flow magnitudes coupled with lower flows during the typical daily peaking cycle did not necessarily increase flood-plain water levels (fig. 21). Weekly mean flows in the 10,000–12,000 ft^3/s range can have extended durations of peaking and large differences between the flow at peak power generation and the minimum discharge. Hydropower peaking in the 10,000–12,000 ft^3/s weekly mean flow range may be inundating and draining a portion of the flood plain on a daily basis if flows are oscillated between peak operational capacity (20,000 ft^3/s) and minimum flow (3,000 ft^3/s), making in-stream DO concentrations in this range particularly sensitive to peaking. The difference in flow between peak power-generation capacity and minimum flow decreases as weekly mean flows increase above 12,000 ft^3/s.

Hydropower Peaking and Changes in Dissolved Oxygen

Hydropower peaking and travel-time-adjusted hourly DO concentration near Oak City and at Jamesville were plotted for May–November 2005–2009 when the weekly mean flow was both within the 5,000–12,000 ft^3/s range and outside of this range (fig. 22). No peaking within these constraints occurred in 2007; only 1 week of peaking occurred in 2008, and just 2 weeks of peaking occurred in 2009. The shaded areas in figure 22 identify weeks when the weekly mean flow was between 5,000 and 12,000 ft^3/s and when at least 1 day during the week had a daily range in flow of more than 5,000 ft^3/s.

These time-series data present limited information concerning the effects of hydropower peaking on downstream DO concentrations because of the small number of weeks with hydropower peaking. The hourly travel-time adjusted DO values near Oak City and at Jamesville are aligned with the approximate hour when peaking occurred upstream at Roanoke Rapids Dam (fig. 22). Of the three periods of weeks with peaking in 2005, two included consecutive weeks of peaking (fig. 22*A*). The first week of peaking corresponded with a decrease in DO near Oak City, but DO concentrations increased during the second week. During the second period of peaking in July 2005, DO concentrations decreased, with the largest decrease occurring near Oak City in the first week of the period. The third peaking period in 2005 shows a slight increase in DO near Oak City.

Three periods of weeks with peaking occurred in 2006—two periods of 4 weeks and one period of 1 week (fig. 22*B*). In the July peaking period, a rapid and appreciable decrease in DO concentration occurred near Oak City during the first peaking week and then quickly rebounded. The DO concentration downstream at Jamesville decreased after the first 2 consecutive weeks of peaking. The continued weeks of peaking in the first period corresponded with decreasing DO concentrations at Jamesville, until the last week when DO recovered at both stations. As previously described in the "Within-Year and Year-to-Year Dissolved-Oxygen Conditions" section, large precipitation events and an associated sustained discharge of approximately 18,000 ft^3/s from Roanoke Rapids Dam contributed to the decrease in DO concentrations. In the 1-week peaking period, change in DO concentration was minimal. In the final peaking period of 2006, the changes in DO concentrations at Jamesville may indicate an effect of a cycle of flood-plain inundation and drainage. For the study period, 2006 was the wettest year with more than 66 percent of the reported

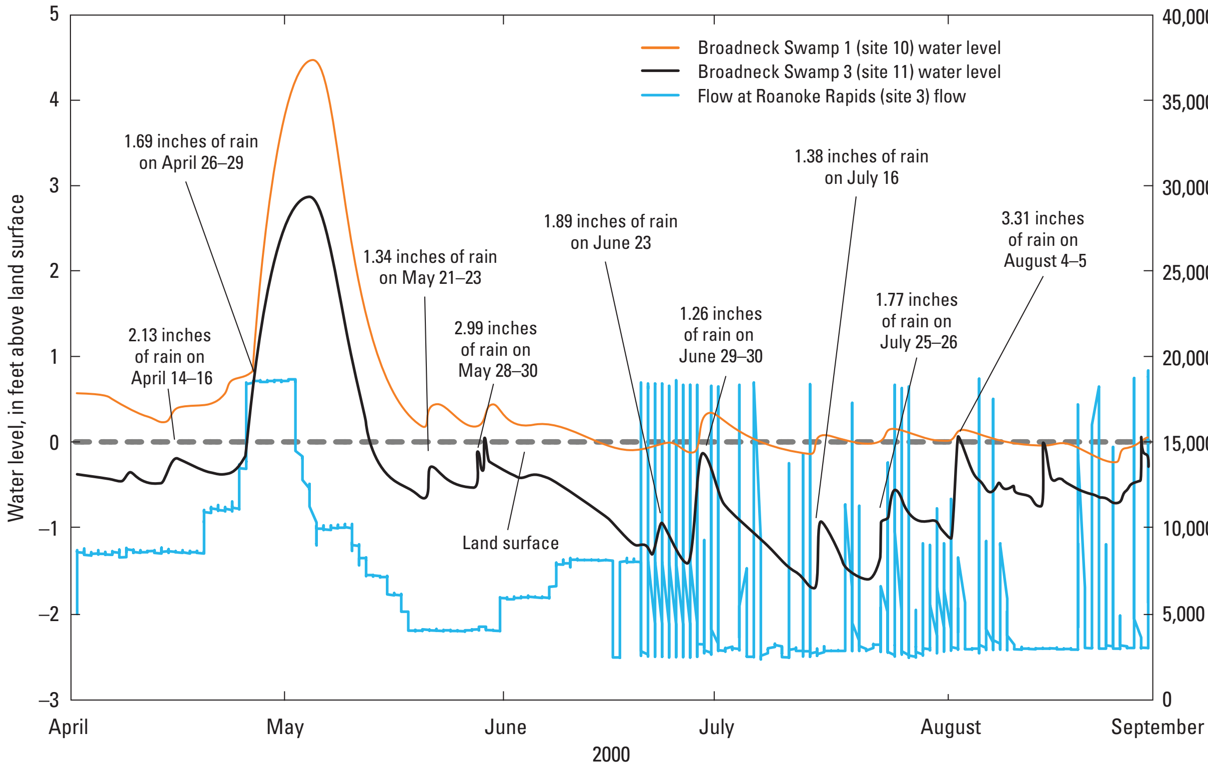


Figure 21. Hourly water levels at Broadneck Swamp 1 and 3, hourly streamflow at Roanoke River at Roanoke Rapids, and daily rainfall for selected dates at the raingage at Williamston, North Carolina (modified from Bales and Walters, 2003).

annual rainfall occurring in June, July, September, October and November (an average total at all stations of 38 inches).

In 2007, no weeks of peaking were recorded because of low flows throughout the spring and summer (fig. 22*C*). In 2008, only 1 week of peaking occurred (fig. 22*D*). The lowest travel-time adjusted DO concentrations occurred near Oak City and at Jamesville between July and November 2008 during the week with peaking when a sustained decrease in the travel-time adjusted DO concentration occurred both near Oak City and at Jamesville. During this period of decreased DO concentration, the Williamston raingage measured a 1-day rainfall total of 4.12 inches.

In 2009, two 1-week periods of peaking occurred (fig. 22*E*). A small decrease (0.5 mg/L) in DO concentration occurred in the first peaking week with no precipitation in the preceding week. The second week of peaking corresponded initially with large DO decreases near Oak City and at Jamesville followed by increases in DO concentrations. The DO concentration decreased to 5.2 mg/L during non-peaking toward the end of November 2009 at Jamesville following the passage of a nor'easter in conjunction with Hurricane Ida. The storm produced appreciable rainfall amounts that were measured at each of the four raingages in the region (total rainfall at Williamston was 6.57 inches of which 5.20 inches occurred in one day). This occurrence is noteworthy because it demonstrates the potential for low DO concentrations occurring throughout November and the effects of nor'easters.

Although some instances occurred where decreased DO concentrations appeared to be associated with peaking operations, between 2005 and 2009, only 1 of 17 peaking weeks in the critical flow range had DO concentrations below the State standard that could be directly related to peaking. Rainfall in the Roanoke River basin was shown by Bales and Walters (2003) to have a larger effect on flood-plain water levels than peaking operations (fig. 21). Correspondingly, large rainfall events (greater than 1.5 inches) also have been shown herein to be the predominant contributor of low in-stream DO concentrations as a result of flood-plain drainage.

Duration curves of travel-time adjusted peaking and non-peaking hourly DO concentrations were prepared for periods when the weekly mean flow was 5,000 to 12,000 ft^3/s during May through November at the Roanoke Rapids Dam tailrace (fig. 23*A*), Halifax (fig. 23*B*), near Oak City (fig. 23*C*), and at Jamesville (fig. 23*D*).

Because DO concentrations generally were higher in May than during June–September, the hourly travel-time adjusted water-temperature record at each station during weekly mean flows of 5,000–12,000 ft^3/s was separated into weeks with and without peaking for each year (2005–2009, table 15). Water temperatures were significantly warmer ($p > 0.01$) during peaking in 2005 and 2008. In 2009, however, no statistically significant ($p > 0.01$) difference in water temperature occurred between peaking and non-peaking periods according to the Fisher exact probability test (Fisher, 1922). The higher

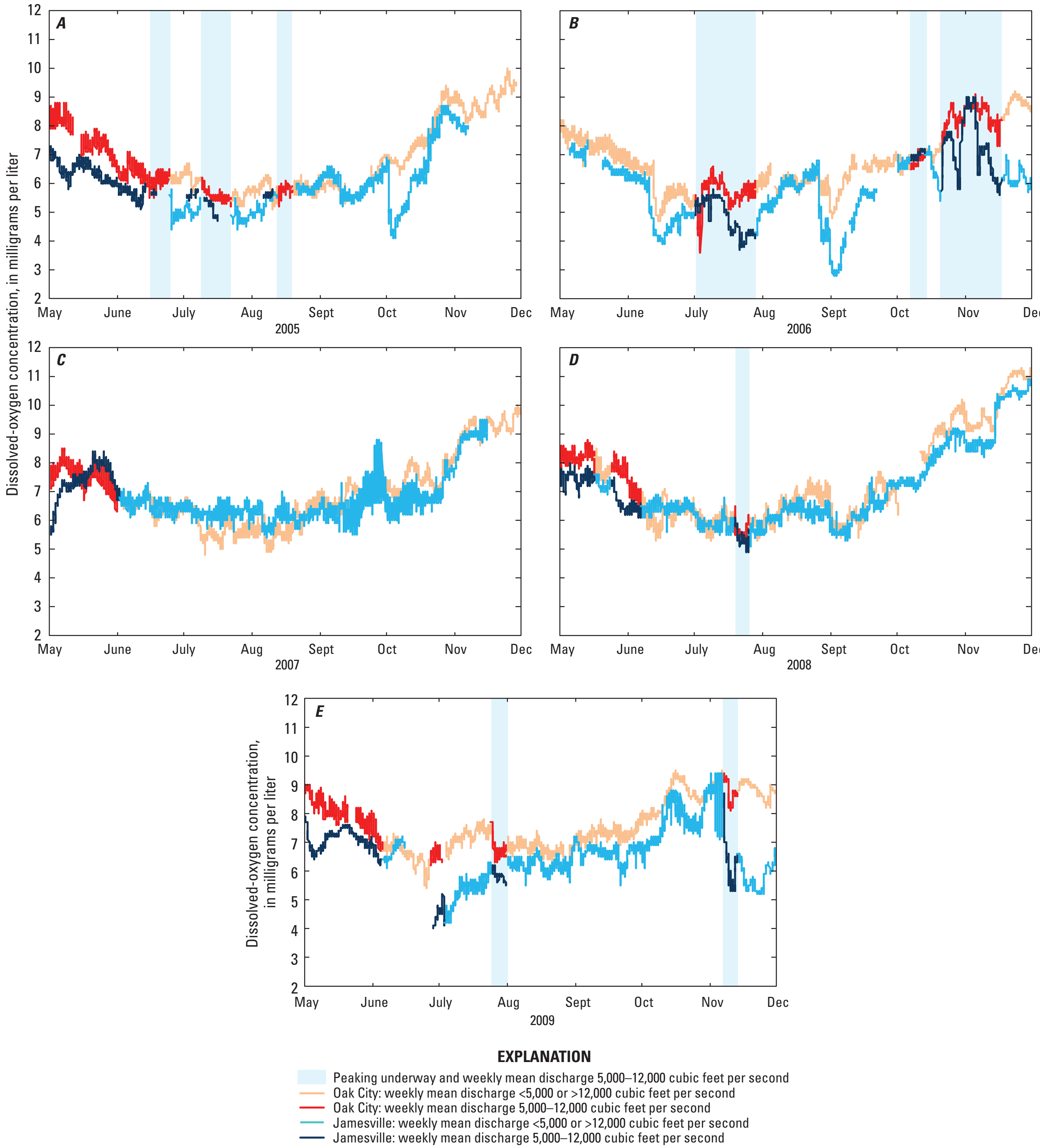


Figure 22. May–November hourly dissolved-oxygen concentration in the Roanoke River near Oak City and at Jamesville showing periods when weekly mean flows were 5,000–12,000 cubic feet per second and below and above this range for *(A)* 2005, *(B)* 2006, *(C)* 2007, *(D)* 2008, and *(E)* 2009.

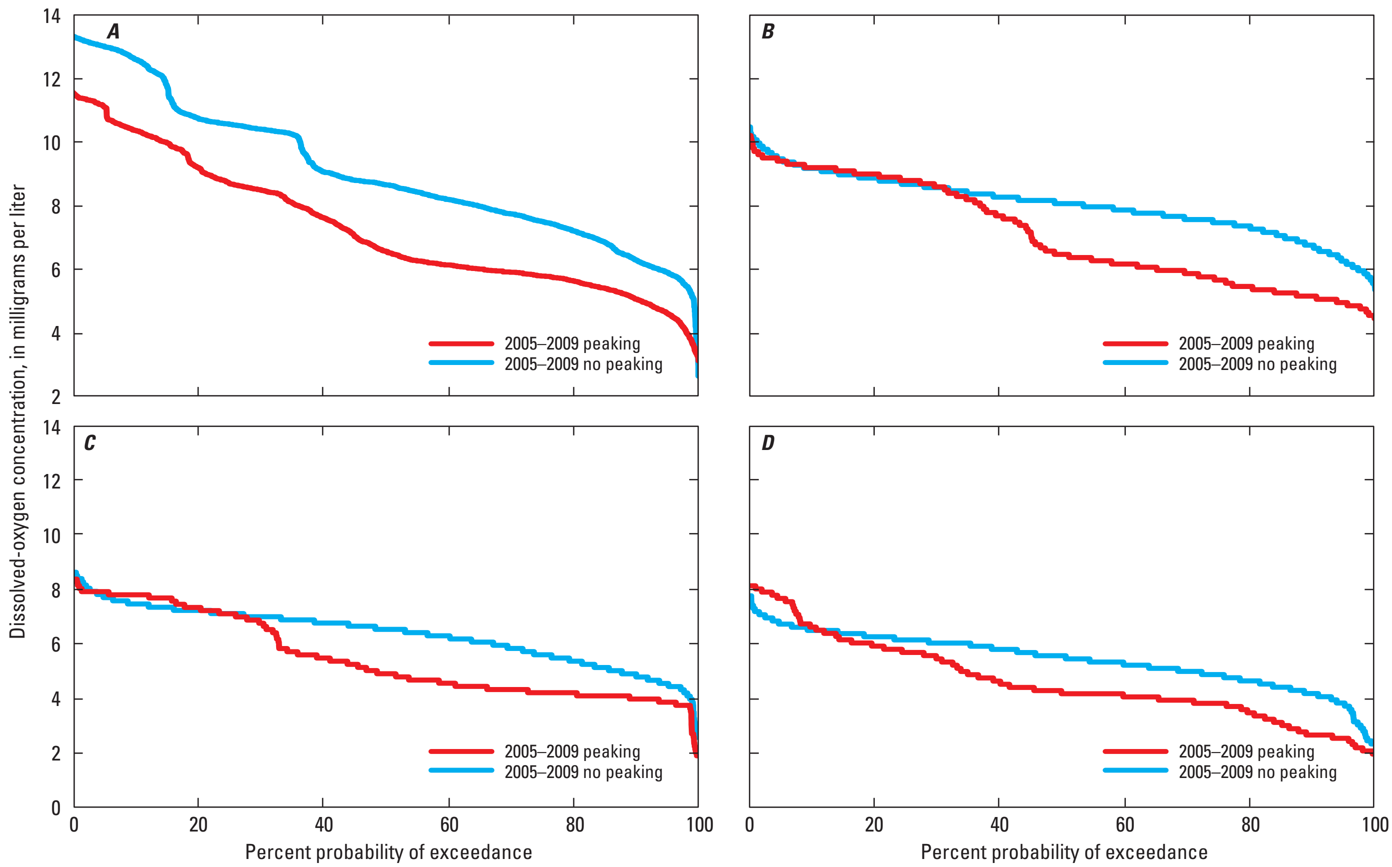


Figure 23. Duration curves of hourly dissolved-oxygen concentration for peaking and non-peaking weeks between May and November 2005–2009 on the Roanoke River at *(A)* Roanoke Rapids Dam tailrace, *(B)* Halifax, *(C)* near Oak City, and *(D)* at Jamesville, when weekly mean flow was 5,000 to 12,000 cubic feet per second.

Table 15. Summary of travel-time adjusted mean annual water temperature in the Roanoke River during May to November 2005–2009 for weeks with weekly mean flow between 5,000 and 12,000 cubic feet per second.

[Bold values indicate statistically significant differences at the 99-percent confidence interval; red values were higher during peaking; blue values were lower during peaking; —, no data]

	Mean annual May to November water temperature in degrees Celsius				
	2005	**2006**	**2007**	**2008**	**2009**
Roanoke Rapids Dam tailrace					
Peaking	**26.3**	**20.9**	—	**27.0**	22.0
No peaking	**20.2**	**26.3**	19.5	**20.9**	21.3
Halifax					
Peaking	**27.0**	**21.0**	—	**27.8**	21.7
No peaking	**20.4**	**25.9**	19.9	**20.3**	21.2
Oak City					
Peaking	**28.0**	**20.8**	—	**27.7**	21.6
No peaking	**20.9**	**26.5**	20.3	**20.8**	22.0
Jamesville					
Peaking	**28.3**	**19.8**	—	**27.9**	21.8
No peaking	**21.4**	**26.7**	20.6	**20.8**	22.3

temperatures during peaking in 2005 and 2008 partially explain the lower DO concentrations. In 2009, which had no statistically significant difference in water temperature, DO during peaking was significantly ($p > 0.01$) lower than during non-peaking. This indicates that water temperature alone cannot explain why DO concentrations are lower during peaking than non-peaking, and the large rainfall amounts associated with the nor'easter in 2009 likely played a large role in DO concentrations.

Median hourly DO measurements for May–November when the weekly mean flow was 5,000–12,000 ft^3/s were computed for each year (2005–2009) and separated into travel-time adjusted periods with and without peaking for DO concentration (table 16), DO saturation percentage (table 17), and DO deficit (table 18). Median values were compared because they are less likely than mean values to be influenced by outliers. The results in tables 16–18 for 2007, 2008, and 2009 need to be viewed with caution because these years had two or fewer full peaking weeks during May–November when the weekly mean flow was 5,000–12,000 ft^3/s.

Median hourly measurements for DO concentration, percentage of saturation, and deficit tell a similar story. (DO was generally lower during peaking periods in 2005, 2008 and 2009 and higher in 2006, the year with the most rainfall and the greatest number of peaking weeks.) In all years with at least 1 week of both peaking and non-peaking during a weekly mean flow of 5,000–12,000 ft^3/s, the DO difference was statistically significant using a two-tailed p-test (Agresti, 1992) at the 99-percent confidence interval for at least one of the three DO metrics (concentration, saturation percentage, or deficit). During peaking in 2005 at Jamesville, the DO deficit decreased and was statistically significant, but both the DO concentration and DO saturation percentage at Jamesville also decreased and were statistically significant.

In summary, changes in median hourly DO concentrations were detected between peaking and non-peaking weeks within the 5,000–12,000 ft^3/s weekly mean flow range. The key to detecting the changes was using model-estimated travel-time adjusted values that compared DO in the Roanoke River as it moved downstream. Without attempting to make the adjustment for travel time, the quantification of the relation between Roanoke Rapids Dam discharge and downstream DO was not possible. Statistical testing of the travel-time adjusted hourly data indicate that median DO concentrations downstream from Roanoke Rapids Dam during peaking generally was lower than during non-peaking in 2005, 2008, and 2009, and higher during peaking in 2006 when the weekly mean flow was between 5,000 and 12,000 ft^3/s.

Table 16. Summary of travel-time-adjusted median hourly dissolved-oxygen concentration in the Roanoke River for weeks during May to November 2005–2009 when weekly mean flow was between 5,000 and 12,000 cubic feet per second.

[mg/L, milligram per liter; bold values indicate statistically significant differences at the 99-percent confidence interval; blue values were lower during peaking; red values were higher during peaking; —, no data]

	Median dissolved-oxygen concentration (mg/L)				
	2005	2006	2007	2008	2009
Roanoke Rapids Dam tailrace					
Peaking	**5.8**	**8.0**	—	**6.0**	9.0
Peaking hourly measurements	576	1,296	0	97	240
No peaking	**8.3**	**6.2**	7.8	**12.8**	10.4
No peaking hourly measurements	1,247	216	767	790	1,127
Halifax					
Peaking	**5.7**	8.0	—	**5.9**	8.4
Peaking hourly measurements	352	1,071	0	97	240
No peaking	**7.9**	7.3	8.1	**8.4**	8.1
No peaking hourly measurements	1,148	216	767	790	1,127
Oak City					
Peaking	**5.6**	**6.9**	—	**5.5**	7.9
Peaking hourly measurements	576	1,296	0	97	240
No peaking	**7.0**	**6.0**	7.6	**8.0**	7.9
No peaking hourly measurements	1,153	216	734	790	998
Jamesville					
Peaking	**5.5**	**6.3**	—	**5.3**	**5.8**
Peaking hourly measurements	375	1,296	0	97	229
No peaking	**6.2**	**5.5**	7.4	**7.1**	**7.0**
No peaking hourly measurements	1,049	216	767	790	1,093

Table 17. Summary of travel-time adjusted median hourly dissolved oxygen saturation percentage in the Roanoke River for weeks during May to November 2005–2009 when weekly mean flow was between 5,000 and 12,000 cubic feet per second.

[Bold values indicate statistically significant differences at the 99-percent confidence interval; blue values were lower during peaking; red values were higher during peaking; —, no data]

	Median dissolved-oxygen saturation (percent)				
	2005	**2006**	**2007**	**2008**	**2009**
Roanoke Rapids Dam tailrace					
Peaking	**71.6**	**87.2**	—	**75.6**	**101.8**
Peaking hourly measurements	576	1,296	0	97	240
No peaking	**89.7**	**77.4**	86.1	**141.5**	**113.8**
No peaking hourly measurements	1,196	216	767	790	1,127
Halifax					
Peaking	**70.3**	85.0	—	**75.1**	**89.1**
Peaking hourly measurements	352	1,071	0	97	240
No peaking	**87.4**	84.5	87.5	**93.1**	**92.0**
No peaking hourly measurements	1,148	216	767	790	1,127
Oak City					
Peaking	**72.2**	77.1	—	**70.2**	**84.9**
Peaking hourly measurements	576	1,296	0	97	195
No peaking	**79.5**	75.3	84.4	**88.7**	**90.3**
No peaking hourly measurements	1,153	216	734	790	962
Jamesville					
Peaking	**70.3**	**68.9**	—	**68.0**	**64.9**
Peaking hourly measurements	375	1,296	0	97	229
No peaking	**71.7**	**67.4**	83.4	**80.5**	**81.1**
No peaking hourly measurements	1,049	216	767	790	1,093

Table 18. Summary of travel-time adjusted median hourly dissolved-oxygen deficit in the Roanoke River for weeks during May–November 2005–2009 when the weekly mean flow was between 5,000 and 12,000 cubic feet per second.

[mg/L, milligram per liter; bold values indicate statistically significant differences at the 99-percent confidence interval; blue values were higher during peaking; red values were lower during peaking; — no data]

	Median dissolved-oxygen deficit (mg/L)				
	2005	**2006**	**2007**	**2008**	**2009**
Roanoke Rapids Dam tailrace					
Peaking	**2.3**	**1.2**	—	**1.9**	–0.2
Peaking hourly measurements	576	1,296	0	97	240
No peaking	**1.0**	**1.8**	1.3	**–3.8**	–1.3
No peaking hourly measurements	1,196	216	767	790	1,127
Halifax					
Peaking	**2.3**	1.4	—	**1.9**	**1.1**
Peaking hourly measurements	352	1,058	0	97	233
No peaking	**1.3**	1.5	1.3	**0.8**	**0.8**
No peaking hourly measurements	1,027	200	662	616	930
Oak City					
Peaking	**2.2**	2.0	—	**2.3**	**1.5**
Peaking hourly measurements	576	1,296	0	97	195
No peaking	**1.8**	2.1	1.4	**1.0**	**0.9**
No peaking hourly measurements	1,153	216	734	790	951
Jamesville					
Peaking	**2.3**	**2.8**	—	**2.5**	**3.6**
Peaking hourly measurements	375	1,296	0	97	229
No peaking	**2.4**	**2.7**	1.5	**1.7**	**1.7**
No peaking hourly measurements	1,049	216	766	790	1,093

Summary and Conclusions

The FERC license for Virginia Electric and Power Company requires an analysis of DO and streamflow data for at least one 5-year study cycle, and the first 5-year period ended in 2009. This study was conducted to characterize the relation between streamflows and DO levels in the Roanoke River in the 112-mi reach downstream from Roanoke Rapids Dam to Jamesville, North Carolina, during 2005–2009. Interannual, intraannual, daily, and hourly streamflow, precipitation (excluding hourly), and water-quality data were used in the analysis to determine if discernible quantitative or qualitative patterns linked Roanoke River in-stream DO levels to releases at Roanoke Rapids Dam.

The 2005–2009 period represents a normal precipitation period in the region. Averaging data from the four raingages indicated that 2006 was the wettest and 2007 was the driest during the 5-year period. No statistical correlation was identified between mean annual May–November precipitation and mean annual May-November DO. Storms with measured rainfall amounts do not have to be large to inundate portions of the flood plains and tributaries and cause DO in the Roanoke River to decrease.

The maximum daily mean discharge from 2005 to 2009 was 22,329 ft^3/s, which is not much above the approximate full hydropower generation capacity of Roanoke Rapids Dam (20,000 ft^3/s). The opportunities for hydropower peaking during 2005–2009 from June 16 through November 30 when the weekly mean flow was between 5,000 and 12,000 ft^3/s varied depending on water availability. The year 2007 was unusually dry and did not have a single day within this range; only one week in 2008 was within this range. However, there were nine weeks of hydropower peaking during 2006. The daily range in flow generally was either small (less than 1,000 ft^3/s) or large (greater than 12,000 ft^3/s). The duration of consecutive days with at least a 2,000 ft^3/s difference between the daily mean flow and the weekly mean flow identifies periods when hydropower peaking likely altered the interaction of the flood plain with the river.

Travel-time adjusted DO duration curves between May and November when the weekly mean flow was in the 5,000–12,000 ft^3/s range demonstrate the difference in the DO at each of four water-quality stations during weeks with and without hydropower peaking. At Jamesville, where DO often was the lowest for the longest period of time, DO was lower during weeks with peaking than during weeks without peaking in 3 of the 5 years, and higher during peaking in 1 of the 5 years. This difference was statistically signifcant at the 0.01-probability level for these 4 individual years (2005, 2006, 2008 and 2009). Limiting the years without a statistically significant difference in water temperature between peaking and non-peaking weeks yields 1 year (2009) with lower DO during peaking.

Only once between 2005 and 2009 did the following conditions occur: (1) the daily mean DO concentration downstream from the Roanoke Rapids Dam tailrace was below the State standard of 5 mg/L; (2) the weekly mean flow was within the range where it would likely alter the river and flood-plain interaction (between 5,000 and 12,000 ft^3/s); (3) no large precipitation events occurred; (4) peaking was occurring; and (5) in-stream daily mean DO concentrations were not below 5 mg/L prior to the onset of peaking. These conditions all occurred at Jamesville and were confined to a travel-time adjusted 9-day period between July 21 and July 31, 2005, when the daily maximum air temperatures approached or exceeded 100 degrees Fahrenheit. This occurrence at Jamesville corresponded to discharge from Roanoke Rapids Dam on July 21–22, 2005, during a weekly flow declaration of 7,425 ft^3/s, and on July 26–27, 2005, during a weekly flow declaration of 3,822 ft^3/s with peaking of 16,500–18,900 ft^3/s for up to 6 consecutive hours. These peak releases were followed by minimal peaking in the next several days, possibly allowing the flood plain to drain more than it would have if peaks were not absent for the 3 consecutive days following the peaking. Between 2005 and 2009, when the weekly mean flow was 5,000–12,000 ft^3/s, peaking operations resulted in daily mean DO concentrations below the State standard (5 mg/L) in only 1 of the 17 (6 percent) peaking weeks with no occurrences of instantaneous DO concentrations decreasing below the State standard (4 mg/L). Other than this event, no other occurrences of daily mean DO or instantaneous DO concentrations below the State standards were linked to hydropower peaking independent of large precipitation events.

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3916 Sunset Ridge Road
Raleigh, NC 27607

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Director
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