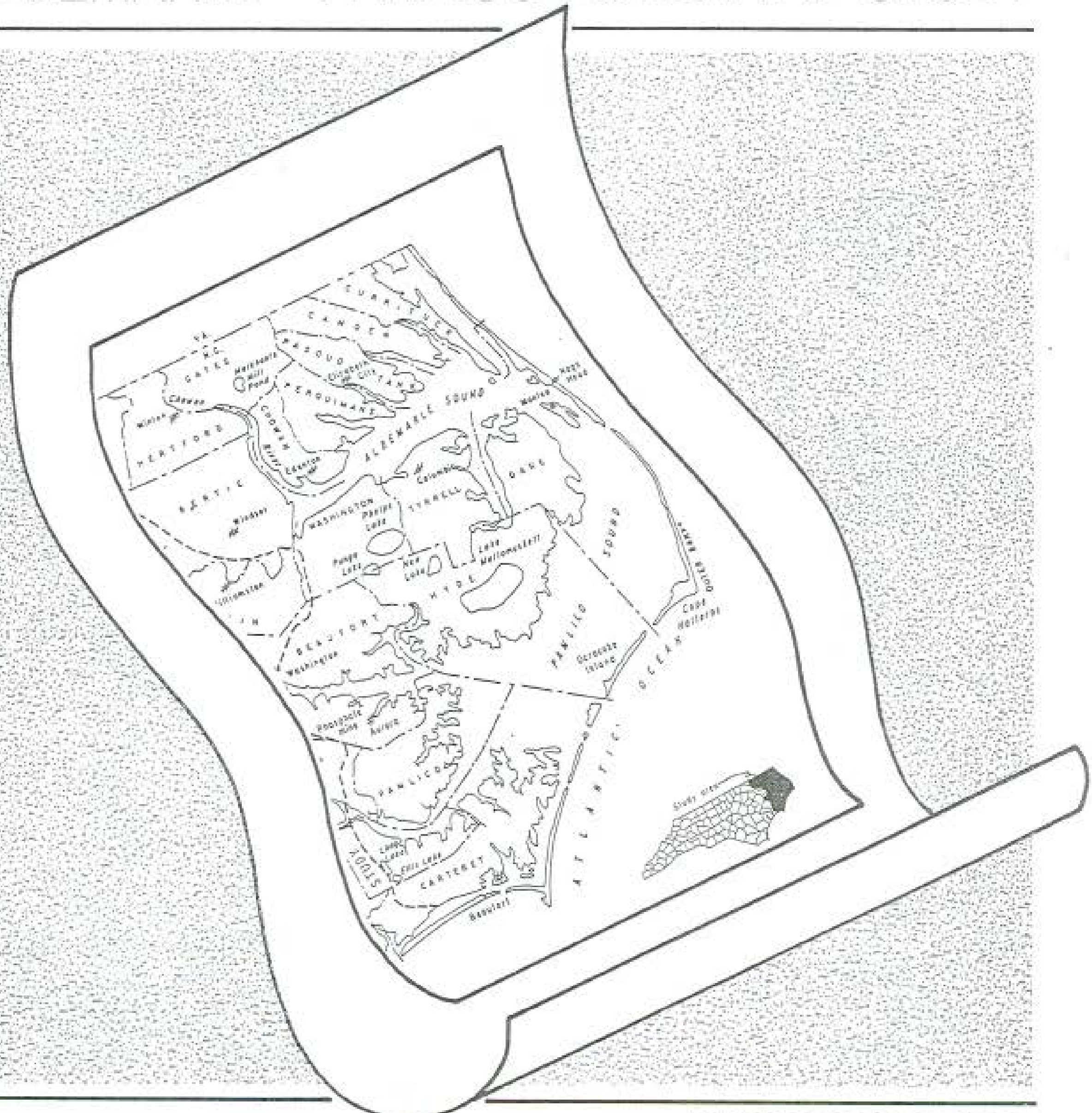
October, 1990 Project No. 90-12

Water Quality As A Function Of Discharge From The Roanoke Rapids Reservoir During Hydropower Generation

ALBEMARLE - PAMLICO ESTUARINE STUDY



Funding Provided By
North Carolina Department of Natural Resources and Community Development
Environmental Protection Agency
National Estuary Program

ALBEMARLE-PAMLICO

WATER QUALITY AS A FUNCTION OF DISCHARGE FROM THE ROANOKE RAPIDS RESERVOIR DURING HYDROPOWER GENERATION

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The research on which the report is based was financed, in part, by the United States Environmental Protection Agency and the North Carolina Department of Environment, Health, and Natural Resources through the Albemarle-Pamlico Estuarine Study. Additional financial support was provided by the Weyerhaeuser Company, Pulp and Paperboard Mill, Plymouth, North Carolina.

Project No. Apes 90-12

October 1990

Acknowledgments

Our thanks go to Michael T. Ball, Jose I. Escorriola-Giovannini, Andrew E. Tate, and Scott F. Wood for sampling efforts. The Pollock's Ferry Hunting Club provided initial on-site facilities. This research could not have been accomplished without the generosity of Weyerhaeuser Company's Pulp and Paperboard Mill, which supported the laboratory facilities and water quality laboratory analyses, and provided major funding for the project. James Fromm, water quality analyst, performed most of the water quality testing. The study was funded, in part, by the Albemarle-Pamlico Estuarine Study, which is a cooperative state-federal initiative of the North Carolina Department of Environment, Health, and Natural Resources, and the U.S. Environmental Protection Agency.

Executive Summary

The effect of springtime water releases from Roanoke River reservoirs on downstream water quality was examined by whole water grab samples collected at two locations. At Pollock's Ferry (River Mile 105) near Scotland Neck, North Carolina, surface water samples were collected one day each week from 14 April to 8 June 1988. Within the Roanoke River delta, water samples were collected at four stations once each week for nine weeks starting 14 April and ending 10 June. Water releases from Roanoke Rapids Reservoir caused instream flows to fluctuate from 1,100 to 18,000 cubic feet per second (cfs) in January and February. During the major portion of striped bass (*Morone saxatilis*) spawning activity (from mid-April through late May), the hydroelectric peaking activity moderated and flows ranged from 5,900 to 8,300 cfs. In early June, normal hydropower operations resulted in river flows fluctuating between about 2,000 and 15,000 cfs. Rainfall events during the study period influenced water release schedules and influenced water quality downstream. Generally, water quality was good at Pollock's Ferry and in the Roanoke delta in the Middle River, Cashie River, and Roanoke River at Plymouth, NC. Significant diel variation in water quality was evident at Pollock's Ferry on only one of nine sampling dates. During the 31 May-1 June diel sampling period, reservoir releases more than doubled from 5,600 cfs to 14,000 cfs over a 12-hour period. No consistent vertical water quality differences were evident in the lower river near Plymouth, indicating good vertical mixing at these moderate flows. Roanoke delta waters had higher average values than Pollock's Ferry waters for many of the dissolved and particulate parameters: color, turbidity, total and volatile suspended solids, total and soluble organic carbon, most nutrient (N, P) species, and several metals including aluminum, iron, manganese, and sodium. Downstream increases in these constituents reflect both swamp drainage, which is higher in color and carbon, and waste discharges, which are high in nutrients and contain metals. Pulp mill effluents are also highly colored. Levels of dissolved oxygen remained above 5 mg/L at Pollock's Ferry, but dropped below 5 mg/L in the Plymouth area in late April and early May. Water temperature and pH values were positively correlated with river flow at Pollock's Ferry; conductivity and nitrate/nitrite were negatively correlated with instream flow. At Pollock's Ferry for the 31 May-1 June sampling period, many water quality parameters were positively correlated with rapid rise in river stage: turbidity, VSS, NH_3-N, TPO_4-P, Al, Fe, and Mn. Nominal river flow in the delta was negatively correlated with NH_3-N for the Cashie River station and with TPO_4-P for the Middle River station. We conclude that water quality at Pollock's Ferry, 22 miles below Roanoke Rapids Dam, was largely influenced by water releases from Roanoke Rapids reservoir. Water quality in the Roanoke delta was modified by drainage from extensive riverine swamps bordering the river, and municipal and industrial waste discharge. We recommend that studies of this nature continue and be extended into the summer months so that water quality during minimal flow periods can be quantified.

Table of Contents

List of Figures

List of Tables

Introduction

The heightened interest in water quality and watershed management of the lower Roanoke River Basin in recent years has been the result of a number of events: the establishment of a national wildlife refuge within the floodplain; potential interbasin transfer of water; increased water consumption and withdrawal by industry and municipalities, the decline of fishery resources in Albemarle Sound, especially striped bass (*Morone saxatilis*), and initiation of the Albemarle-Pamlico Estuarine Study. The coarse thread that ties these issues and activities together is the manner in which the flow regime is managed by the system of reservoirs located in the Piedmont region of the watershed (Figure 1).

Flow of the lower Roanoke River is highly regulated by a number of reservoirs upstream: Smith Mountain Lake, Philpott Lake, Leesville Lake, John H. Kerr Reservoir, Lake Gaston, and Roanoke Rapids Lake. The most important of these reservoirs in relation to the lower Roanoke and Albemarle Sound is Kerr Reservoir, which controls input to Gaston and Roanoke Rapids reservoirs, and provides 87 percent of the flow to the coastal watershed (Giese et al. 1985). Regulation of flow by the reservoir system virtually precludes intrusion of saltwater into the lower Roanoke River except in cases of severe drought (Giese et al. 1985).

Recently, the manner in which water is released from Roanoke Rapids Dam during the spring months has come under close scrutiny. Provisions for minimum flows were established within the guidelines of the Memorandum of Understanding (MOU) signed in 1971 by regulatory agencies (Federal Energy Regulatory Commission or FERC, the North Carolina Wildlife Resources Commission, and Virginia Power Company). The required minimum flow releases change throughout the year based upon specific biological and water quality requirements. For example, during the two-month striped bass spawning season from mid-April to mid-June, the minimum daily discharge is supposed to be 6,000 cfs (cubic feet per second). This level of flow functions in several ways: provides access by boaters to fishing areas upstream of the rapids at Weldon, ensures adequate dilution of municipal and industrial wastes, and provides an attractant flow for adult striped bass migrating upstream. The minimum summer flow required after the spawning season is only 2,000 cfs; in late fall and early winter (November/December) the minimum release is 1,000 cfs. Discharge requirements and the chronology of events concerning these impoundments were summarized by Manooch and Rulifson (1989).

One problem with the minimum flow guidelines is that no provision was made for maximum flows, resulting from peaking activity, or the manner in which the average daily discharge is derived. Under flooding conditions upstream, the dams release as much water as possible through the turbines. The usual maximum in the USGS (U.S. Geological Survey) gage records measured below Roanoke Rapids Dam is about 20,000 cfs. Under extreme conditions, additional water is released via spillways. In 1987, the USGS gage records indicated a maximum daily flow of 35,300 cfs on 4 May (Manooch and Rulifson 1989).

Release of large volumes of water causes extensive flooding downstream, which particularly affect agricultural activities, nesting of wild turkey, fawning of deer, and spawning of a variety of commercially and recreationally important fish species. The flooding event *per se* is not new to the Roanoke watershed, but the timing of the flooding event or events is now controlled for the most part by the reservoir system. Historically, flooding occurred during the late spring (Manooch and Rulifson 1989), but now the timing and duration of high discharges are not necessarily related to the inflow to Kerr Reservoir and/or high rainfall situations.

As early as 1954, the downstream flooding problem associated with hydropower generation was recognized and documented. Velz (1954) presented the instantaneous hydrograph record from the Roanoke Rapids gage for the period 15-27 July 1953, which indicated routine changes in river flow of 8,000 cfs within a two-hour period (Figure 2). Even more dramatic changes in flow are commonly found in the USGS records from 1954 until the present time, many of which occur during striped bass spawning activity. These sudden changes in the flow regime caused by on-demand hydropower generation also result in dramatic changes in water depth on the striped bass spawning grounds within one to two hours. Personal observations by Rulifson and Wildlife Resources Commission personnel indicate that these changes can exceed eight feet in one hour.

Although these rapid changes in instream flow are well-known, no studies have been conducted to determine how downstream water quality and fish habitat are changed by this sudden release of water. The annual reports produced by Dr. W.W. Hassler and co-workers (1963-1985) show rapid changes in water temperatures on the spawning grounds. Wildlife Resources Commission personnel routinely cope with slugs of sediment-laden water, caused by quickly rising waters, entering the Weldon hatchery water system, which draws its water from the Roanoke River at Weldon (River Mile 130).

River sediments typically contain trace quantities of heavy metals, pesticides, fertilizers, and other materials originating from industries, municipalities, and adjacent farmlands upstream (Golterman 1975). The resuspension of these fine sediments and the sudden changes in water temperature, dissolved oxygen, and pH associated with reservoir discharge alters water quality. One of the metals of recent concern is aluminum, which occurs at naturally high concentrations within the coastal plain. Rulifson et al. (1987) suspected that sudden reservoir discharge in the Roanoke River caused resuspension of the silt clay particles laden with aluminum, resulting in changes in the aluminum chemistry. This action may result in sudden input of dissolved monomeric aluminum, a form that is highly toxic to young fish (Schofield and Trojnar 1980; Baker 1981; Muniz and Leivestad 1980; Baker and Schofield 1982; Mehrle et al. 1984; Hall et al. 1985). Although Rulifson et al. (1987) did not test this hypothesis for hydropower discharge, the principle was demonstrated in water samples they collected from the Tar River under low flow (drought) and high flow (sudden rainstorm) conditions in 1986. Other metals of concern include lead, zinc, copper, and mercury, which were found above the minimum detectable limits in the lower Roanoke River below Plymouth, North Carolina, in the spring of 1985 (Rulifson et al. 1986). Water quality standards applicable to the lower Roanoke River are listed in Appendix Table A-1; USEPA water quality criteria also are included for reference.

The study described herein had three objectives: (1) to document the water quality conditions at Pollock's Ferry immediately below the striped bass spawning grounds, and the Plymouth area downstream near the river mouth where striped bass larvae occur, during the spring spawning period; (2) to document changes in water quality at Pollock's Ferry as a function of sudden fluctuations in instream flow caused by on-demand hydropower generation; and (3) to determine the vertical variation in water quality at key locations in the Roanoke delta area. Data collection was concurrent with collections of striped bass eggs downstream of the spawning grounds near Scotland Neck, North Carolina (Rulifson 1989). Additional water quality information was collected in the lower Roanoke River, delta, and western Albemarle Sound.

Study Site Description

Major portions of southeastern Virginia and northeastern North Carolina are drained by the Roanoke watershed, which encompasses approximately 9,666 mi^2. Nearly six percent of North Carolina's land area (3,506 mi^2) is drained by the Roanoke River watershed (Moody et al. 1985). Major tributaries include the Dan, Mayo, Smith, and Hyco rivers (Figure 1).

The Roanoke River carries more water than any other river in North Carolina, with a daily average of about 8,500 cfs. The watershed itself contributes about 50 percent of the freshwater input to Albemarle Sound. Waters of the Roanoke River are used for municipal, industrial, and agricultural purposes, and for maintenance of fish and wildlife habitats (Manooch and Rulifson 1989).

The six major dams within the watershed control river flow to the coastal plain (Figure 1). Total water volume held by these dams is 4,372,000 acre-feet or 1,420,000 million gallons (MG) (Moody et al. 1985). Daily instream flow and flood peaks are modified by operation of these reservoirs.

Hydrological data for the lower Roanoke River basin were summarized by the U.S. Army Corps of Engineers (1968, 1984). Depending on location, precipitation within the lower basin averages from 41 to 53 inches per year. Widespread precipitation throughout the entire watershed causes increased discharge of mainstream tributaries. Localized rainfall events usually cause increased discharge only in smaller tributaries. Precipitation is the primary source of water input to the lower river basin; snowfall within the lower basin ranges from 3 to 10 inches.

Discharge from the Roanoke Rapids Reservoir is monitored every 15 minutes by the U.S. Geological Survey water gage No. 02080500 at Roanoke Rapids. This gage is located in Halifax County on the right bank 2.8 miles downstream from the Roanoke Rapids Dam and 133.6 river miles (RM) from the river mouth at Albemarle Sound (Manooch and Rulifson 1989). The period of record for this gage is from 1911 to the current year. The unit (quarter-hour) values are used to determine an average daily discharge measured in cubic feet per second (cfs). The instantaneous maximum discharge for the period of record was 261,000 cfs on 18 August 1940, caused by the landing of an unnamed hurricane (naming hurricanes was initiated in 1950). This flood was the maximum flow known since at least 1771. The minimum recorded discharge was 250 cfs on 16 December 1955. Differences between pre-impoundment (prior to August 1950) and post-impoundment (1955 and later) flows were described in detail by Manooch and Rulifson (1989).

The portion of the Roanoke River downstream of Roanoke Rapids Lake is classified as a "C" stream by the North Carolina Division of Environmental Management (DEM). The river receives wastes from a number of municipal and industrial sources in addition to agricultural runoff. National Pollution Discharge Elimination System (NPDES) permittees are regulated based primarily on the volume of wastewater measured in millions of gallons per day (MGD) and on the biochemical oxygen demand (BOD) in mg/L and/or pounds per day. Table 1 lists the NPDES permit allowable waste discharge volumes and biological oxygen demand (BOD) by facility downstream of the Roanoke Rapids Dam to the river mouth.

The DEM has assigned a "water quality limited" category to the Roanoke River near Plymouth because of observed dissolved oxygen levels below the 5.0 mg/L limit. Low dissolved oxygen values are observed especially near the Weyerhaeuser plant at Plymouth.

Methods

Sampling Methods

The upstream sampling site, Station 1, was located at River Mile (RM) 105 near the town of Scotland Neck in a straight section of the Roanoke River adjacent to the Pollock's Ferry Hunting Club and slightly below the power lines (Figure 3). Surface water samples were collected on nine different occasions beginning 14 April and ending 8 June. This station also was the site for monitoring striped bass spawning activity as determined by egg abundance in the spring of 1988 (Rulifson 1989). Water velocities and river stage elevations at this station reflect rates of discharge from Roanoke Rapids Reservoir. The profile of the river between the natural levies on either side is represented by steep banks alternating with narrow plateaus cut at intervals reflecting changing water levels. The main river bed is uniformly deep and consists of sand and silt interspersed among sunken debris and bedrock.

At the Pollock's Ferry station, water samples were collected one day each week. Grab samples were taken every four hours for a 24-hour sampling period and composited into one sample; composited water quality samples were collected every two weeks. On alternate weeks, samples collected every four hours were kept as discrete samples to detect any diel variations in water quality. All composite and discrete samples were kept refrigerated, then placed on ice and transported to the Weyerhaeuser Environmental Field Station laboratory in New Bern for analyses. The water quality sampling protocol is depicted in Table 2.

Water quality samples were also collected from the Roanoke River delta at four stations on nine separate occasions beginning 14 April and ending 10 June. These stations corresponded to the standard sampling stations in existence since 1984 for determining the abundance and species composition of phytoplankton algae, zooplankton, and larval fish in the spring (Rulifson et al. 1988). Station 6 was located in the Middle River distributary just downstream of its junction with the Roanoke mainstem. Moderate currents prevail; depth averages 6.6 m but ranges from 3.0 to 18.3 m over a short distance (Rulifson et al. 1988). Station 7 was located in the Roanoke River mainstem near the Weyerhaeuser public boat ramp just above Welch Creek. This station was positioned just upstream of the waste diffuser pipe of the Weyerhaeuser mill. Depth averages 7.7 m but ranges from 4.6 to 9.1 m. Moderate currents are common; the right shore (Plymouth) has steep banks and is deep compared to the left shore, which gradates to an extensive shallow shelf covered with emergent (lilypad) vegetation. Station 8 was in the Cashie River just upstream of the Highway 45 bridge. Also characterized by moderate currents, the steep bank and deep water on the left side gradates to an extensive shallow, un-navigable shelf with emergent lilypads on the right shore. The mud bottom averages 5.8 m in depth but ranges from 1.8 to 13.7 m within a short distance (Rulifson et al. 1988). Station 10 was located in the Roanoke mainstem downstream of Weyerhaeuser and Plymouth, but just upstream of the Highway 45 bridge. Moderate currents prevail; a fairly uniform river channel averaging 4.6 m deep gradates into extensive shallow shelves covered with lilypads on either side of the channel. Under low flow conditions, Weyerhaeuser effluent and low salinity are detectable. Under extreme low flow and lunar flood tide and/or wind tide conditions, river flow actually reverses to travel upstream past Plymouth.

In the lower Roanoke, Middle, and Cashie Rivers at Stations 6, 7, 8, and 10, water samples were collected at the surface, mid-depth, and bottom with a Kemmerer sampler. The discrete samples for each station were composited to form one sample. The discrete surface, mid-depth, and bottom samples collected at Station 7 and Station 10 during the second and fourth weeks of May were not composited but analyzed separately as a check for any vertical variation in water quality.

There were two deviations from the sampling protocol. Discrete water samples were collected on 14-15 April at Pollock's Ferry, and water quality at Stations 6 and 7 were not sampled on 31 May and 9 June. However, on 31 May Stations 13 and 15 in Bachelor Bay off the river mouth were substituted for Stations 6 and 7 because ichthyoplankton data collected in late May showed that striped bass larvae were moving from the river into Bachelor Bay (Rulifson, Stanley, and Cooper, East Carolina University, unpublished data).

Water samples were collected at each station in four pre-cleaned glass 1-L bottles. Precleaning for three bottles involved acid-washing in 1:1 HCl and flushing with distilled water. The fourth bottle was prepped for metals analysis by soaking in 1:1 HNO_3 for 24 hours and rinsing with distilled water.

Analytical Methods

Water quality analysis was conducted at the Weyerhaeuser Field Station Lab at New Bern with the exception of metals, soluble organic carbon (SOC), and total organic carbon (TOC). The samples for metals analysis were preserved with 1 ml of HNO_3, iced, and shipped to the Weyerhaeuser Technology Center (WTC) laboratory in Federal Way, Washington, for processing. One acid-washed 1-L bottle was preserved with 1 ml of HgCl and kept refrigerated until analyzed for nutrients. The remaining analyses were taken from the two unpreserved 1-L bottles. From these two bottles, an aliquot was split into two 20-ml polyethylene scintillation vials: one aliquot maintained whole, and the other filtered through a glass fiber filter for analysis of soluble organic carbon (SOC). The vials were preserved with 0.05 ml H_2SO_4 using an Eppendorf pipetter and shipped to the WTC lab for TOC/SOC analysis. Another 50-ml aliquot was prepared for chlorophyll analysis (Pollock's Ferry samples only). Detection limits for the laboratory-tested water quality parameters are listed in Appendix Table A-2.

River samples were analyzed for pH with a Corning model 4 pH meter. Alkalinity was determined titrimetrically to pH 4.5 with 0.8 N H_2SO_4 and a Hach autotitrator with a pH meter to note the pH endpoint.

True color was determined on samples filtered through Gelman 0.8-µm membrane filters and pH-adjusted to 7.6. Color absorbence was measured at 465 nanometers with a Perkin-Elmer spectrophotometer model 575.

Turbidity was determined with a Hach ratio turbidimeter model 18900 and reported in nephelometric turbidity units (ntu). Latex turbidity standards were used for calibration. Total suspended solids (TSS) and volatile suspended solids (VSS) were determined gravimetrically on samples filtered through previously fired and weighed Whatman 934-AH glass fiber filters using a Gelman filtration manifold system. The TSS was determined on samples dried at 103°C for 1 to 2 hours; VSS was determined on samples combusted at 550°C for one hour.

Determinations of BOD_5 were determined at 20°C according to procedures in the 16th Edition of Standard Methods (APHA 1985). A YSI Model 54A dissolved oxygen meter with a YSI BOD bottle probe-stirrer was used to measure initial and final dissolved oxygen (DO) concentrations.

Sulfate was measured turbidimetrically on a Hach ratio turbidimeter by precipitating sulfate with barium chloride according to Standard Methods 16th Edition (APHA 1985).

Ammonia nitrogen was analyzed using the colorimetric phenate method (Strickland and Parsons 1972).

Total Kjeldahl nitrogen was determined as ammonia on samples digested using a Tecator model 1016 forty tube block digester as described by EPA method No. 351.4 (USEPA 1979). Ammonia was measured with a Technicon Autoanalyzer II using the manufacturer's method No. 329-74 W/A.

Nitrite nitrogen was analyzed according to the diazotization colorimetric method described by Wetzel and Likens (1979). Nitrate and nitrite (NO_3/NO_2-N) were analyzed together as mg/L of total oxidized nitrogen using the Wetzel (Wetzel and Likens 1979) modifications of the cadmium-reduction method (Strickland and Parsons 1972).

Preliminary results of recent unpublished research conducted in tributaries of Chesapeake Bay suggest that inappropriate preservation of water samples for subsequent nitrite determinations could give rise to erroneously low values. In order to ensure the quality of the NO_2-N values in this study, a second split of the sample was isolated specifically for a duplicate determination of NO_2-N by ECU's Shared Resources Research Laboratory, with the requirement that it be completed either immediately on return of samples to the lab (i.e., the day of sampling), or within three days of sampling, provided the sample was frozen on return to the lab. The procedure for this duplicate analysis was the classical diazotization, colorimetric method described by many but adapted from Strickland and Parsons (1972). Proportional reduction in the volumes of samples and reagents were made such that sample size of 5 to 10 ml could be used. Except for a few samples that were missed, duplicate determinations were performed on each sample and the mean reported as the final value.

Total phosphorus (TPO_4-P) was determined after a persulfate/sulfuric acid digestion in an autoclave using a heteropoly blue colorimetric determination on the spectrophotometer described in the 16th Edition of Standard Methods 424C III and 424E (APHA 1975). Orthophosphorus was determined with the ascorbic acid, two reagent, colorimetric procedure according to the EPA method No. 365.3 (USEPA 1979).

Total and soluble organic carbon (TOC and SOC) were determined by injection to a high temperature resistance furnace and an infrared analyzer as described by the EPA method No. 415.1 (USEPA 1979).

Chlorophyll *a* was determined on samples concentrated by filtration on Whatman 934-AH glass fiber filters sealed in a foil pouch and kept frozen in a dessicator until analyzed. The chlorophyll on the frozen filter was extracted in 15 ml of 90 percent alkaline acetone and analyzed by a Turner fluorometer model no. 111 according to procedures described in the Handbook of Seawater Analysis (Strickland and Parsons 1972).

Metals were determined by inductively coupled emission spectroscopy according to the EPA method No. 200.7 (USEPA 1979), except arsenic and selenium, which were analyzed by a Perkin Elmer graphite furnace atomic adsorption (AA) spectrometer according to the EPA method No. 206.2 and EPA method No. 270.2, respectively (USEPA 1979).

This study provided an opportunity to apply an experimental analytical procedure for the determination of dissolved monomeric aluminum (DMAl) that was currently under investigation by the ECU laboratory at the time. The procedure was developed by Dobb et al. (1986) for the USEPA-Las Vegas. Work completed up to the time of this project in trying to adapt this protocol to our coastal waters was described by Bray et al. (1988). Additional information on the method was presented in Lewis et al. (1988).

The DMAl procedure is based on the measurable rate of reaction for the complexation of monomeric aluminum species with fluoride ions. The sample is first acidified to pH 3.5 after which it is spiked with a measured excess of fluoride ions. The rate of decrease in fluoride ion concentration (which is first order during the initial stages of reaction and hence linear) is followed with a fluoride specific ion electrode. Aluminum concentration is related to changes in fluoride concentration through an equation that is based on classical principals of electrochemistry and kinetics and which involves a rate constant empirically derived by Dobb et al. (1986). Complete details of the procedure were described in the references cited above.

Water quality parameters at each of the five stations were used in a correlation analysis (SAS 1987) to determine possible relationships of each to river flow. For Pollock's Ferry samples, river flow was the Roanoke Rapids USGS gage flow value for the day; discrete sample data were averaged to provide one value for statistical comparisons. For the Plymouth area, nominal river flows were used for the water quality correlation analysis for each station. Nominal river flow in the Plymouth area was based on the river discharge at Roanoke Rapids plus tributary inflows between the dam and the Plymouth area.

The river discharge-travel time relationship used in determining flows at the Plymouth area stations was developed from dye studies under various flow regimes between Roanoke Rapids and Scotland Neck (Fish 1959) and between the Oak City - Williamston area and Plymouth (Herrmann et al. 1983). Tributary inflow from the approximately 1,000 mi^2 drainage area between Roanoke Rapids and Plymouth (Cashie basin excluded) was calculated from cfs/mi values (mid-April to mid-June 1988) for the five small tributary basins adjoining the lower Roanoke.

The nominal flows at the Plymouth area stations were based on adjusted time-lagged flows at Roanoke Rapids plus the tributary inflow estimate. The Cashie flow estimate was the sum of the USGS gaged Cashie flow near Windsor (Station No. 208111310) and 18 percent of the Roanoke River flow upstream of the Thoroughfare distributary channel. River hydraulic studies of the Roanoke instream flow near Plymouth by Weyerhaeuser (Herrmann 1985) determined that about 18 percent of the discharge passes through the Thoroughfare channel; 22 percent passes down Middle River. The nominal flow in the main channel near the Plymouth mill boat launch and near the Highway 45 bridge was 60 percent of the Roanoke flow upstream of the distributary channels.

Results

Roanoke River Flow

In 1988, hydropower operations at Roanoke Rapids Dam exhibited a marked change between the "normal" operating pattern, where flows fluctuated over a broad range in response to dam releases, and dam operations during the spawning season. For January and February, instream flows at the Roanoke Rapids gage commonly ranged between 1,100 and 18,000 cfs. During the spawning period, hydropower peaking activity was moderated; instream flow ranged between 5,900 cfs and 8,300 cfs.

Two major factors contributed to this change in water release. The first event was the acceptance in principal by the U.S. Army Corps of Engineers and Virginia Power Company of a flow regime developed by the Roanoke River Water Flow Committee (Manooch and Rulifson 1989). Briefly, the Flow Committee's proposal called for the Corps of Engineers and Virginia Power to regulate flows between the historical 25 percent and 75 percent quartiles of the daily flows between 1 March and 30 June each year (Table 3); that is, between the 25 percent low flow (Q_1) and 75 percent high flow (Q_3). Subsequent negotiations resulted in a "Negotiated Flow Regime" that was acceptable to Flow Committee advisors from the U.S. Army Corps of Engineers, Wilmington District, and Virginia Power. In addition, the Flow Committee recommended that hourly variation in flow should not exceed 1,500 cfs (under the FERC license, the power company may double or half the flow within one hour). The Corps of Engineers and Virginia Power Company agreed to test the feasibility of this flow regime during the spring of 1988. The actual Negotiated Flow Regime was formally adopted for a four-year trial period on 23 June.

The second major factor was moderate input of runoff from the watershed to storage in Kerr Reservoir. Flow records for the first six months of 1988 depict a regulation of flood events by the reservoir early in the year, followed by controlled releases for striped bass spawning flows in the spring. Power operations from Roanoke Rapids Dam show a curtailment of peaking in late March (Figure 4), which corresponded to the lower outflow from Kerr Reservoir associated with the Corps of Engineers' efforts to store additional water for release during spawning season. Rainfall for March was 1.63 inches (below Kerr Reservoir, Corps data), well below the normal March rainfall (3.81 inches). Kerr Dam started releasing augmentation flows for spawning on 11 April; Virginia Power again resumed peaking operations at Roanoke Rapids Dam but within the guidelines of the Negotiated Flow Regime (Figure 5). Throughout the remainder of April and all of May, Roanoke Rapids power operations limited flow fluctuations to within the limits of the Flow Committee guidelines and with a lower limit of 6,000 cfs (Figures 5, 6). Throughout this period, Kerr Reservoir was the driving force by releasing water from storage. Rainfall for April (4.67 inches) was 55 percent above average (3.01 inches); May rainfall (3.87 inches) was slightly below average (4.09 inches). However, two rather large rainfall events in early and mid-May may have influenced some water quality parameters downstream in the delta. In early June, reservoir operations resumed normal patterns and Roanoke Rapids operations resumed daily fluctuations between about 2,000 and 15,000 cfs (Figure 7).

These two factors resulted in rather stable flows at the Pollock's Ferry sampling site during the study. The water quality information obtained by our study therefore represented good baseline data on the results of moderating flows downstream of hydropower projects. Unfortunately, our objective to document resultant effects of large changes in river flow (2,000 to 20,000 cfs) on water quality was only partially realized during the study period.

General Comments on Water Quality

Water quality of the Roanoke, Middle, and Cashie Rivers was generally good compared to North Carolina water quality standards during the 1988 striped bass spawning period. There were some changes in water quality between Pollock's Ferry and the lower Roanoke. Except for one sampling date (31 May-1 June), we saw no significant diel variations in water quality at Pollock's Ferry (Appendix Table A-3). Also, there was little variation in water quality vertically in the water column at Stations 7 and 10 in the lower Roanoke River. The vertical variation in water quality was examined for two sets of depth discrete samples (surface, mid-depth, bottom) taken at Stations 7 and 10 on 12 May and 26 May. The nominal river flows in the Plymouth area on these dates were about the same: 4,425 cfs (12 May) and 4,600 cfs (26 May). At both stations under these discharge conditions, the only water quality features that showed a consistent relationship with depth were turbidity and TSS. Both parameters increased from the surface to the bottom (Appendix Table A-4).

Table 4 is a summary of the water quality averages and coefficients of variation for Pollock's Ferry station and the four Plymouth area stations for all sample dates. For many of the dissolved and particulate constituents, the Plymouth area station averages were higher: color; turbidity; TSS and VSS; TOC and SOC; most nutrient (N, P) species; and certain metals -- aluminum (Al), iron (Fe), manganese (Mg) and sodium (Na). These higher downstream values reflect both swamp drainage, which is higher in color and carbon, and waste discharges, which are high in nutrients and certain metals; pulp mill effluents are also highly colored. At Pollock's Ferry, the low concentrations of particulate constituents reflect both the trapping of particulates in the upstream reservoirs and the (mostly) gravel and bedrock substrate in the river channel downstream of Roanoke Rapids Dam.

Temperature, pH, and Dissolved Oxygen

At Pollock's Ferry, water temperature was positively correlated with instream flow ($n=9$, $r=0.72$, $P=0.03$). Water pH also was positively correlated with river flow ($n=8$, $r=0.86$, $P=0.01$). *In situ* pH ranged from 6.7 to 7.9 (Appendix Table A-3). The lowest pH value (6.7) was recorded on 17 May. Water temperature was 13°C on 14 April and increased to 24°C at the end of May (Appendix Table A-3). Levels of dissolved oxygen (DO) remained above 5.0 mg/L throughout the study and exhibited no significant correlation with river flow.

Water temperatures at the four Plymouth area stations ranged from a low of 11°C on 14 April to a high of 24°C on 9 June (Appendix Table A-4). Temperatures were not significantly correlated with nominal river discharge at any of these stations. Dissolved oxygen concentrations at these stations were mostly 6 mg/L; however, concentrations dropped below 5 mg/L during one week's sampling in early May (Roanoke at Plymouth) to three weeks sampling in late April and early May (Cashie River and Roanoke at Highway 45 bridge). Minimum DO values recorded at the latter two stations were 4.0 mg/L and 4.4 mg/L respectively (Appendix Table A-4). The antecedent flow conditions upstream at Roanoke Rapids were relatively stable during the late April-early May DO period, and showed a drop of only about 1,000 cfs. However, at this same time the Cashie River instream flow at Windsor declined by 60 percent to 80 cfs. Probably concurrent to declining instream flows and falling river stage, oxygen-deficient waters stored in the adjacent swamps entered the river and depressed DO levels. Decreased dissolved oxygen levels with depth was evident particularly at the Cashie and Roanoke stations just upstream of the Highway 45 bridge (Appendix Table A-4). Values of pH at these four stations usually remained above 7.0 (Appendix Table A-4) and were not correlated with instream flow.

Alkalinity, Conductivity, and Salinity

There was little variation in alkalinity among sampling sites (Appendix Table A-5). Alkalinity, which is the ability of water to neutralize an acid, averaged about 26 mg/L as $CaCO_3$ at all sample locations in the Roanoke (including Pollock's Ferry) and Middle Rivers. However, the Cashie River alkalinity averaged slightly lower (22 mg/L as $CaCO_3$). Little temporal variation was apparent during the study (Figure 8). The low alkalinities recorded indicate that waters of the lower Roanoke watershed are soft and poorly buffered.

Conductivity, an indicator of dissolved substances in the water, was negatively correlated ($n=9$, $r=-0.77$, $P=0.015$) with river flow at Pollock's Ferry. Conductivity averaged 120 μmhos at Pollock's Ferry and about 100 μmhos in the Middle and Roanoke Rivers, except for the area near the Highway 45 bridge (below Weyerhaeuser's pulp mill and the Plymouth wastewater treatment plant), which averaged 130 μmhos (Table 4). There was no relationship between conductivity and river flow for the Plymouth area stations. The Cashie station conductivity also averaged higher (131 μmhos). Salinity remained consistently below 1.0 ‰ at all stations throughout the study.

Color, Turbidity, and Suspended Solids

Color of the Roanoke River water increased with distance downstream (Figure 9). Color and turbidity in streams and rivers absorb light, reducing the depth of the photic zone, which can reduce primary production. The color of the lower Roanoke Middle, and Cashie Rivers averaged about 52 color units, more than twice the color found upstream at Pollock's Ferry. This increase is due to swamp drainage and color from pulp mill discharge. The Plymouth Pulp Mill effluent, which has a color between 1,100 and 1,900 units (Herrmann and Backman 1979), probably contributed to the consistently higher color (average of 57 color units) at the Highway 45 bridge (Figure 9, Table 4). A peak of 110 color units at the Roanoke (Stations 7 and 10) and Middle River (Station 8) on 12 May appears to correspond with heavy rainfall in the lower watershed during 4-6 May (Figure 6), though color was not significantly correlated with river flows.

Suspended material in the water column was measured by turbidity and total suspended solids (TSS). Turbidity, a measure of water opacity caused by suspended organic and inorganic colloidal and particulate matter, ranged from 12 ntu at Pollock's Ferry to 22 ntu in the Cashie River (Table 4). Middle River turbidity averaged 20 ntu and lower Roanoke Stations 7 and 10 averaged 18 ntu and 17 ntu, respectively. Increased values of turbidity and total suspended solids are often associated with storms and subsequent runoff and increased river flow. The low turbidity values of this study indicated the relative stability of river flow (Figure 10). Average TSS values were also low for the Roanoke, ranging from 13.8 mg/L at Pollock's Ferry to a high of 24.8 mg/L in the Cashie River (Table 4). The Cashie River exhibited several high values during mid-May (Figure 11), which correlate with increased river flow at the gaging station near Windsor. The volatile fraction of the suspended solids (VSS) ranged between 15 percent and 20 percent of the TSS. These turbidity and suspended solids concentrations are within the 5 mg/L to 25 mg/L range reported by Simmons and Heath (1979).

Organic Matter

The biochemical oxygen demand (BOD), defined as the amount of oxygen consumed by biological respiration over a five-day period at 20°C, was low at all locations and averaged about 1.2 mg/L (Table 4). The BOD is a function of the type and amount of carbonaceous material present in the water. There was a general decline in BOD values during early May at the Roanoke delta stations (Figure 12), which corresponded with rainfall during 4-6 May (Figure 6).

Carbon content of Roanoke water doubled between Pollock's Ferry and the Plymouth area. Carbon content of the water was characterized by analyzing total (TOC) and soluble (SOC) organic fractions. TOC at Pollock's Ferry averaged 5.4 mg/L, increasing to an average value of 10.3 mg/L downstream. The soluble organic fraction is biologically more available for BOD respiration. Nearly half (average of 3.2 mg/L) of the TOC content at Pollock's Ferry was SOC (Table 4). The Cashie River had the highest TOC concentration (Figure 13), which averaged 21.7 mg/L; about 76 percent (16.6 mg/L) of the total carbon content was SOC.

Apparently, there was some contamination problem with several of the organic carbon samples. The problem appeared to be completely random, and obvious outliers were omitted from the calculated averages. A duplication of the tests on a few samples suspected of contamination confirmed the analytical results.

Nitrogen and Phosphorus

Concentrations of inorganic nitrogen (NO_3/NO_2-N and NH_3-N) in the lower Roanoke watershed increased somewhat between the two sampling areas; NH_3-N values in the Cashie River were negatively correlated with river flow ($n=9$, $r=-0.61$, $P=0.082$).

NO_3/NO_2-N showed a similar trend ($n=8$, $r=-0.87$, $P=0.005$) with river flow at Pollock's Ferry. The inorganic nitrogen fraction is the form most readily available for plant growth. At Pollock's Ferry, the ammonia nitrogen (NH_3-N) concentration averaged 0.06 mg/L and the nitrate/nitrite (NO_3/NO_2-N) concentration averaged 0.15 mg/L (Table 4). Downstream, total inorganic nitrogen (NH_3N and NO_3/NO_2N combined) increased by almost 50 percent at Stations 6 and 7, averaging about 0.28 mg/L. Total inorganic nitrogen increased to 0.33 mg/L at the Highway 45 bridge. The Cashie River had lowest inorganic nitrogen concentrations of the Roanoke delta stations, averaging 0.08 mg/L NH_3-N and 0.15 mg/L NO_3/NO_2-N. Only trace quantities of NO_2-N, averaging 0.006 mg/L, were found at all locations during the study.

Comparisons of duplicate NO_2-N samples analyzed by the ECU lab and by Weyerhaeuser resulted in similar values (Table 5). Given the potential for some slight bias due to blanks, instruments, and the potential for some slight variance, there appears to be virtually no difference in these results.

Concentrations of NO_3/NO_2-N typically are much lower in the Roanoke than in the neighboring Neuse River. Winter-spring NO_3/NO_2-N values average about 0.80 mg/L in the Neuse (Stanley 1983, Paerl 1987), compared to a 1988 average of 0.18 mg/L in the lower Roanoke, Middle, and Cashie Rivers. In 1985, during ongoing larval striped bass studies, the average Roanoke NO_3/NO_2-N concentrations at each station between April and June ranged from 0.16 to 0.23 mg/L (Rulifson et al. 1986). However, the Roanoke NO_3/NO_2-N average is more than double the 0.07 mg/L reported by Simmons and Heath (1979) for streams draining small rural and forested watersheds in the coastal plain of North Carolina.

Total organic and ammonia nitrogen, known as total Kjeldahl nitrogen (TKN), also increased in the Roanoke with distance downstream. At Pollock's Ferry, waters had an average TKN of 0.33 mg/L, of which about 0.27 mg/L was organic nitrogen. Higher TKN values were found downstream at Stations 6 and 7, averaging about 0.44 mg/L (Table 4); organic nitrogen concentration rose slightly to 0.36 mg/L. For the Roanoke mainstem, TKN was consistently highest below Weyerhaeuser at Station 10 (Figure 14) with an average of 0.62 mg/L; organic nitrogen was 0.47 mg/L. The TKN in the Plymouth Mill effluent averages 7 mg/L (Herrmann and Backman 1979, Herrman 1983). The Cashie River exhibited a similar organic nitrogen concentration of 0.46 mg/L.

Total phosphate (TPO_4-P) concentrations did not vary significantly among stations but exhibited a tendency to increase with distance downstream later in the season (Figure 15). Pollock's Ferry was lowest with an average of 0.15 mg/L, while the lower Roanoke, Middle, and Cashie Rivers ranged from 0.16 to 0.18 mg/L (Table 4). Soluble reactive phosphorus or orthophosphorus increased from an average of 0.05 mg/L at Pollock's Ferry to 0.08 mg/L in the Middle River and 0.09 mg/L at the Highway 45 bridge (Table 4; Figure 16). Total phosphate at the Middle River station was negatively correlated with river flow ($n=7$, $r=-0.88$, $P=0.010$).

Phosphorus concentrations were in sufficient supply to support good algae growth. According to Hobbie and Smith (1975), algae growth is nitrogen limited if the soluble N/P ratio is less than 10. The N/P ratios for the Cashie, Middle, and all Roanoke stations were less than 5, indicating that these waters are nitrogen-limited.

Algal biomass, represented by chlorophyll *a* measurements, was very low at Pollock's Ferry with concentrations usually less than 2 µg/L (Appendix Table A-5). These values are lower than those reported for the lower river in 1984 (4 to µg/L) and 1985 (5 to 15 µg/L) (Rulifson et al. 1986). In 1986, chlorophyll *a* concentrations in the delta averaged around 10 µg/L, ranging from <1.0 to 34.0 µg/L (Rulifson et al. 1988). Chlorophyll levels were not determined for the Plymouth area samples in 1988.

Sulfate

On average, sulfate (SO_4^{2-}) concentrations were similar throughout the study area, averaging about 10 mg/L, except for the Cashie River, which averaged lower, 6.7 mg/L (Table 4). Simmons and Heath (1979) reported low sulfate levels averaging 4.0 mg/L for a stream draining Turner Swamp, a tributary to Swift Creek (Neuse River). The Roanoke River below Weyerhaeuser at Station 10 exhibited consistently higher values compared to upstream station from 26 April through the remainder of the study (Figure 17). These sulfate concentrations, except those for the Cashie River, are similar to those reported for the Neuse River (Harned 1980) and for streams draining small rural and forested watershed in the coastal plain (Simmons and Heath 1979).

Metals

All heavy metals (total) concentrations in the Roanoke, Middle, and Cashie Rivers were below the North Carolina criteria for freshwaters except for iron (Appendix Tables A-1 and A-5). The North Carolina criteria for cadmium and lead in freshwaters are 2.0 µg/L and 25 µg/L, respectively, below the minimum detection limit of our analytical methods. Chromium and copper concentrations in the water samples were also below detection limits. Toxicity of heavy metals to aquatic life will often vary with the stream's pH, alkalinity, redox, and concentrations of dissolved oxygen and organic carbon.

Iron concentrations in the Roanoke increased downstream. Pollock's Ferry values averaged 0.623 mg/L, below the 1986 EPA criteria of 1.0 mg/L for protection of freshwater aquatic life (USEPA 1986). However, iron concentrations doubled downstream where averages ranged from 1.071 mg/L at Station 10 at the Highway 45 bridge to 1.510 mg/L in the Cashie River. No seasonal changes were evident (Figure 18).

Manganese concentrations also increased downstream, averaging 0.050 mg/L at Pollock's Ferry, 0.081 mg/L above Weyerhaeuser (Station 7), and 0.085 at the Highway 45 bridge (Table 4). The highest average, 0.119 mg/L, was found in the Cashie River. A seasonal increase in manganese was apparent in the Cashie River, but the cause was undetermined (Figure 19).

Iron and manganese can complex to form ferro-manganese compounds and are often bound in organic and humic compounds that are non-toxic. However, under anoxic conditions at low pH and redox, ferrous and mangous ions can be released from the sediments (Wetzel 1975).

Sodium exhibited no change from late April through early June, averaging about 9 mg/L (Table 4). Station 10 below Weyerhaeuser and Plymouth consistently was highest in sodium concentrations (Figure 20), averaging 14 mg/L. Pulpmill effluents contain both $NaSO_4$ and NaCl.

Zinc concentrations were highest in Middle and Cashie Rivers, averaging 0.034 mg/L and 0.028 mg/L, respectively, and lower at the other sites (Table 4, Figure 21). Several relatively high values were observed in the Middle and Cashie Rivers on 10 May, 25 May, and 31 May (Figure 21), the origin of which remained unknown. Within the Roanoke River, an increase in zinc values was observed in mid-May, followed by a general decline (Figure 21).

Arsenic and selenium analysis on samples from mid-April to mid-May showed no detectable concentrations (Appendix Table A-5). Analysis for these elements was discontinued on the sixth week of the study due to budgetary constraints.

Several metals exhibited temporal variation in concentration during the study. Total aluminum (Al) concentrations increased in May, most noticeably in the Middle and Cashie Rivers where concentrations peaked at 2.7 mg/L and 2.0 mg/L, respectively (Figure 22). Iron, manganese, barium (Figure 23), TSS and VSS concentrations followed the temporal trend in aluminum concentrations. The Roanoke larval striped bass study conducted in 1985 found similarly high total aluminum concentrations (Rulifson et al. 1986).

Table 6 compares the total metals concentrations from our study with 1988 soluble metals data collected at Roanoke Rapids by the USGS (Ragland et al. 1989). Comparisons were possible only for 10 of the approximately 25 metals, since most of the metals were present in concentrations below the detection limits. The soluble concentrations of barium, calcium, magnesium, potassium, sodium, and strontium at Roanoke Rapids were essentially the same as the total metals concentrations at the other five Roanoke stations. This indicates that these metals are not associated with suspended solids. However, there were marked differences between the soluble and total concentrations of aluminum, iron, manganese, and zinc where the soluble fraction was only five to 10 percent of the totals. This situation indicates that these metals are predominately solids-associated or in a colloidal form.

A comparison of dissolved monomeric aluminum (DMAl) determined electrometrically to total aluminum determined by ICP indicated that DMAl was roughly two percent of the total aluminum present in Pollock's Ferry samples (Table 5). As applied to this study, the DMAl procedure had several problems associated with it that were later discovered and corrected. The principal limitation to the method as applied herein is the lack of precision. Because of this, it is not possible to draw conclusions concerning the discrimination among sample values. The values reported in Table 5 were presented merely to indicate the general order of magnitude of DMAl in comparison to total aluminum.

Diel Water Quality Changes at Pollock's Ferry

During four of the five diel discrete water quality samplings at Pollock's Ferry, the changes in river discharge were minimal – usually less than 5,000 cfs in a 24-hour period. However, the diel sampling on 31 May-1 June occurred over a period when instream flow increased about 8,000 cfs within a 12-hour period. On the morning of 31 May, river discharge at the Roanoke Rapids gage, about 30 miles upstream of Pollock's Ferry, was about 6,300 cfs, increasing to about 14,200 cfs in the afternoon. On 1 June instream flow was stable at 9,500 cfs.

Although instream flow was not measured at the Pollock's Ferry station, surface velocity readings (mid-channel) and river stage were recorded (Appendix Table A-5). Dye studies to determine time of travel for water mass downstream were conducted by Fish (1959) to determine rate of travel between Roanoke Rapids and Scotland Neck. Results showed that dye moved between the two sites in 17 hours at a river discharge of 5,000 cfs, and 14.4 hours at 10,000 cfs. Based on this information, river flows on 31 May would have been stable at Pollock's Ferry during the day, but would have continuously increased during the evening and into the morning of 1 June.

Since there was no instream flow data at Pollock's Ferry, river stage (height) was used as an indicator of river discharge. On 31 May at 0600 hours river stage was 7.5 feet, and by 1400 hours the stage reached 7.6 feet. Thereafter, river stage increased continuously until 0600 hours on 1 June when it crested at 13.4 feet (Appendix Table A-3).

During the 24-hour sampling period, neither pH (average of 7.4) nor dissolved oxygen (average of 7.6 mg/L) measured *in situ* showed any change related to river stage (Figure 24). However, water temperature decreased from 26°C to 23°C with the increase in river stage (Figure 25). Temperature was negatively correlated with flow (n=7, r=-0.82, P=0.020).

Many of the particulate-related (sediment, detritus) parameters increased with flow. Total organic carbon (TOC) markedly increased with river stage from an average of 3 mg/L before the rise to 5.2 mg/L (average) during the rise (Figure 26). Increases in turbidity (n=6, r=0.78, P=0.065) and VSS (n=6, r=0.76, P=0.080) also correlated significantly with the rise in river stage. Total suspended solids (TSS) averaged 13.5 mg/L before the rise, and 21.5 mg/L (average) during the increase in river stage (Figure 27).

Of the various nitrogen species, NH_3-N and NO_2-N concentrations were correlated with the changes in river stage (NH_3-N: n=6, r=0.86, P=0.026; NO_2-N: n=6, r=-0.85, P=0.033). Ammonia-nitrogen averaged 0.05 mg/L during the stable stage period and 0.07 mg/L during the increase; NO_2-N averaged 0.011 before, and 0.009 mg/L after the increase. Total Kjeldahl nitrogen concentrations also increased with river stage, averaging 0.30 mg/L before the rise versus 0.50 mg/L after (Figure 28). The TKN, TSS, and TOC concentrations in the 0600 1 June sample were down from the values in the 2200 hours sample despite the higher river stage at 0600 hours.

Nitrate/nitrite-nitrogen (NO_3/NO_2-N) was fairly stable, averaging 0.12 mg/L despite the changes in river stage (Figure 29). Total phosphate (TPO_4-P) was positively correlated with river stage (n=5, r=0.92, P=0.027); however, SO_4 was negatively correlated (n=6, r=-0.91, P=0.012).

Of the metals, the concentrations of several were positively correlated with river stage: aluminum (n=6, r=0.85, P=0.034), iron (n=6, r=0.73, P=0.099), and manganese (n=6, r=0.94, P=0.010) (Figures 30, 31).

Discussion

Water quality from the two sampling areas was influenced to some degree by different background (upstream) conditions. Water quality at Pollock's Ferry was largely influenced by releases from upstream reservoirs. Reservoirs are usually considered to be nutrient and sediment "traps" (Hannon 1979, Ridley and Steel 1975). The 31 May-1 June diel sampling, when reservoir releases increased from 6,300 cfs to 14,200 cfs, provided some insights on the water quality changes associated with hydroelectric peaking activity. Water temperatures dropped as instream flow increased due to release of cooler reservoir waters into the shallower and warmer river channel. Increases in solids-related water quality parameters (e.g., TSS, TOC, TPO_4-P, Al, Fe, Mn) with river flow undoubtedly reflected the resuspension (scour) of sediments and detritus in the river channel rather than material trapped in the reservoir. For the nitrogen species, TKN and NH_3-N increased with reservoir release, probably due more to discharge of water from below the epilimnion area of the reservoir rather than effects from scouring of the river channel. Nitrate-nitrite nitrogen concentrations downstream were unaffected by the rapid increase in instream flow, while NO_2-N concentrations decreased.

Water quality from the Plymouth area stations was modified by drainage from the extensive riverine swamps bordering the lower river. Swamp drainage has high color, and soluble organic carbon (SOC) content but has low DO, BOD, and inorganic nutrient (N,P) levels (Winner and Simmons 1977; Pardue et al. 1975; Mitch and Gosselink 1986) .

In the Roanoke delta area, the water quality of Middle River (Station 6) and the Roanoke River near the Plymouth mill (Station 7) were the most similar; these stations were only one mile apart. Most suspended solids-related water quality parameters were slightly higher for Middle River, a distributary that takes its river flow off the left bank of the Roanoke. Inorganic sediments and detritus from shoreline areas may account for the slightly higher levels of particulate materials in these samples.

Water quality of the Cashie River (Station 8) and Roanoke River near Highway 45 bridge (Station 10) differed from that at Stations 6 and 7. Although about 90-95 percent of the Cashie instream flow at Station 8 comes from the Roanoke River via the Thoroughfare, local storm events in the upper Cashie during May of 1988 increased flow greatly. The particulate-related water quality features in the Cashie samples (turbidity, TSS/VSS, TOC) were the highest of the four delta water quality stations. However, alkalinity, pH, NO_3/NO_2-N and SO_4 averaged less in the Cashie than at the other delta stations. In this regard, Cashie River water quality is more like a coastal plain blackwater stream than the alluvial Roanoke River (Whorton et al. 1982).

In the Roanoke River just upstream of the Highway 45 bridge (Station 10), water quality was affected by swamp drainage, effluents from the Plymouth Mill, and the Plymouth Municipal Wastewater Plant. Levels of color, most N and P species, sulfate, calcium, and sodium were the highest of all stations. The SO_4, Ca, and Na are from chemicals in the wood pulping/bleaching processes, while the increased levels of N and P originate from the pulpwood, domestic wastes, and from nutrient additions to enhance biological treatment of the mill waste. Color compounds are released from the wood in the pulping and bleaching processes; these refractory compounds are not removed during waste treatment.

Results of the correlation analysis for selected water quality parameters are depicted in Figures 32 through 37. The differing influences of the upstream reservoirs at Pollock's Ferry and swamp drainage in the Plymouth area caused shifts between the two data sets in the relationship of flow-independent water quality variables with the dependent water quality variables.

River flow and alkalinity were positively correlated with pH measured in the field (Figure 32) at Pollock's Ferry and at the Middle River and Highway 45 stations. However, color and SOC (indicators of swamp drainage) were negatively correlated with pH values for most of the stations.

For both study sites, river flow was consistently negatively correlated with levels of dissolved oxygen (Figure 33). This implies that at higher spring flows, the riverine swamps are flooded, which brings low DO into the main channel of the river. Both BOD and SOC are causal factors of low DO levels; both were negatively correlated with dissolved oxygen for stations in the Roanoke delta area.

For the inorganic nitrogen species, the concentration of NH_3N at both the Pollock's Ferry and Roanoke delta area stations was positively correlated with color and soluble carbon (SOC) (Figure 34). These correlations may indicate that the ammonia input is of swamp origin. On the other hand, NO_3/NO_2-N was positively correlated with color only for the Pollock's Ferry data set, where there is little swamp drainage input (Figure 35). Ammonia-nitrogen and nitrate/nitrite-nitrogen were positively correlated except at the Middle River station.

Orthophosphorus OPO_4-P) was negatively correlated with NH_3-N at all stations except for Highway 45; on the other hand, orthophosphorus was positively correlated with nitrate/nitrite-nitrogen at all stations except Pollock's Ferry.

Turbidity was positively correlated with instream flow and TSS at all stations but negatively correlated with color (Figure 36). The strong correlation with TSS was expected since turbidity is an optical measure of suspended matter.

For both study areas, aluminum (total element) concentration was positively correlated with pH, river flow, and TSS except for the Highway 45 station (Figure 37). The correlation with TSS is not surprising since aluminum is abundant in coastal soils of North Carolina. However, the positive relation with pH was unexpected. Acidic pH conditions should leach more aluminum into run-off waters. The consistent negative correlation of pH with color at stations in both areas suggests that the primary source of aluminum is not from swamp drainage.

In general, results of our study were similar to a water quality study conducted in the spring of 1985 (Rulifson et al. 1986). Flows in 1985 were much lower than normal due to an extremely dry spring, ranging between 2,000 and 6,000 cfs for much of the period.

One difference between the two studies was levels of total aluminum. In 1985, highest aluminum values were recorded for the Roanoke River near Weldon, North Carolina (maximum of 2,400 µg/L); values decreased with distance downstream. In the present study, total aluminum values tended to be higher in the delta area of the study (Table 4, Table 5).

Also in 1985, several heavy metals were detected in concentrations higher than observed in 1988. These elements included mercury (0.2-0.8 µg/L), lead (200 µg/L), and copper (30 µg/L). Zinc was found at higher concentrations in the Middle and Cashie Rivers in 1988 (Figure 21) than the 20 to 50 µg/L reported in 1985 (Rulifson et al. 1986).

Results obtained by the present study reflect data collection under conditions of moderate, stable river flows. Historical flow records dating prior to the initial flood control efforts of the early 1950s indicate that river flow was similar to that observed in the spring of 1988; i.e., of similar rate and fluctuation (Manooch and Rulifson 1989). Post-construction flow records (after 1955) depict extensive on-demand hydropower production during springtime months, resulting in sudden flow changes ranging from 2,000 to 20,000 cfs within hours.

Although no intensive water quality data base exists prior to the Rulifson et al. (1986) study, we believe that the information gathered in 1988 provides an initial "optimal flow" data base for a number of water quality parameters. Additional studies should be conducted in an effort to further identify how water quality changes as a function of on-demand hydropower production.

During summer and fall months, operation of these hydropower facilities typically results in extremely low flow rates just above the minimum guidelines (1,000 to 2,000 cfs).

Increasing water use demands by industry, municipalities, and agriculture during summer months places additional burden on the watershed to dilute wastes from outfalls. We recommend that future water quality studies also include summer months so that water quality during minimal flow periods can be quantified.

Summary and Conclusions

1. Hydroelectric generating activity by Roanoke Rapids Dam (River Mile 137) resulted in river flows ranging between 1,100 and 18,000 cfs in January and February of 1988; however, during striped bass spawning activity in April and May, peaking activity was apparent though moderate for the two-month period. Virginia Power Company attempted to comply with water release guidelines suggested by the Roanoke River Water Flow Committee (later formally adopted for a four-year trial period). In early June, normal operations resumed causing river flows to fluctuate between about 2,000 and 15,000 cfs.

2. Rainfall events influenced water release schedules from the reservoirs and also affected water quality downstream. Rainfall below Kerr Reservoir was two inches below normal in March, about 1.5 inches above normal in April, and about average in May.

3. Water quality of Middle River, Cashie River, and the lower Roanoke River at Pollock's Ferry (RM 105) and near Plymouth, was generally good relative to North Carolina water quality standards during the 1988 striped bass spawning season (mid-April to mid-June).

4. For most of the striped bass spawning season, there was no significant diel variation in water quality at Pollock's Ferry, perhaps due to the moderation of hydropower peaking activity during the study.

5. There was no significant vertical variability in the water column in the Roanoke River mainstem near Plymouth, indicating that the water column was not stratified during the study.

6. The Plymouth area (Roanoke delta) stations had higher average values for many of the dissolved and particulate constituents: turbidity, total suspended solids (TSS), and volatile suspended solids (VSS); total organic carbon (TOC), and suspended organic carbon (SOC); most forms of nitrogen and phosphorus; and several metals including aluminum, iron, and sodium.

7. The downstream increase in these constituents reflect both swamp drainage, which is higher in color and carbon, and waste discharges, which are high in nutrients and certain metals. Pulp mill effluents are also highly colored.

8. Levels of dissolved oxygen remained above 5 mg/L at Pollock's Ferry, but dropped below 5 mg/L in the Plymouth area in late April and early May.

9. Conductivity (an indicator of dissolved substances) of Roanoke River waters at the Highway 45 bridge below the Weyerhaeuser plant and the Plymouth wastewater treatment plant averaged 130 µmhos compared to 105 µmhos at all other Roanoke stations. The Cashie station also had a relatively high conductivity, averaging 131 umhos.

10. At Pollock's Ferry for the nine sampling dates, water temperature and pH were positively correlated with river stage; conductivity and nitrate/nitrite were negatively correlated with river stage. For diel sampling period of 31 May - 1 June, reservoir releases increased 8,000 cfs within 12 hours and many water quality features exhibited significant correlations with river stage (flow surrogate). Turbidity, VSS, NH_3-N, , TPO_4-P, Al, Fe, and Mn showed positive correlations with river stage; NO_2-N and sulfate were negatively correlated.

11. At Plymouth area stations, NH_3-N for the Cashie station and TPO_4-P for the Middle River station were negatively correlated with nominal river flow.

12. We conclude that water quality at Pollock's Ferry was largely influenced by water releases from Roanoke Rapids Reservoir. Water quality in the Roanoke delta was modified by drainage from the extensive riverine swamps bordering the lower river with the exception of the Highway 45 station downstream of Plymouth, where water quality also was influenced by Weyerhaeuser mill effluent.

13. We recommend that studies of this nature be continued and extended to summer months so that water quality during minimal flow periods can be quantified.

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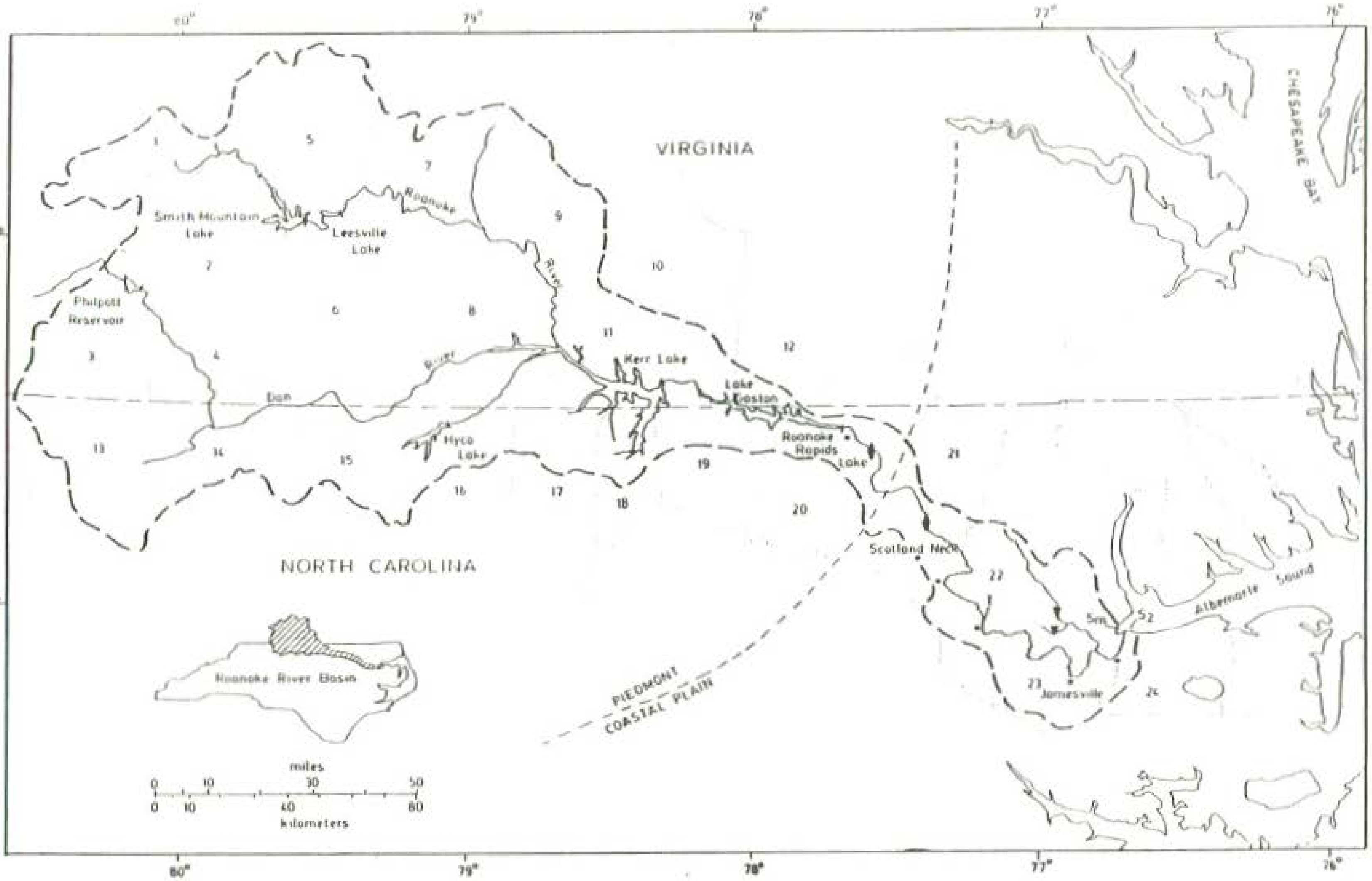


Figure 1. Drainage area of the Roanoke River Basin (from Manooch and Rulifson 1989). Dashed line indicates approximate location of the Fall Line; diamonds = locations of USGS water quality and gaging stations; inverted triangle = USGS water quality station; T = upstream limit of tidal influence; S2 = mean upstream intrusion limit of saltwater front (200 mg/L chloride): Sm = maximum upstream intrusion of saltwater front.

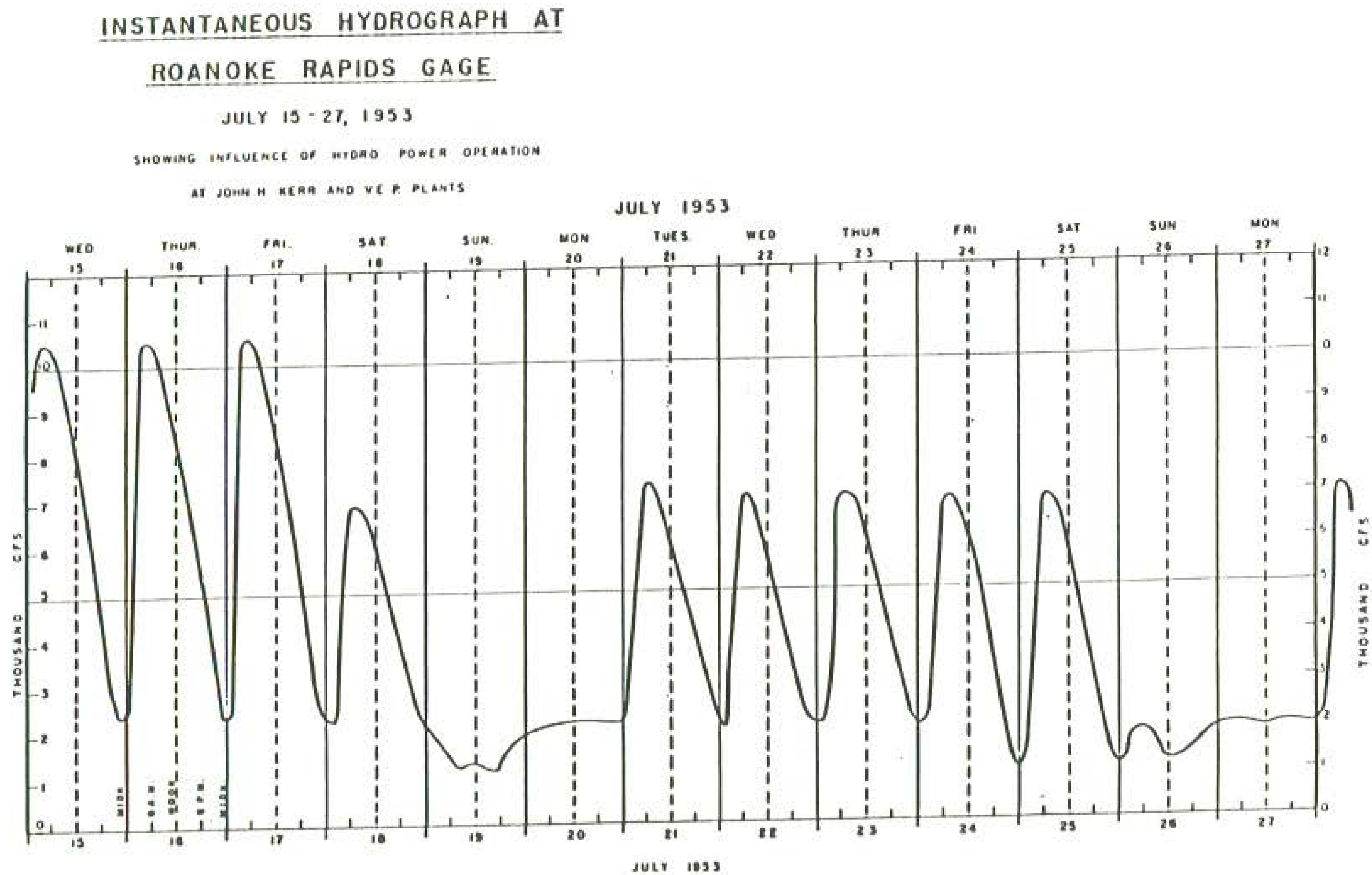


Figure 2. The influence of hydropower operation at John H. Kerr (RM 178.7) and Virginia Power Co. (RM 145.7) plants on the flow rate of the Roanoke River (cfs) recorded at Roanoke Rapids gage (RM 133.6) by USGS for the period July 15-27, 1953 (from Velz 1954).

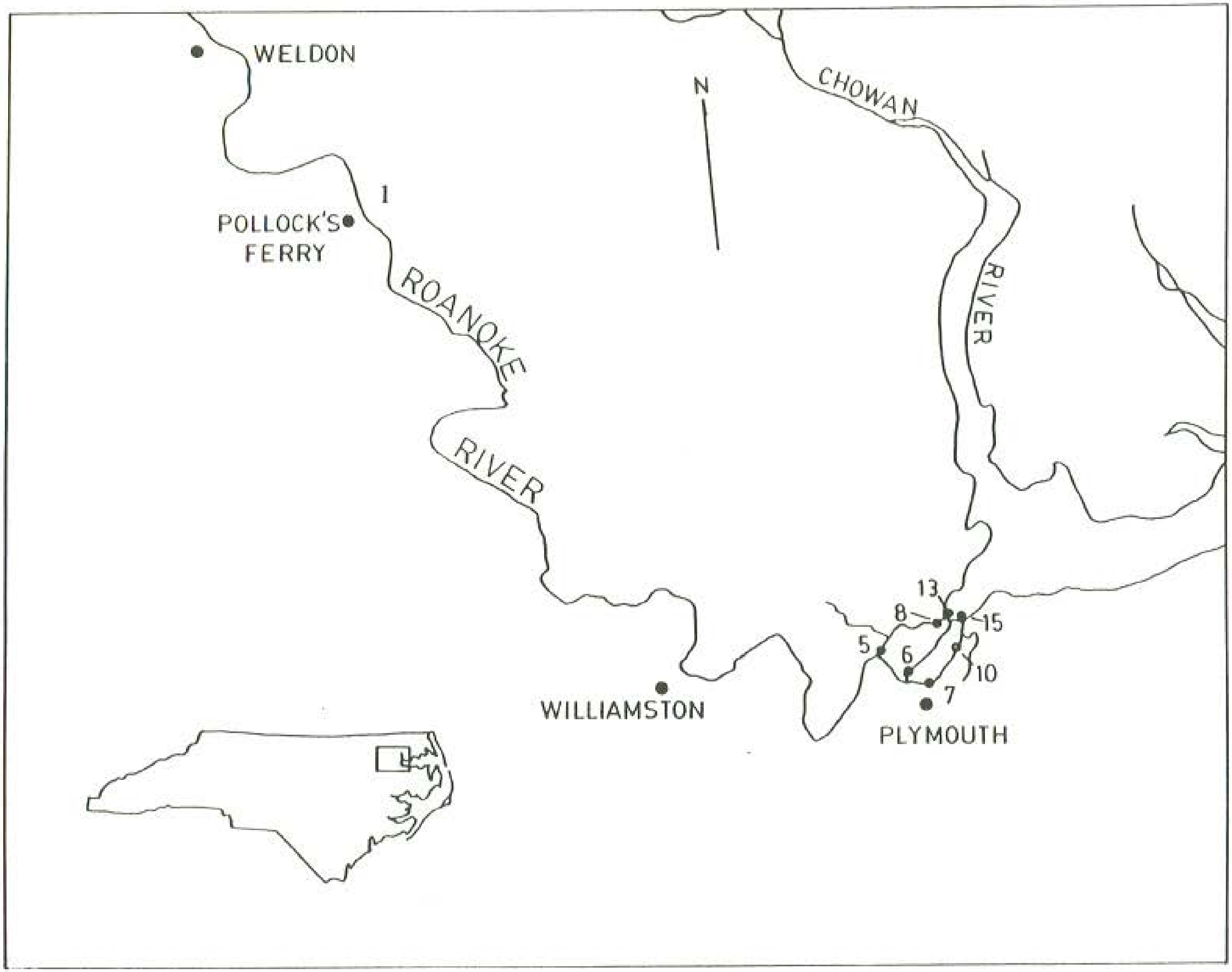


Figure 3. Lower Roanoke River and western Albemarle Sound depicting the sampling locations for water quality (this study).

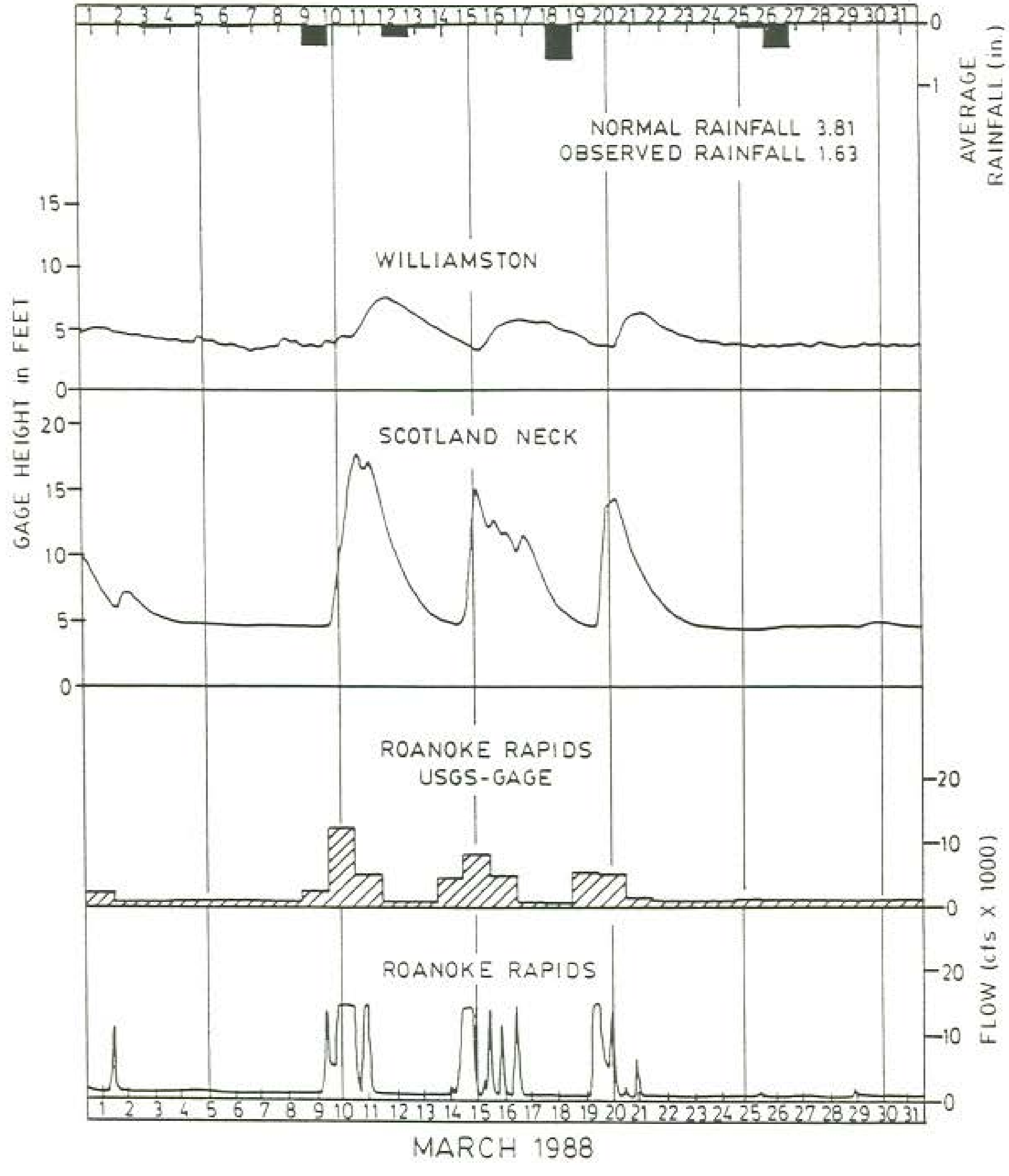


Figure 4. Instream flow of the lower Roanoke River for March 1988 at Roanoke Rapids Dam, USGS gages at Roanoke Rapids, Scotland Neck, and Williamston, North Carolina, and lower basin precipitation.

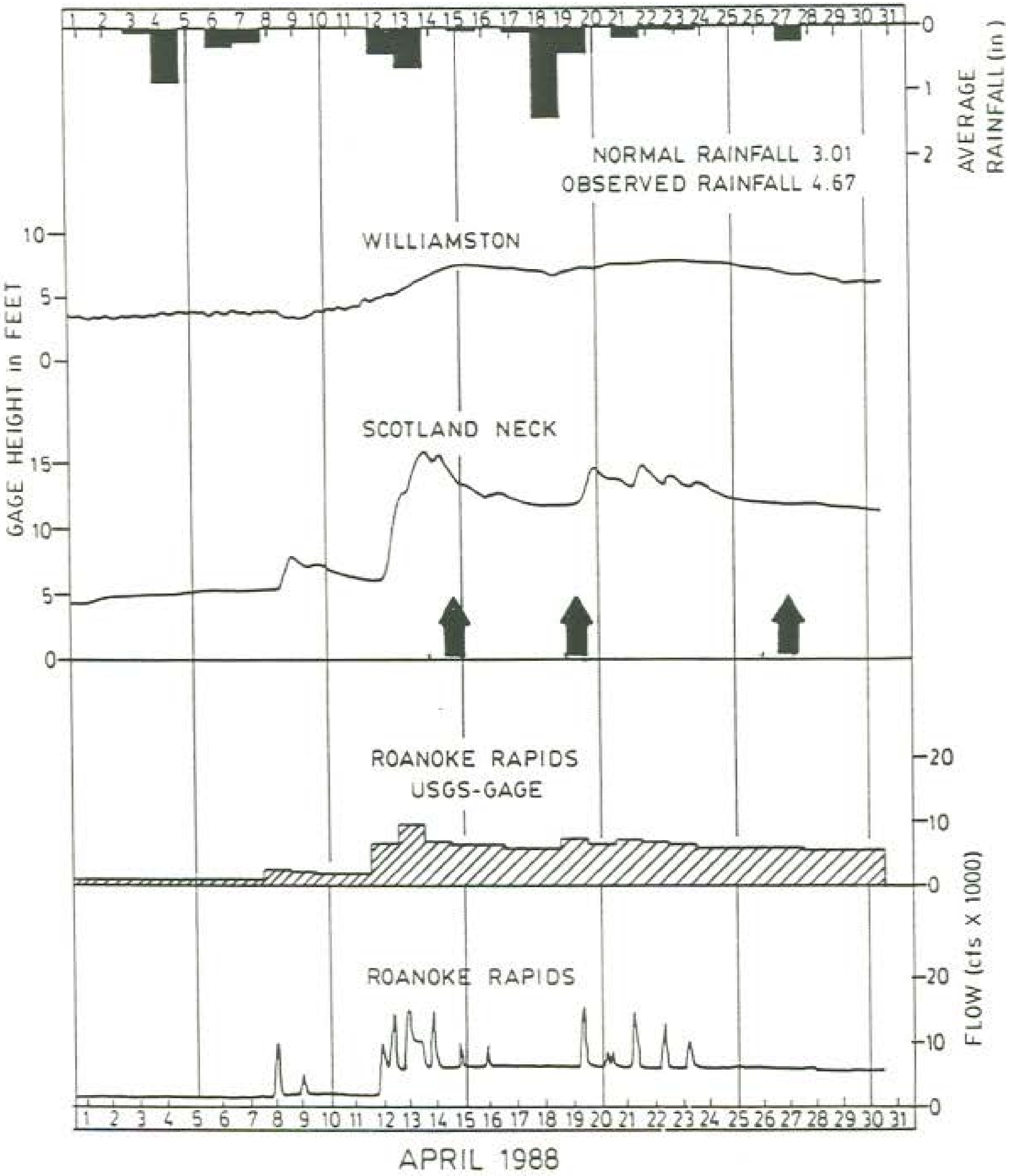


Figure 5. Instream flow of the lower Roanoke River for April 1988 at Roanoke Rapids Dam, USGS gages at Roanoke Rapids, Scotland Neck, and Williamston, North Carolina, and lower basin precipitation (Arrows indicate water sample dates at Pollock's Ferry, near Scotland Neck).

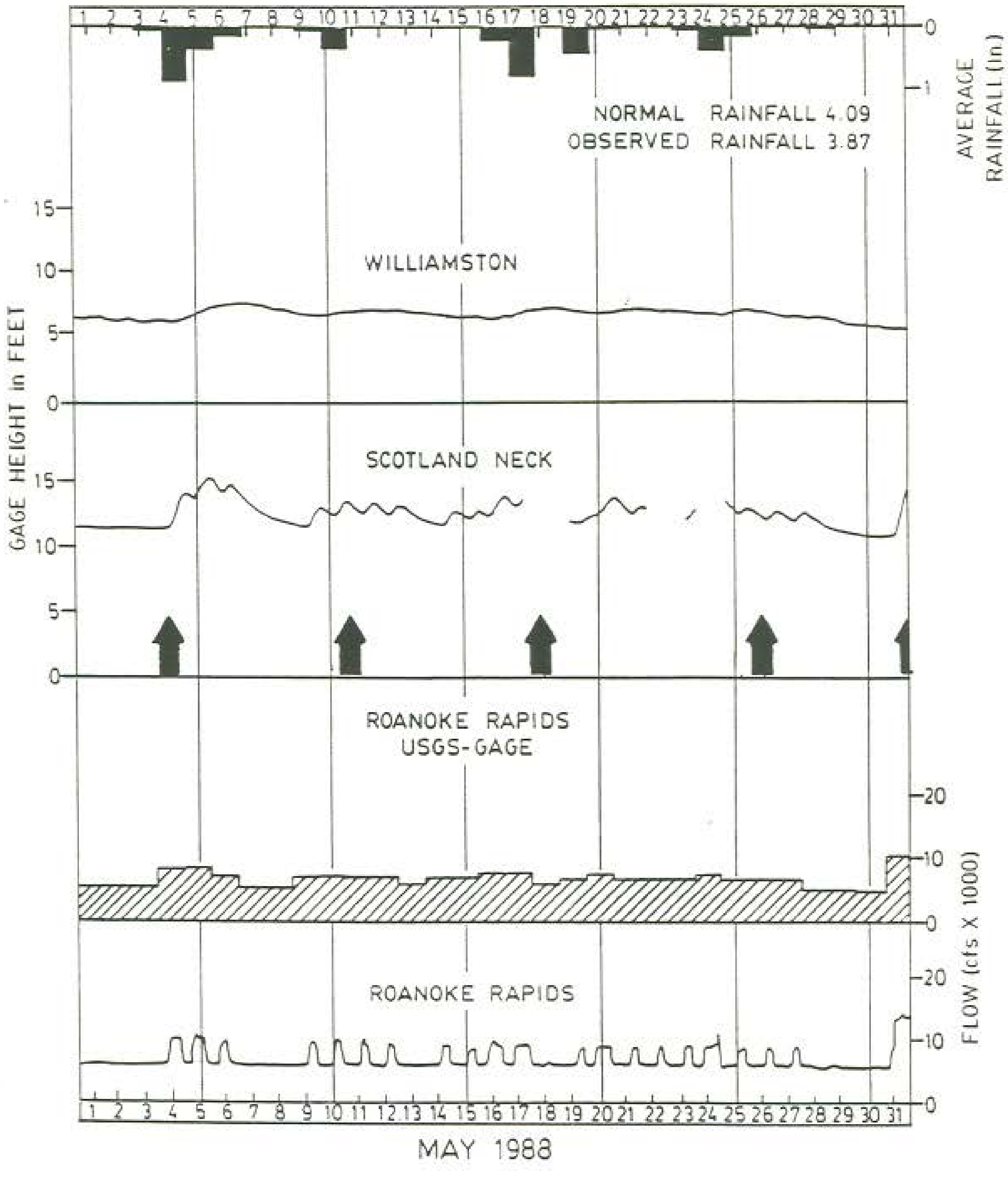


Figure 6. Instream flow of the lower Roanoke River for May 1988 at Roanoke Rapids Dam, USGS gages at Roanoke Rapids, Scotland Neck, and Williamston, North Carolina, and lower basin precipitation (Arrows indicate water sample dates at Pollock's Ferry, near Scotland Neck).

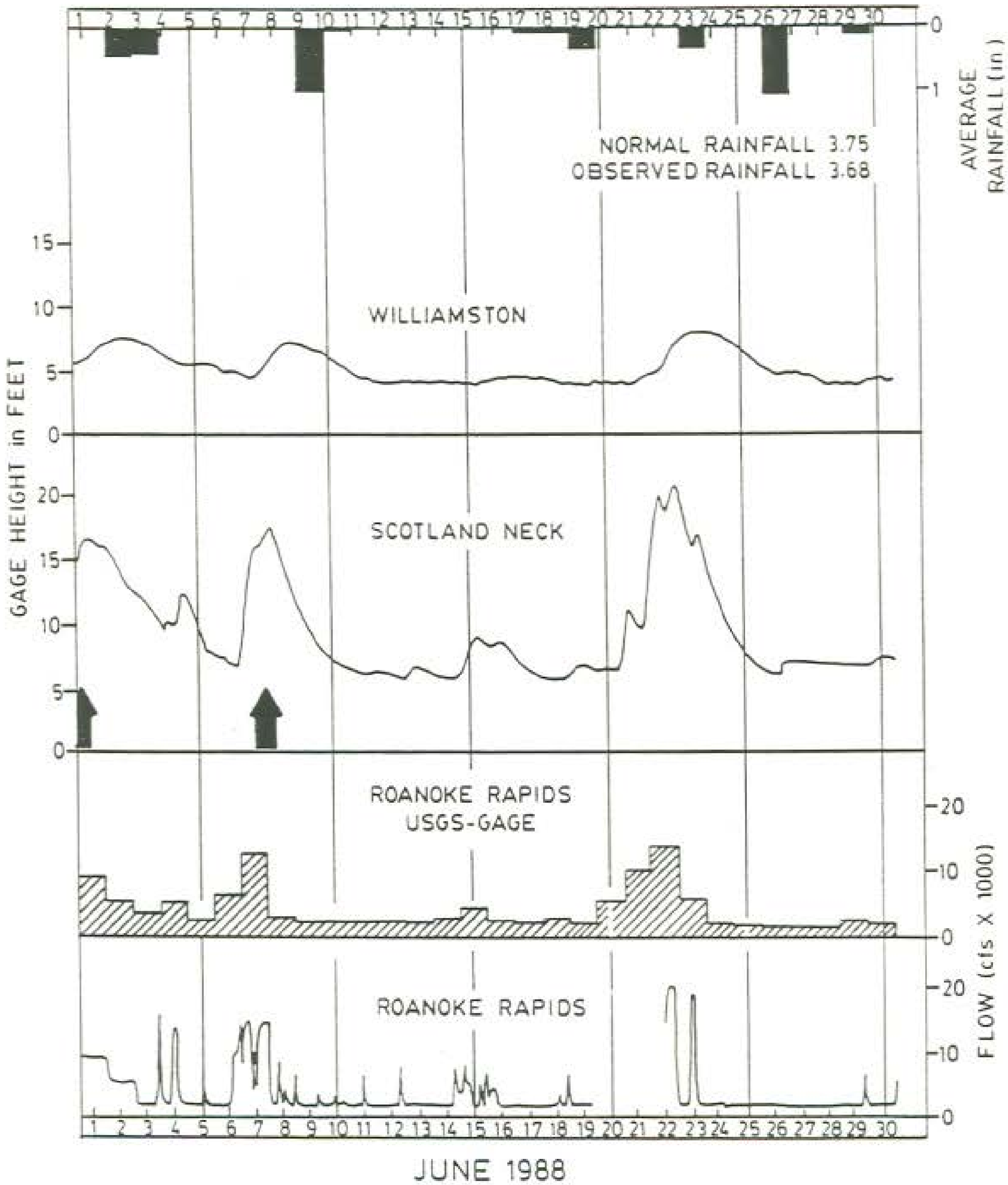
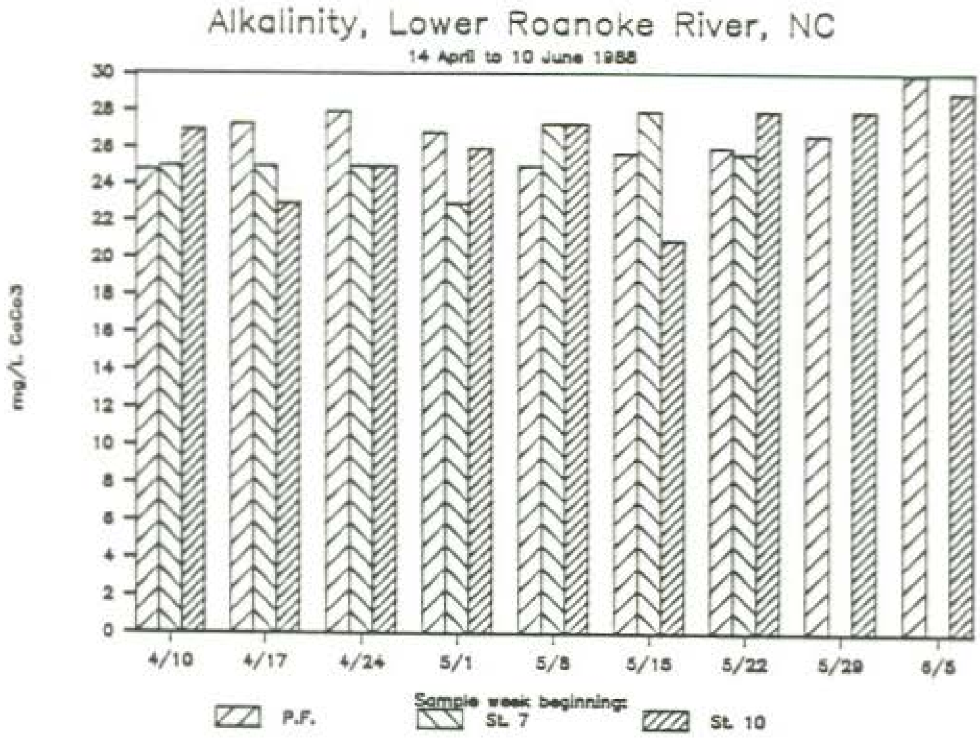


Figure 7. Instream flow of the lower Roanoke River for June 1988 at Roanoke Rapids Dam, USGS gages at Roanoke Rapids, Scotland Neck, and Williamston, North Carolina, and lower basin precipitation (Arrows indicate water sample dates at Pollock's Ferry, near Scotland Neck).



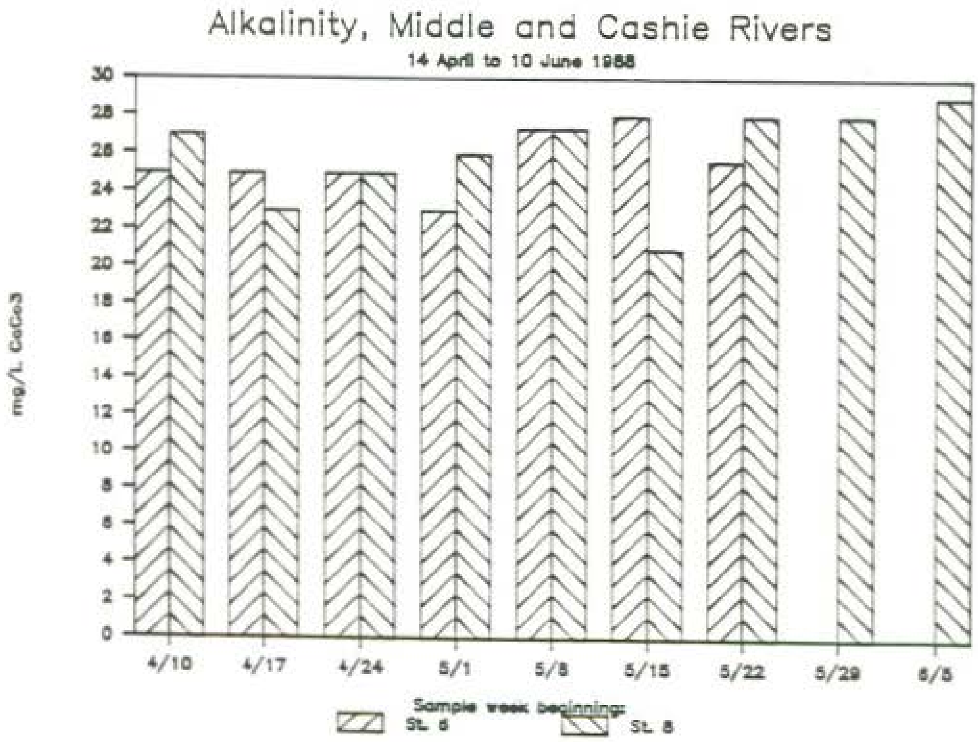
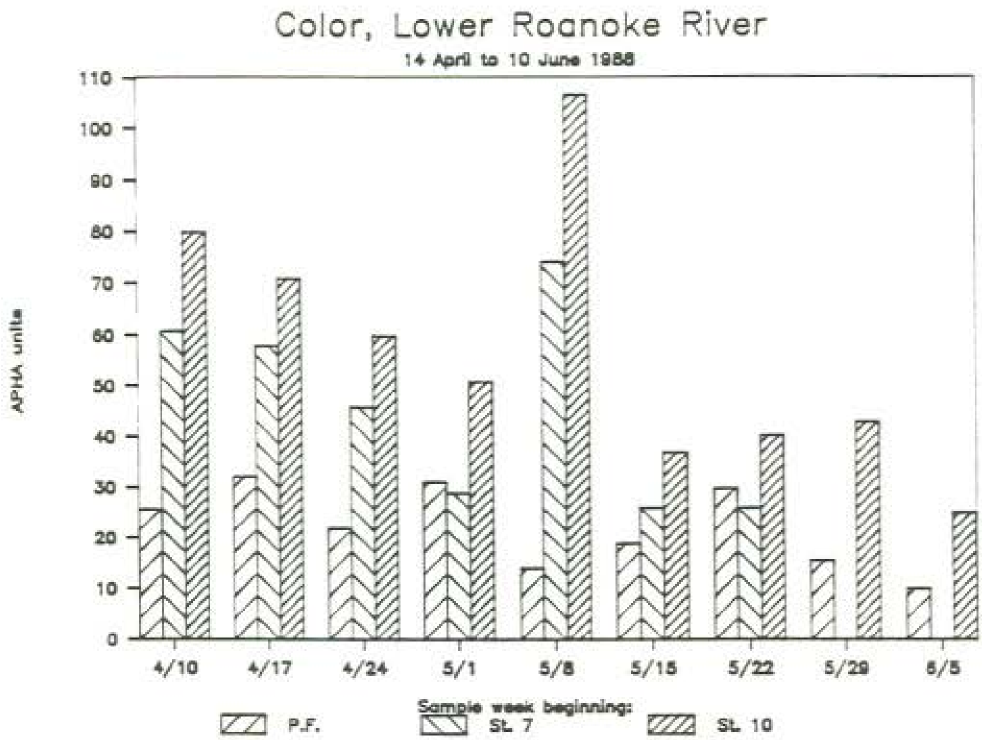


Figure 8. Alkalinity of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



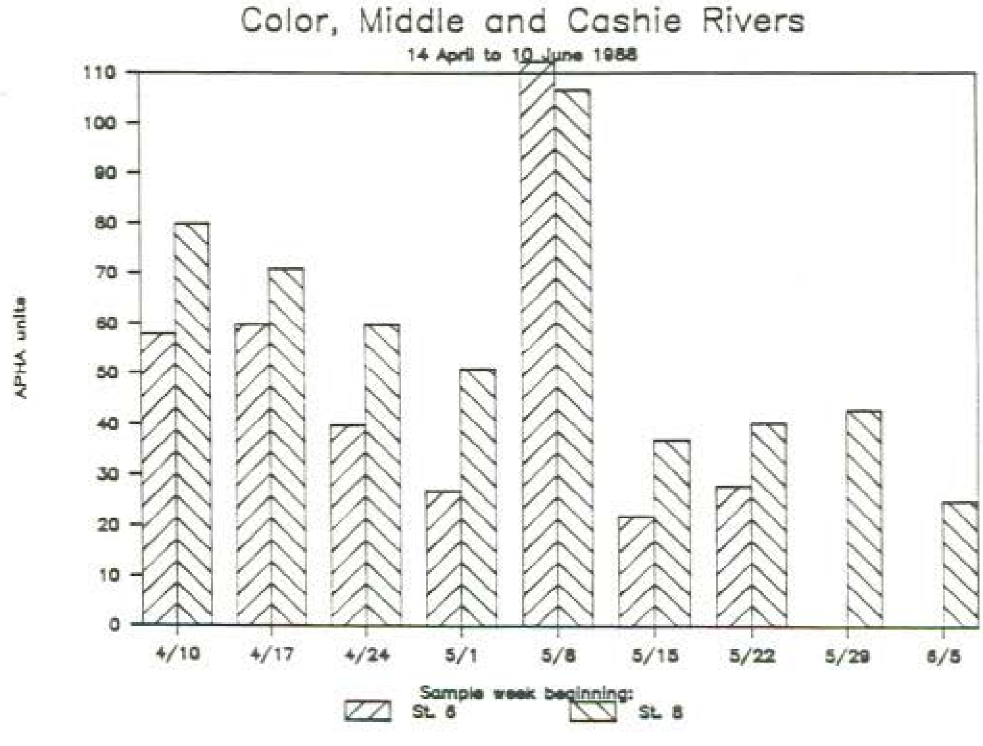
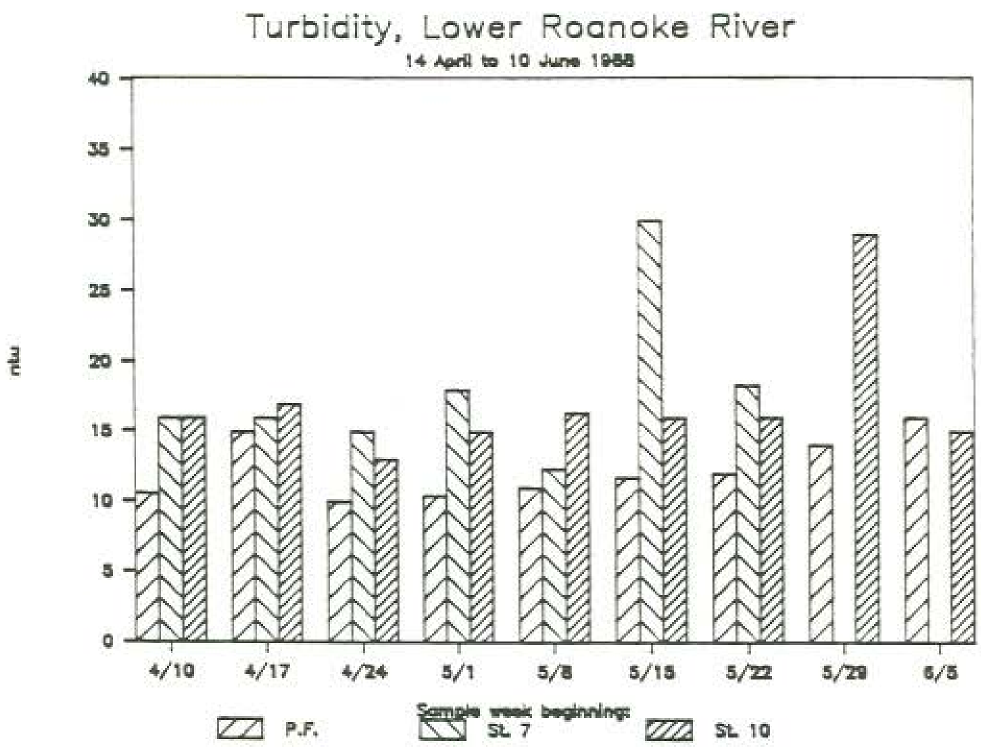


Figure 9. Color of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



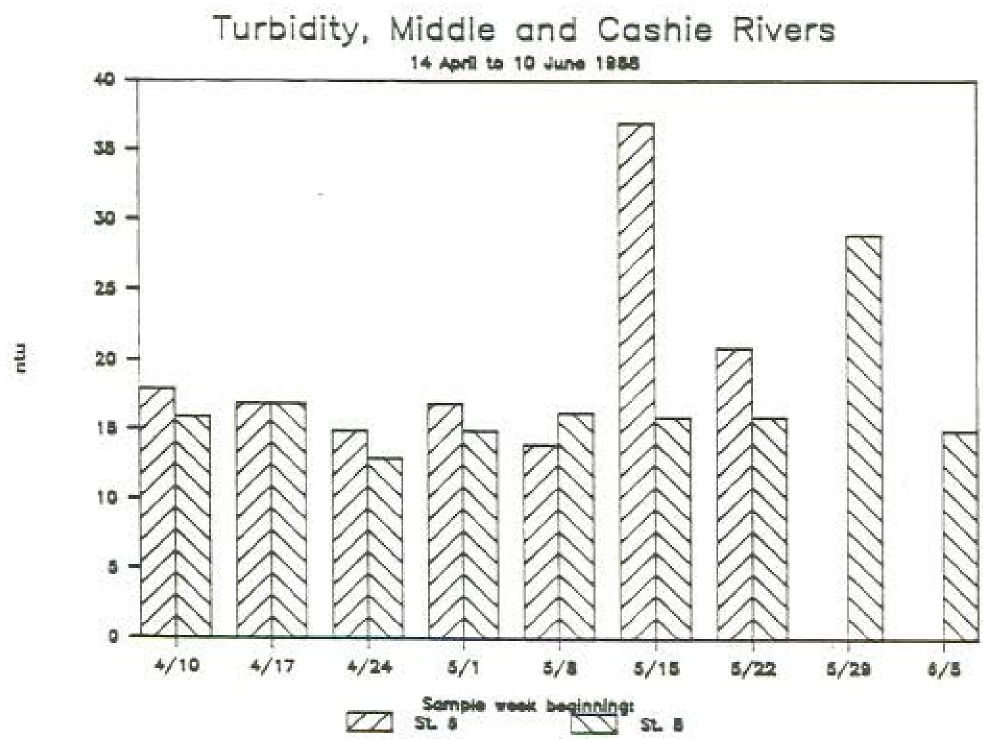
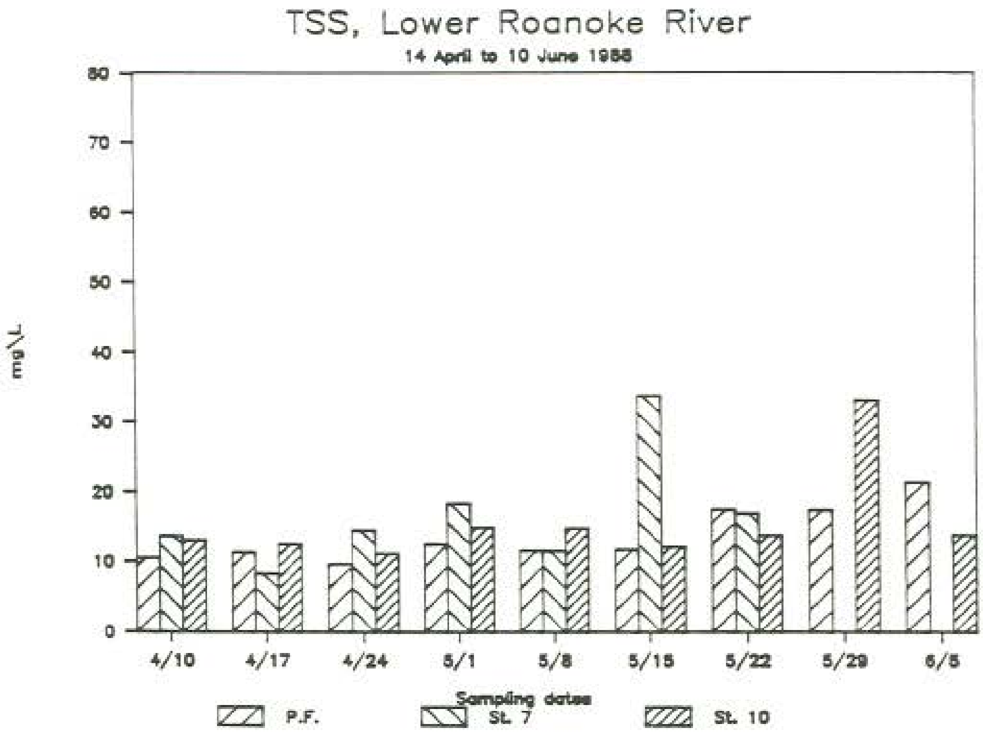


Figure 10. Turbidity of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



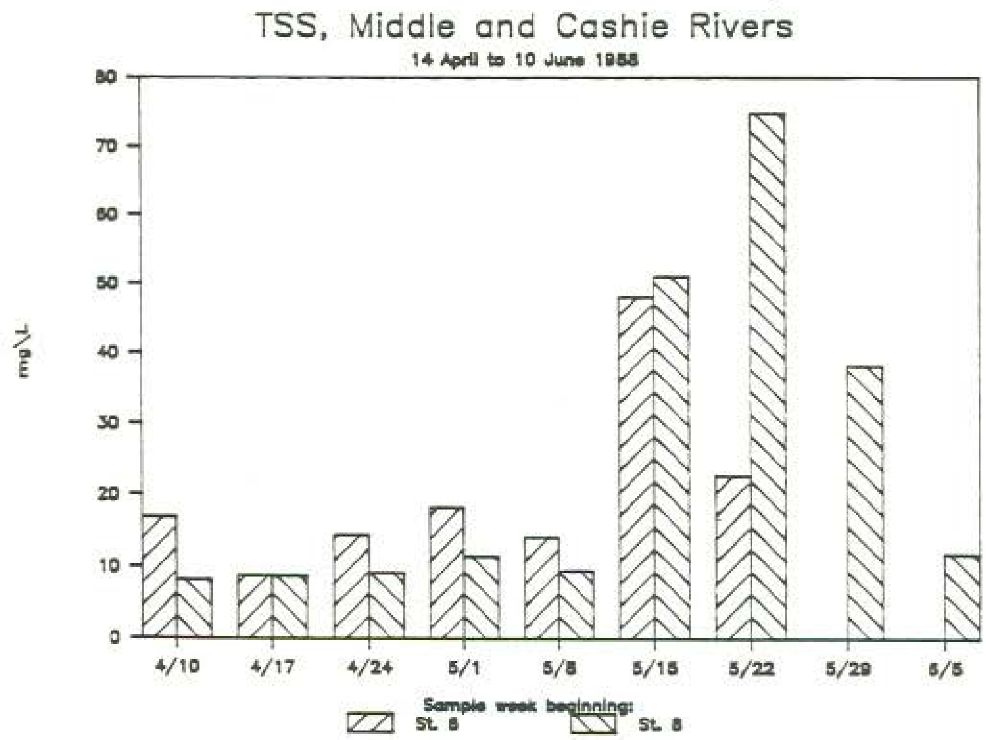
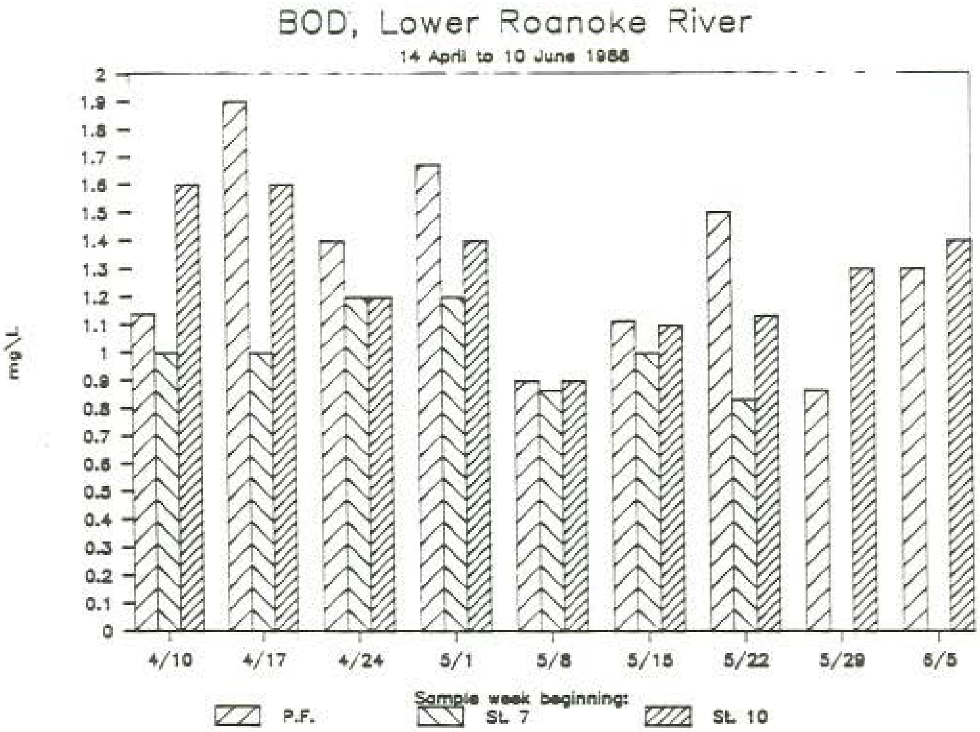


Figure 11. Total suspended solids (TSS) of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



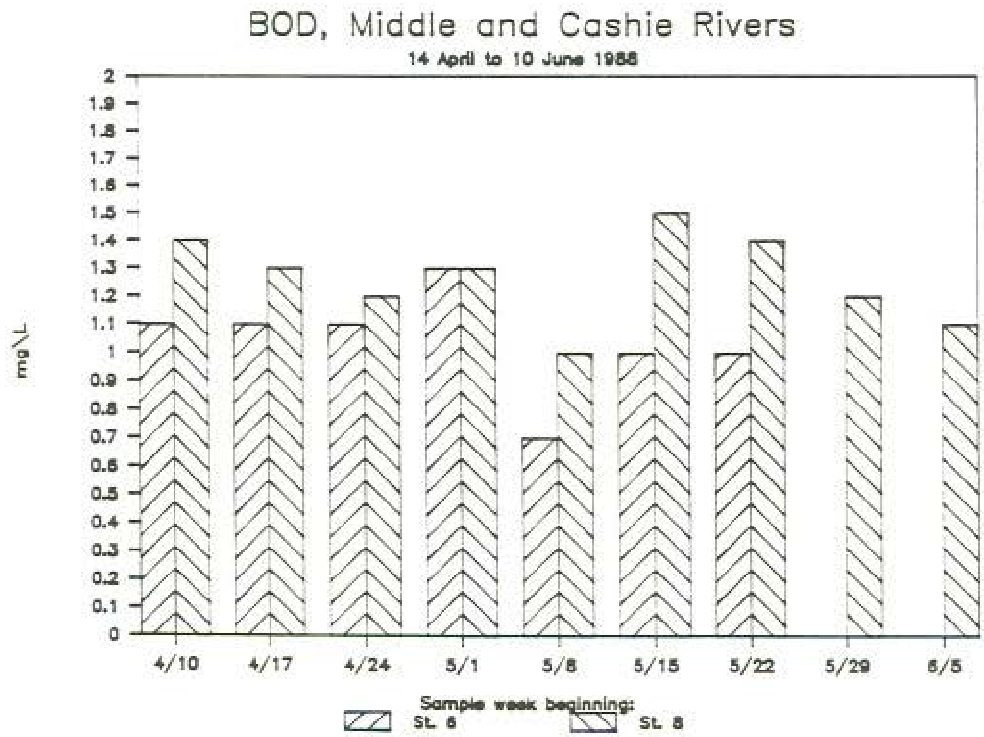
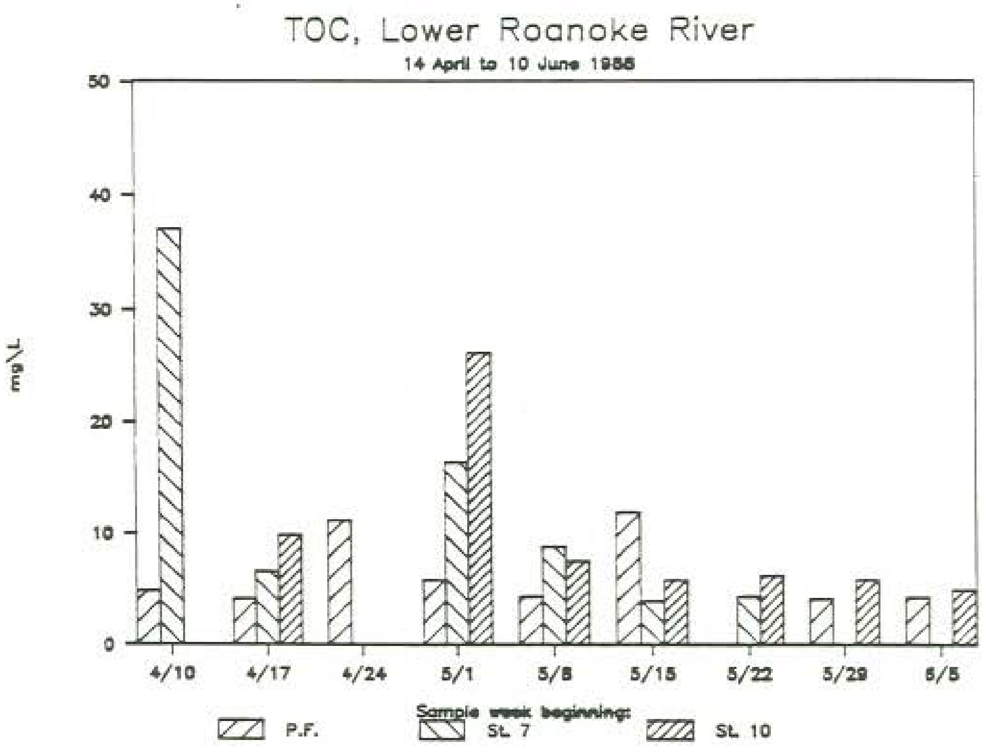


Figure 12. Biological oxygen demand (BOD) of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



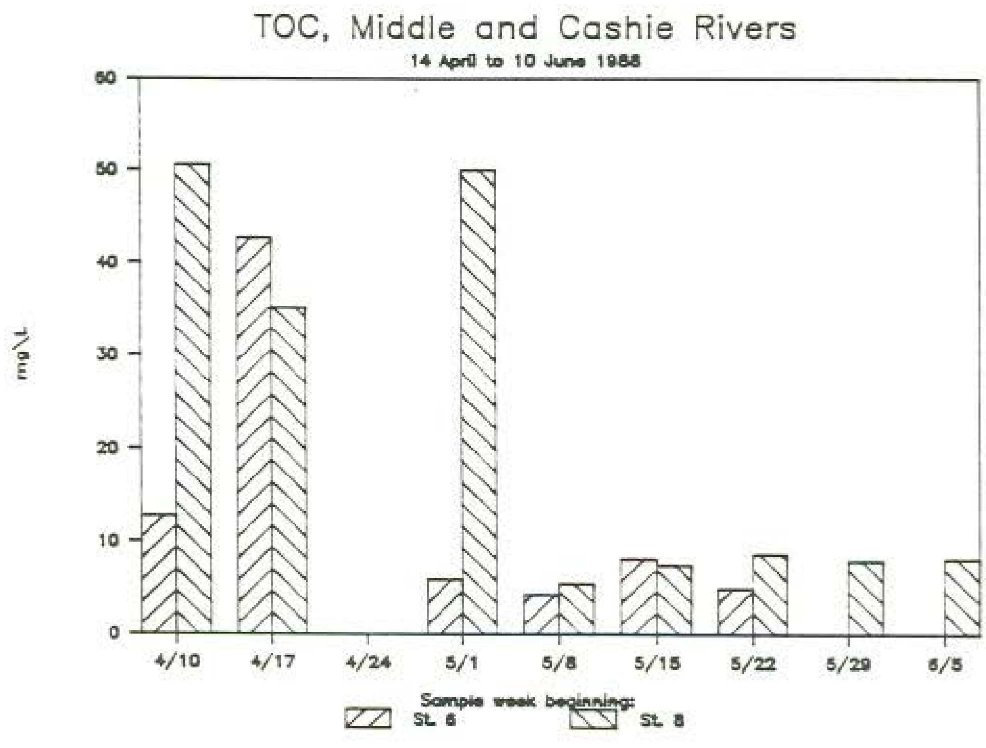
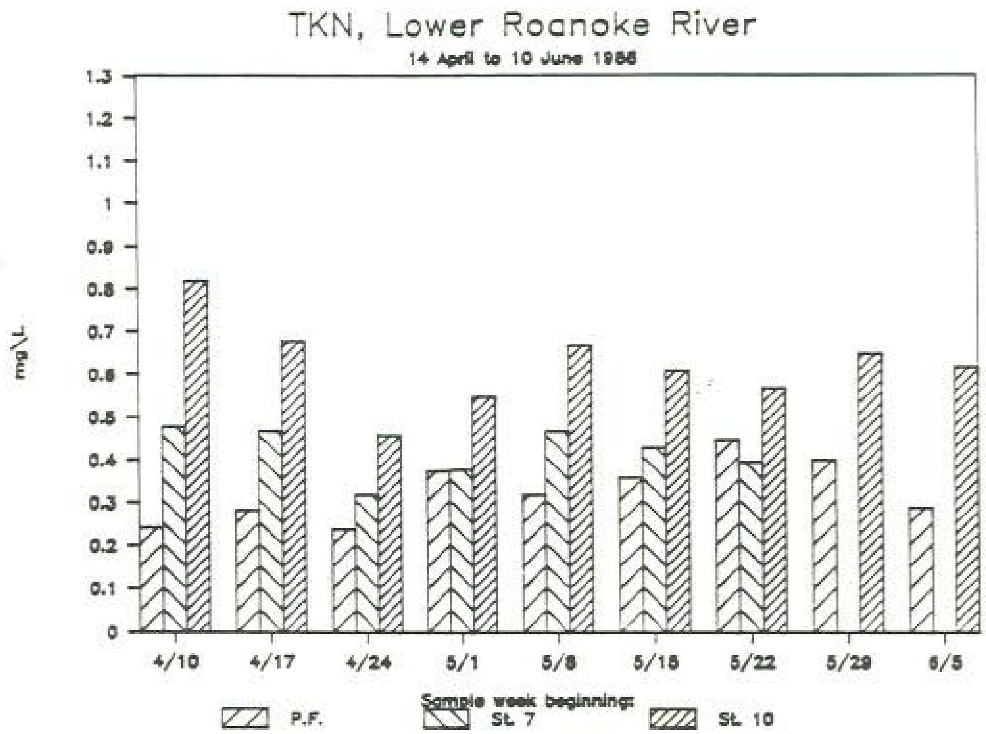


Figure 13. Total organic carbon (TOC) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



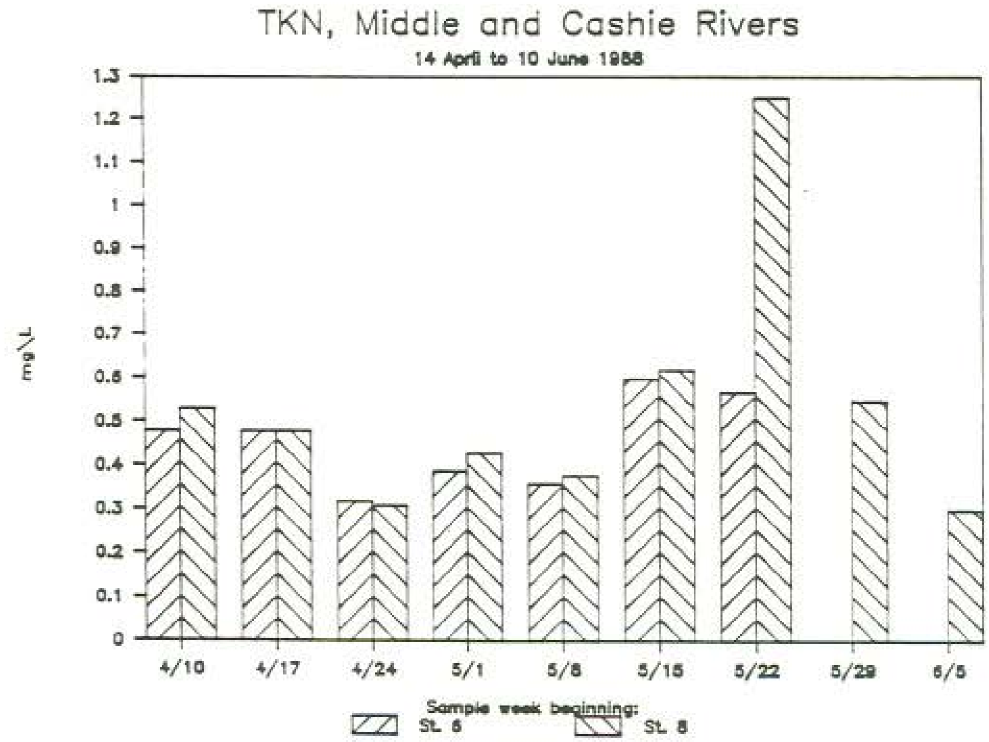
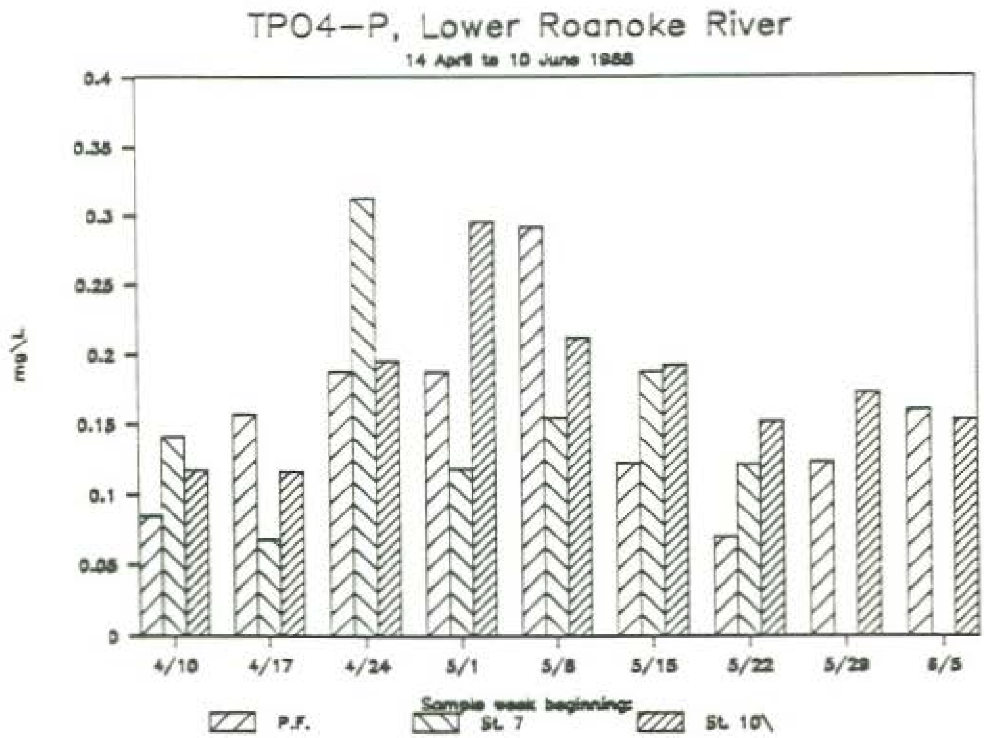


Figure 14. Total Kjeldahl nitrogen (TKN) values of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



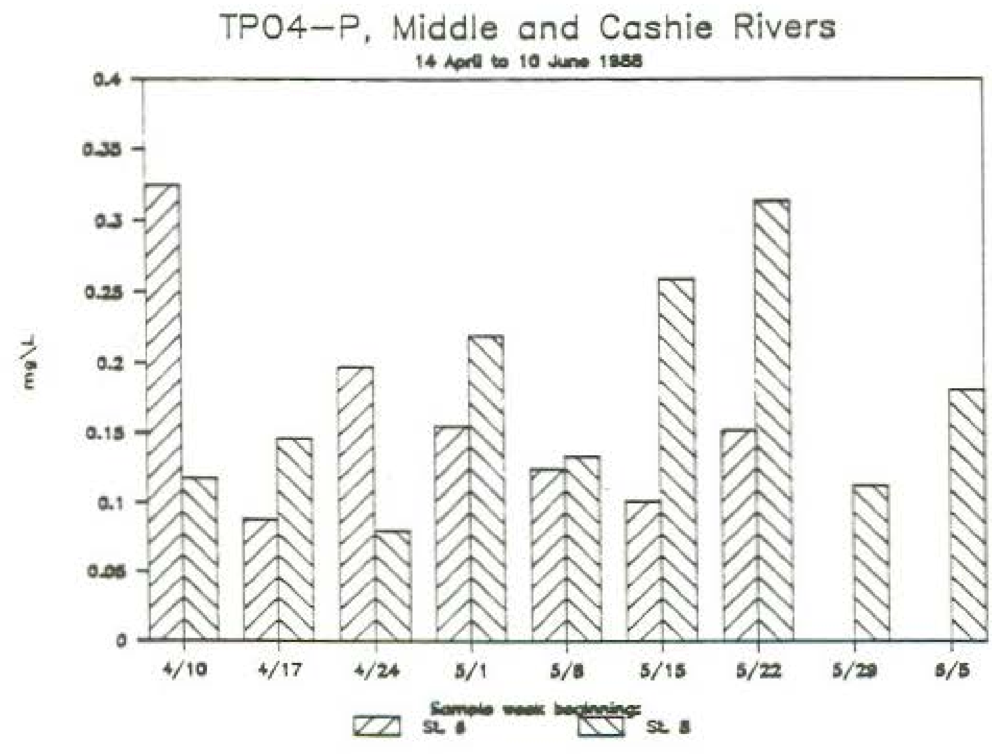
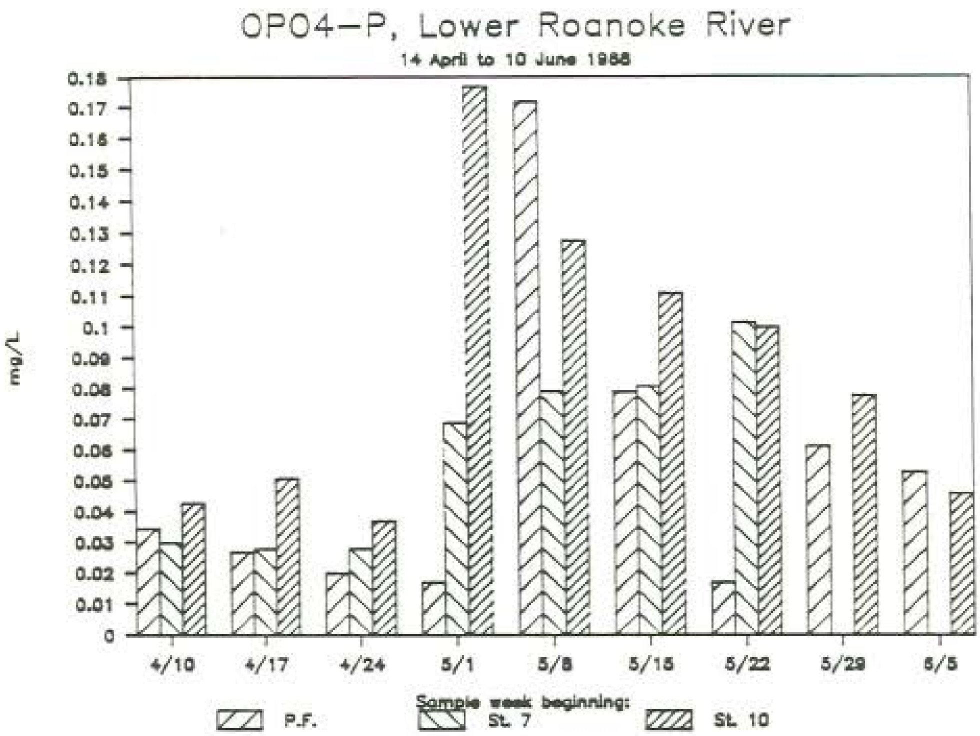


Figure 15. Total phosphate (TPO_4) values of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



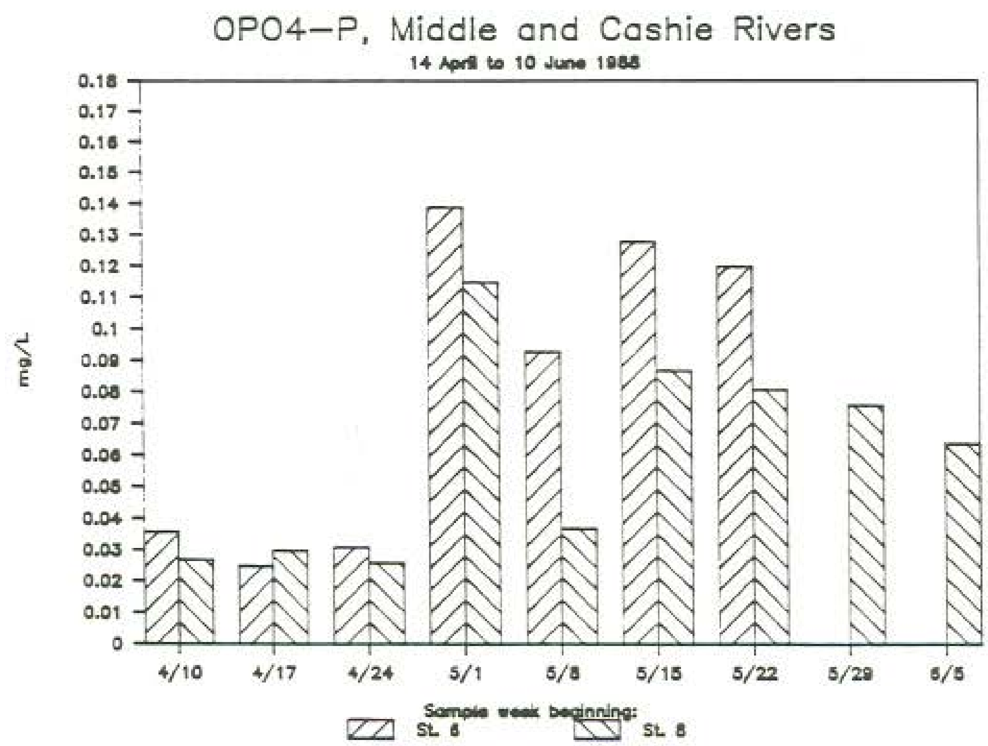


Figure 16. Orthophosphate (OPO_4-P) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.

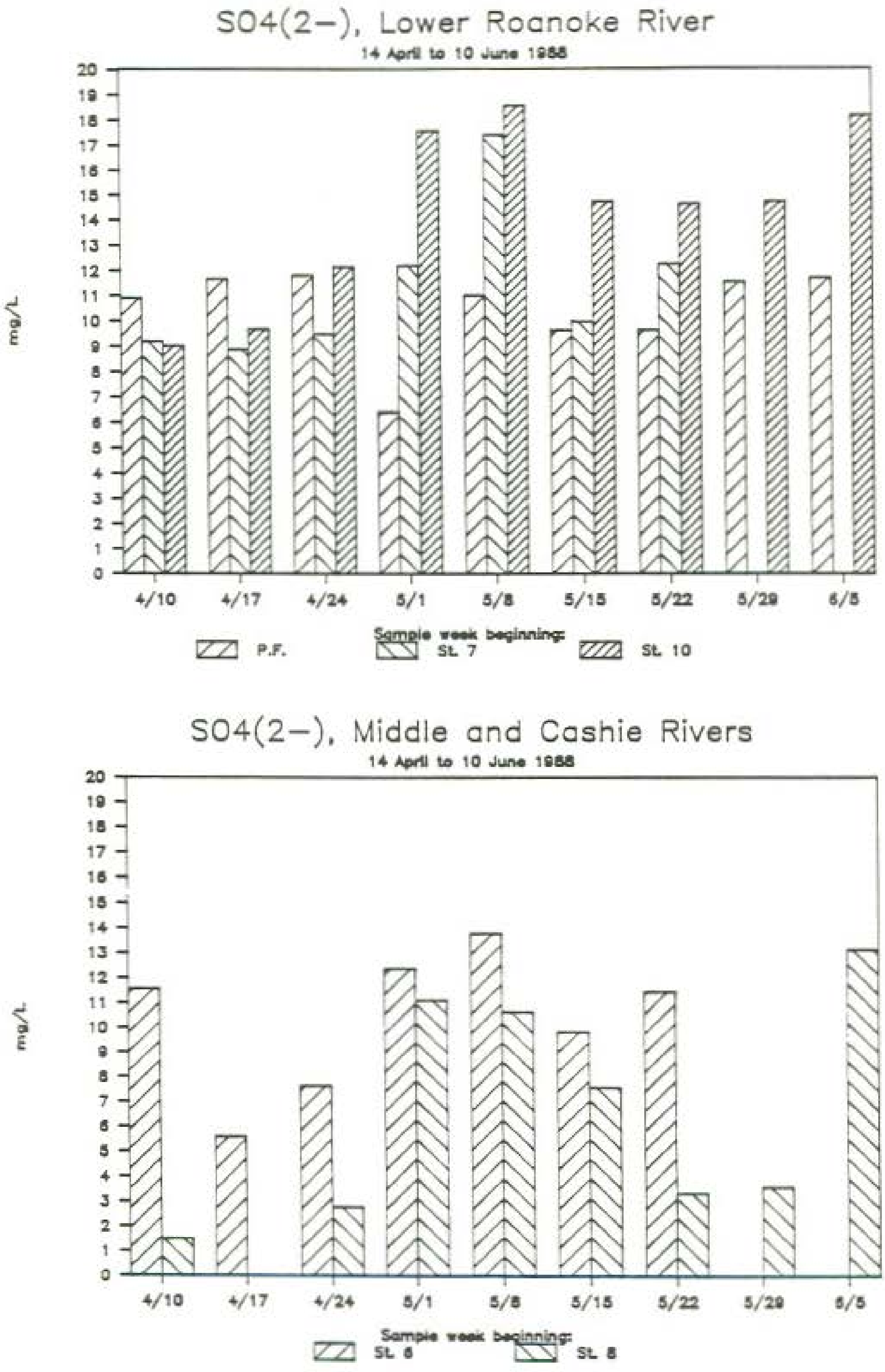
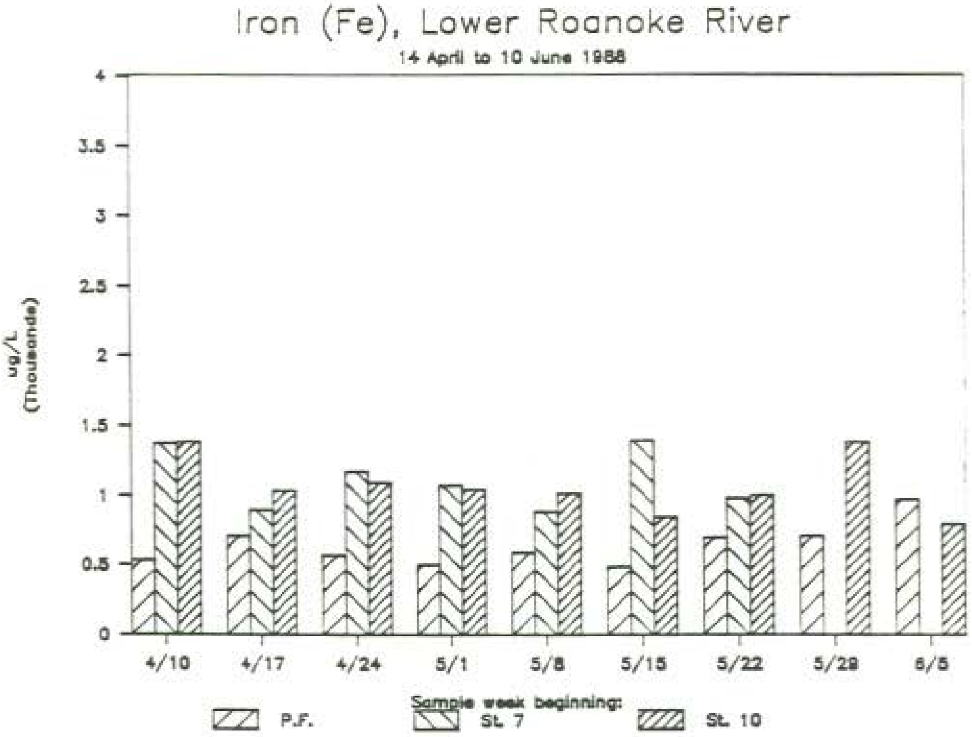


Figure 17. Sulfate (SO_4^{2-}) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



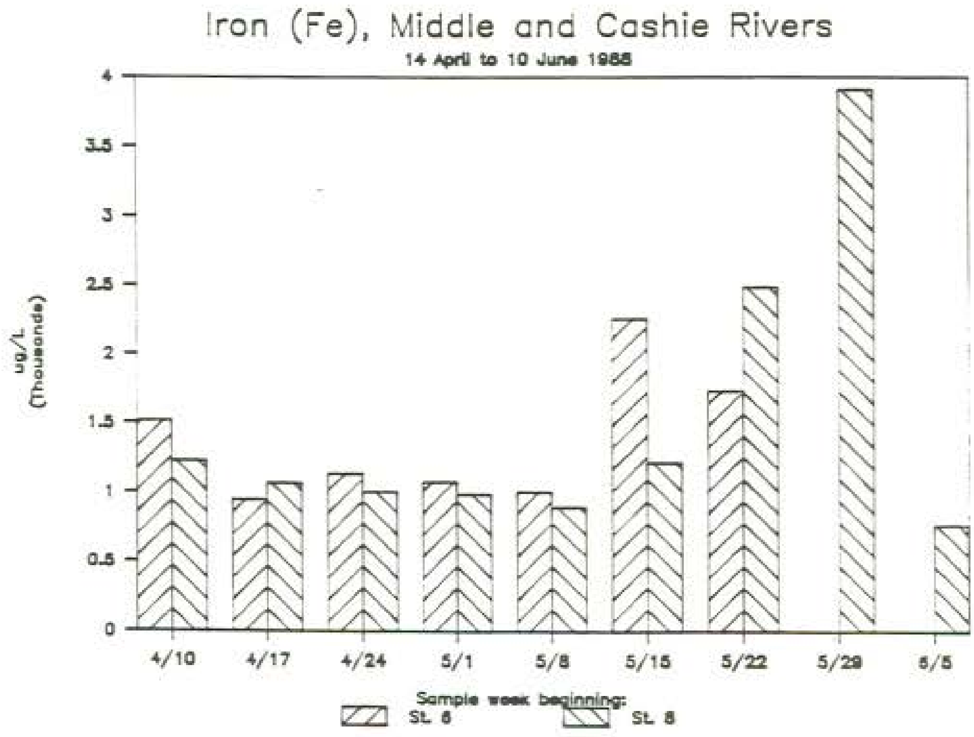
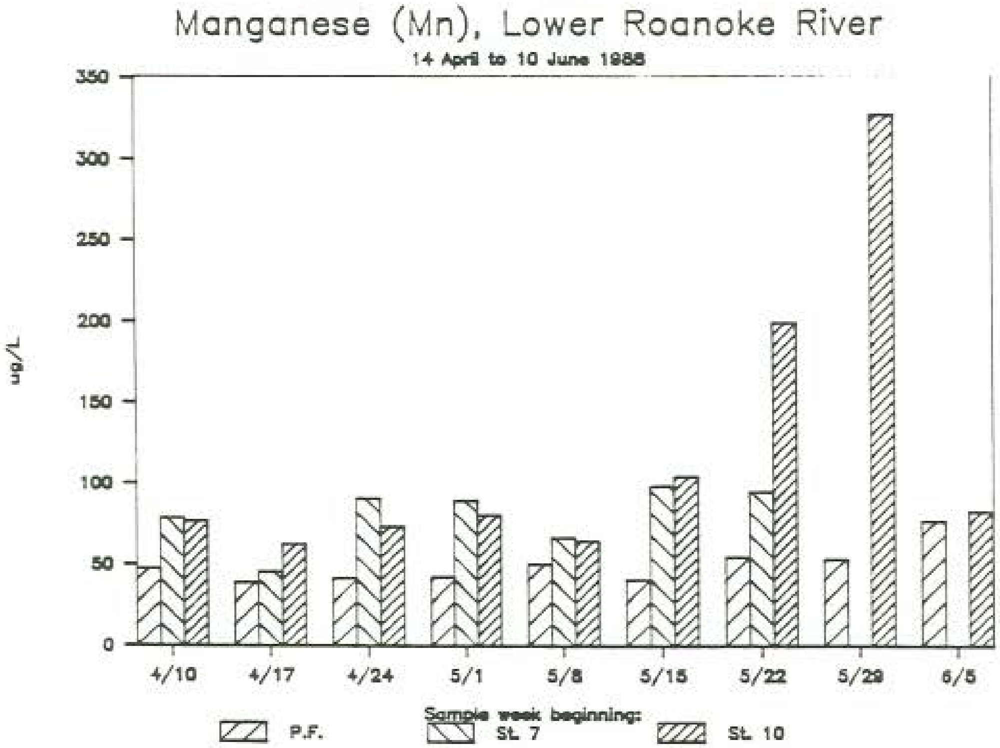


Figure 18. Iron (Fe) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



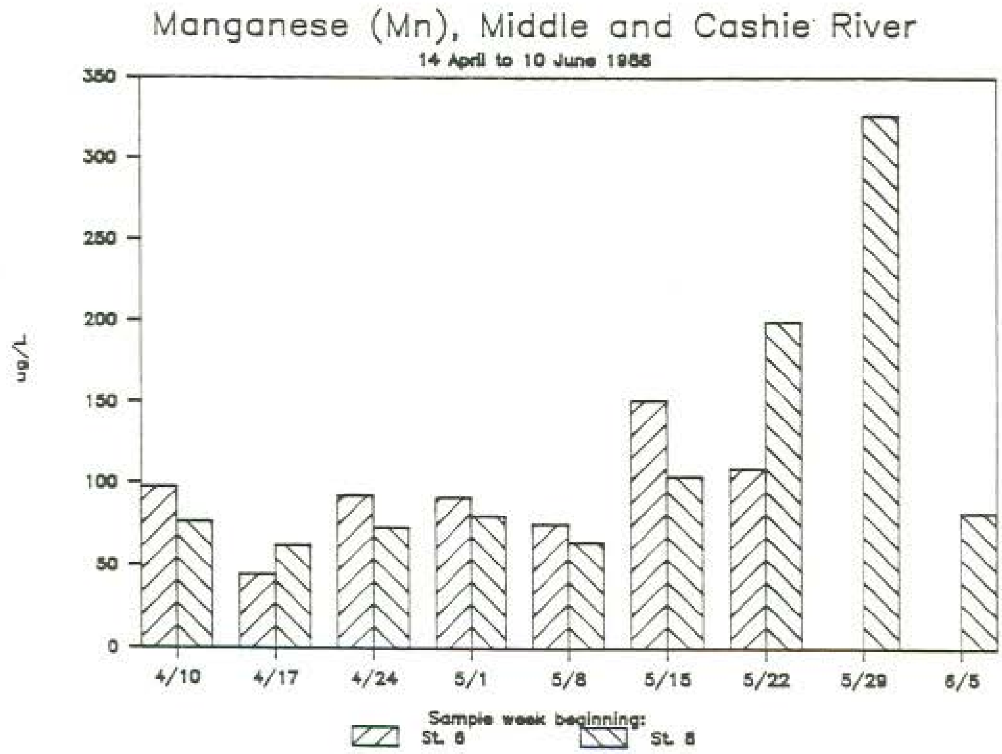
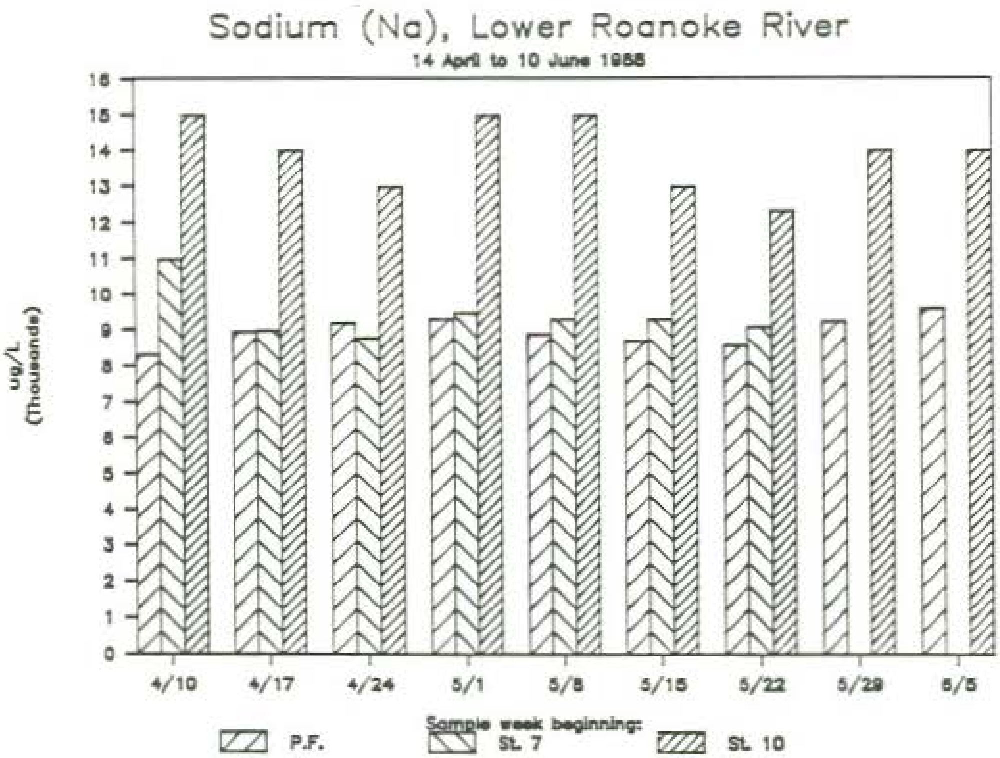


Figure 19. Manganese (Mn) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



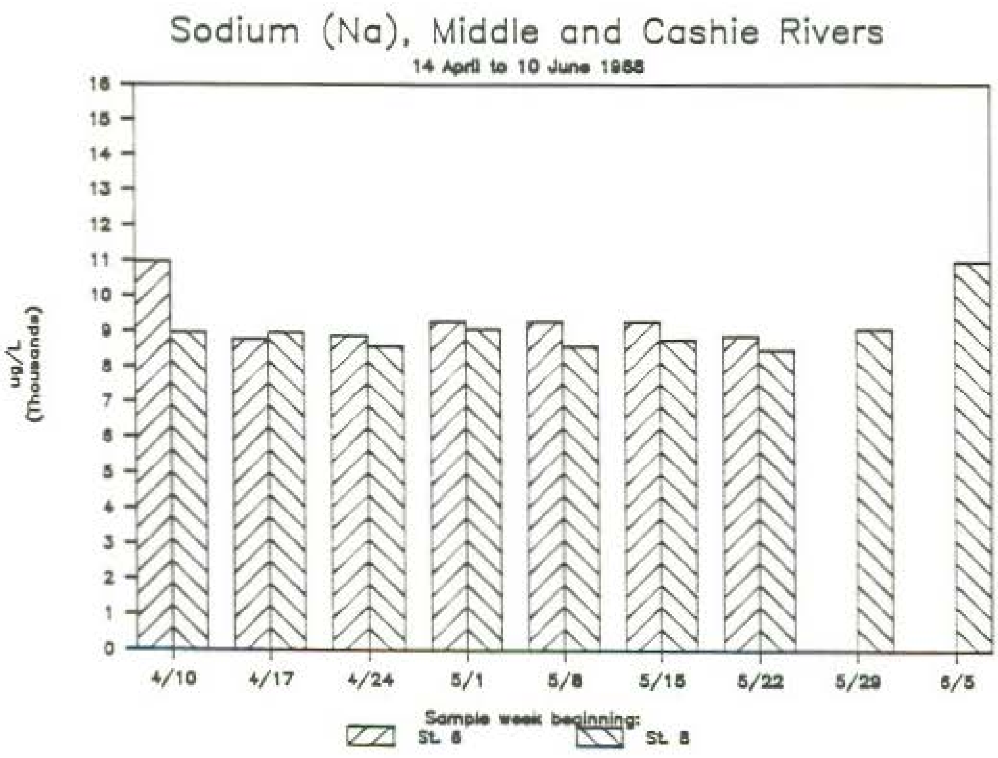
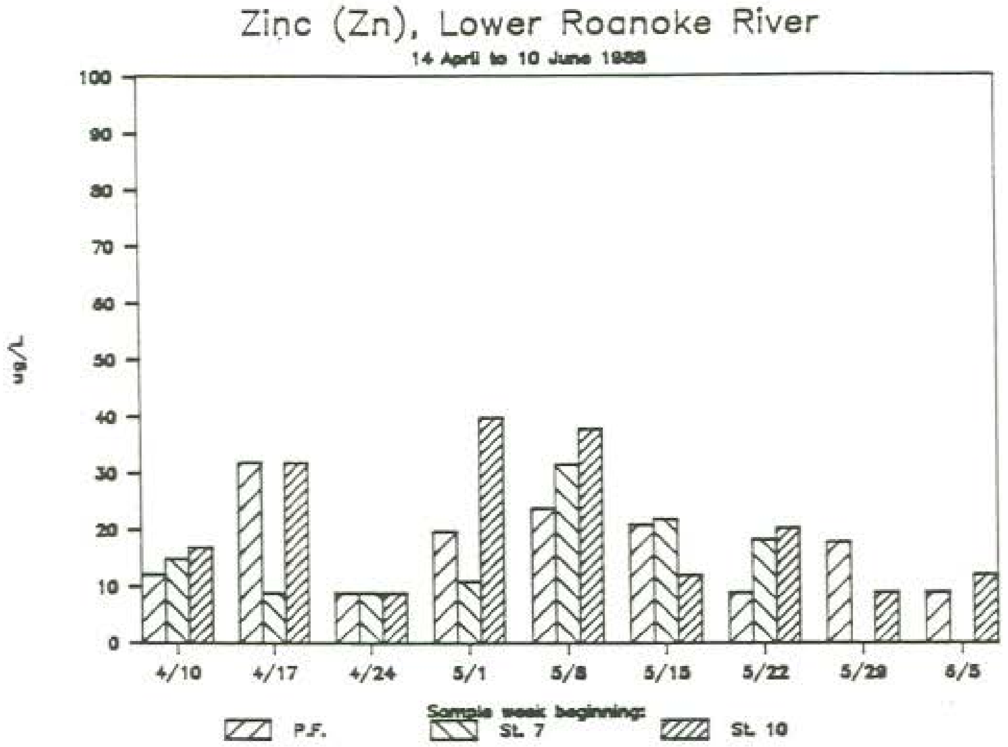


Figure 20. Sodium (Na) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



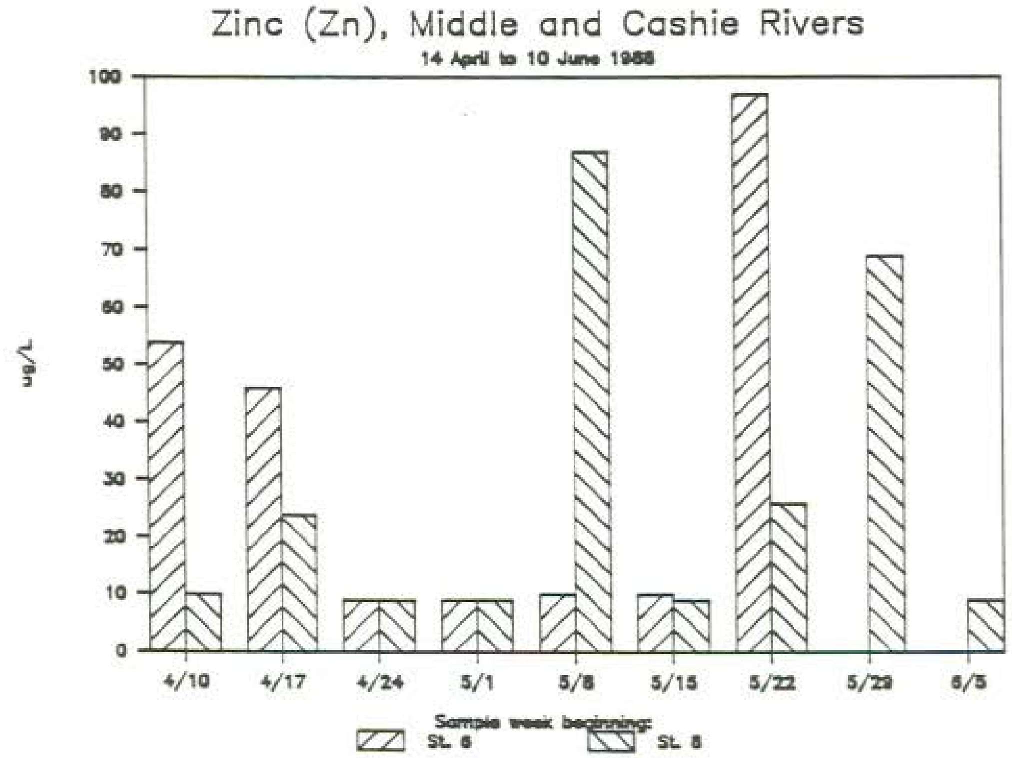
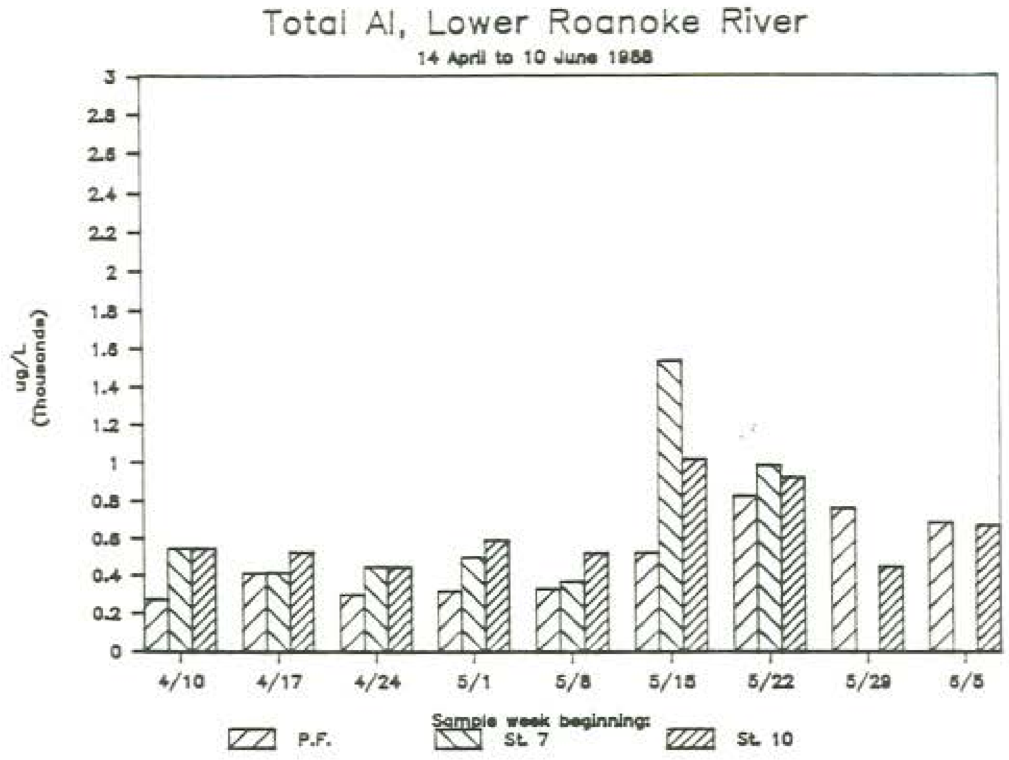


Figure 21. Zinc (Zn) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



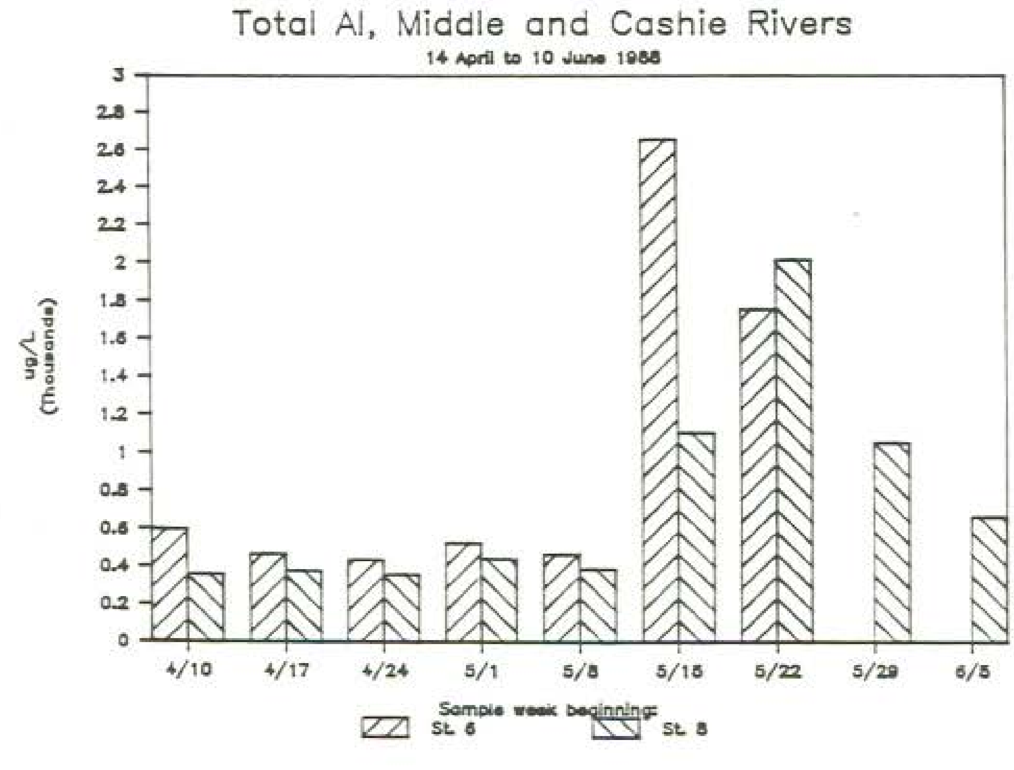
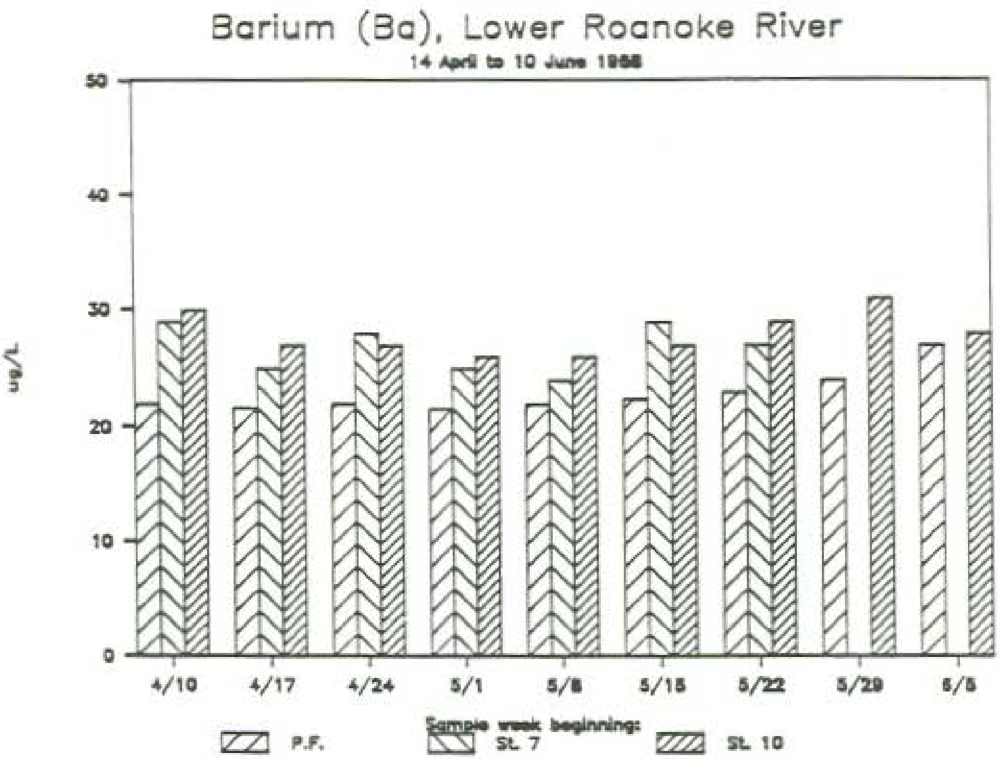


Figure 22. Total Aluminum (Al) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.



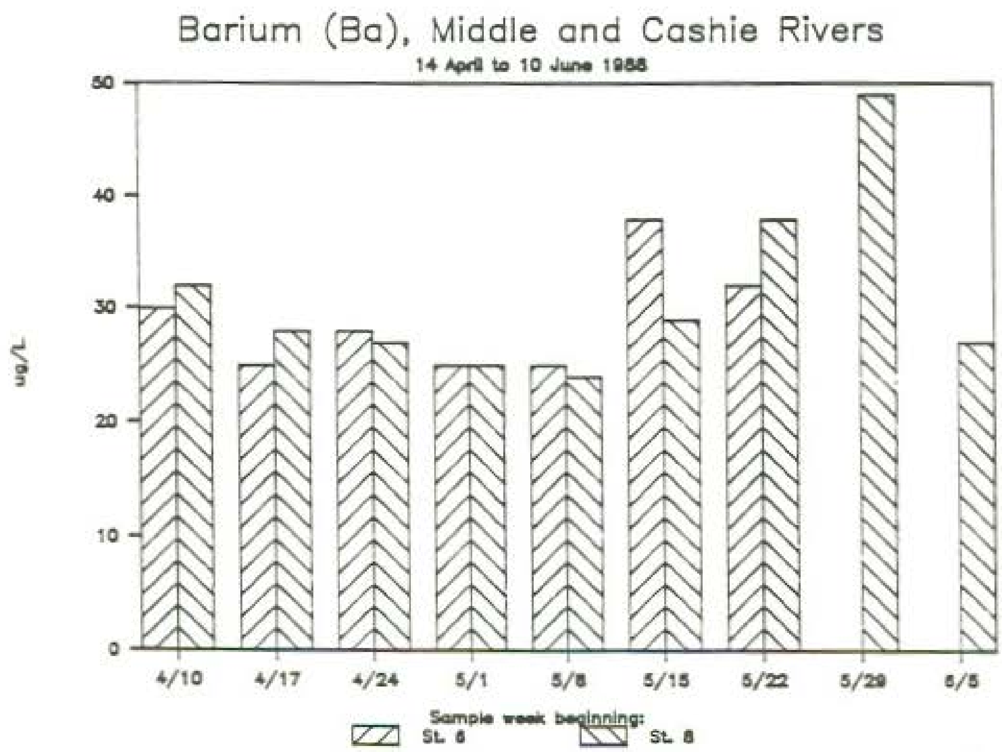


Figure 23. Barium (Ba) concentrations of the lower Roanoke River (Pollock's Ferry, Stations 7 and 10), Middle River (Station 6), and Cashie River (Station 8) for the period 14 April to 10 June 1988.

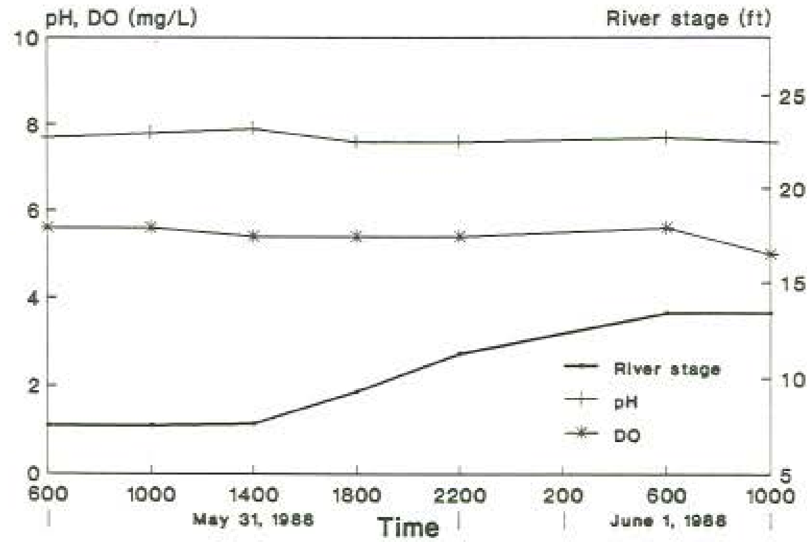


Figure 25. Dissolved oxygen (DO), pH and Roanoke River stage at Pollock's Ferry, 31 May to 1 June 1988.

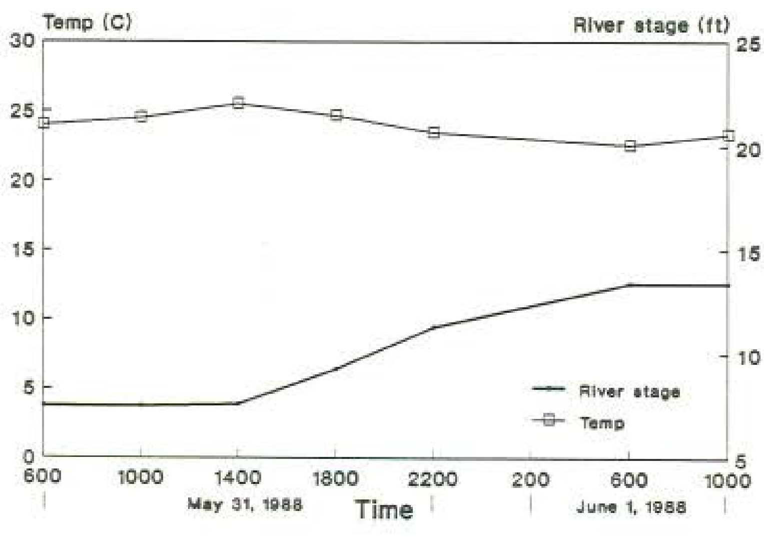


Figure 24. Water temperature and Roanoke River state at Pollock's Ferry, 31 May to 1 June 1988.

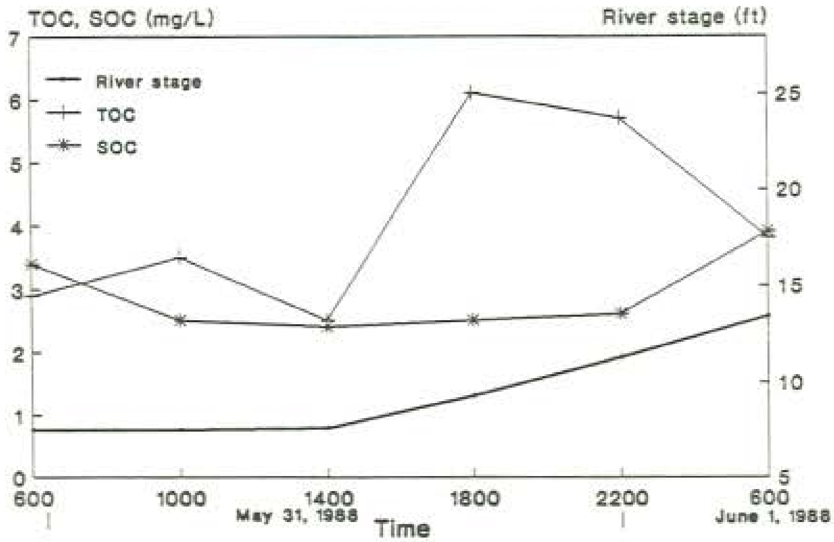


Figure 26. Total organic carbon (TOC), soluble organic carbon (SOC) and Roanoke River stage at Pollock's Ferry, 31 May to 1 June 1988.

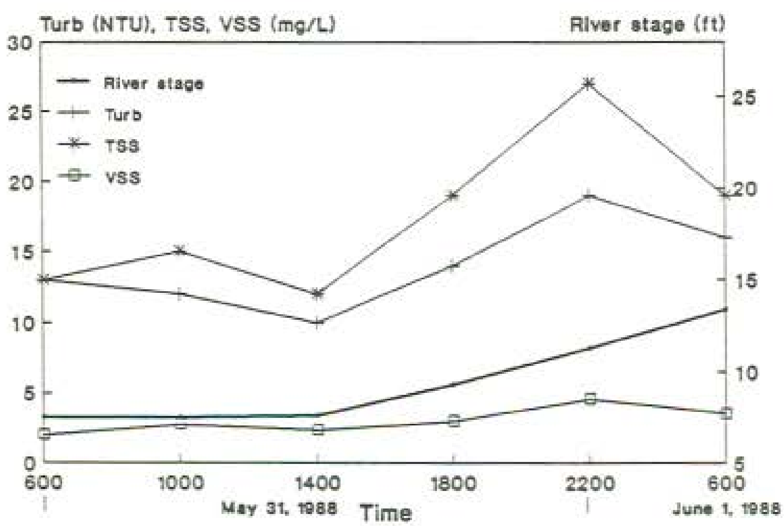


Figure 27. Turbidity, Total Suspended Solids (TSS), Volatile Suspended Solids (VSS) and Roanoke River stage at Pollock's Ferry, 31 May to 1 June 1988.

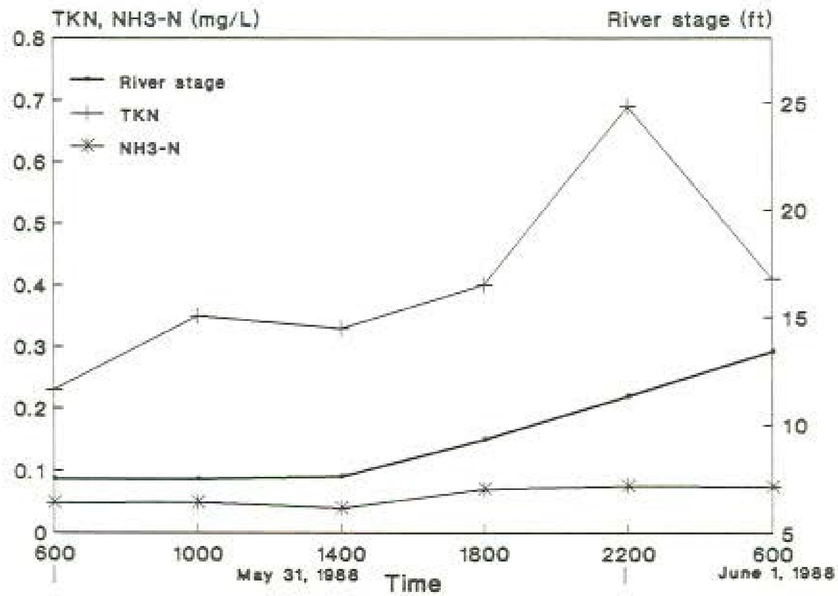


Figure 28. Total Kjeldahl nitrogen (TKN), Ammonia nitrogen (NH_3-N) and Roanoke River stage at Pollock's Ferry, 31 May to 1 June 1988.

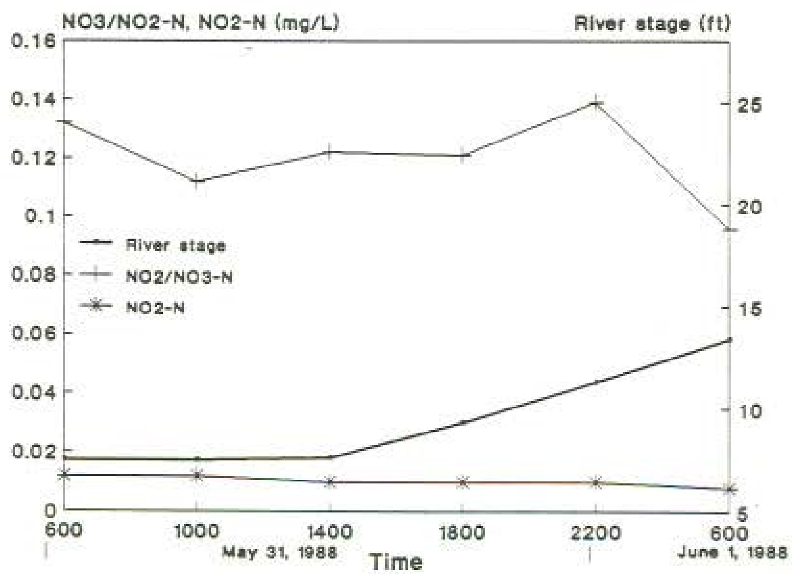


Figure 29. Nitrite/Nitrate Nitrogen (NO_2/NO_3-N), Nitrite-Nitrogen (NO_2-N) and Roanoke River stage at Pollock's Ferry, 31 May to 1 June 1988.

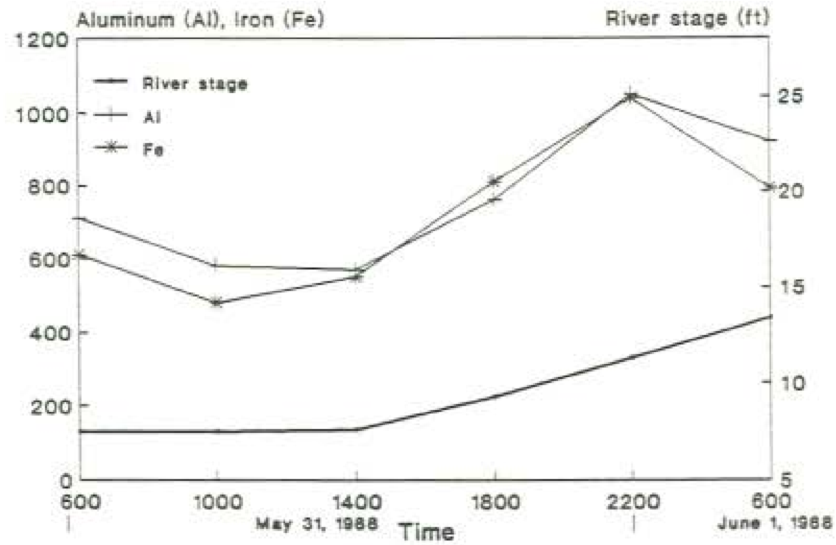


Figure 30. Aluminum (Al), Iron (Fe) and Roanoke River stage at Pollock's Ferry, 31 May to 1 June 1988.

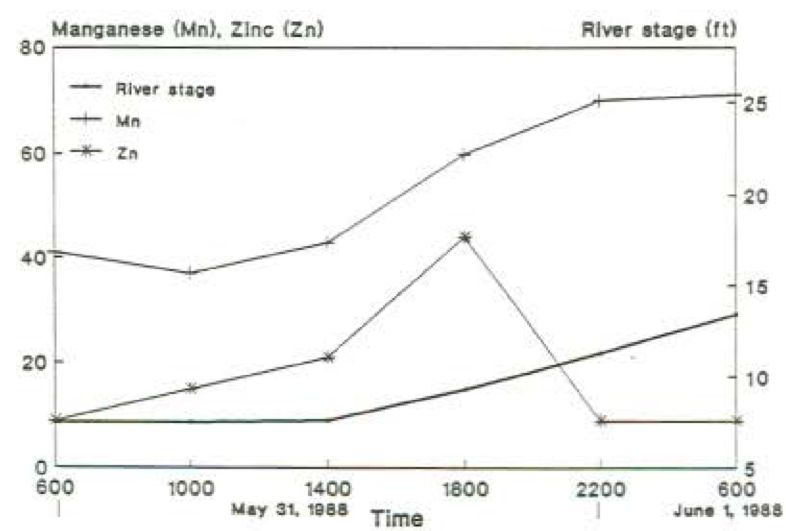


Figure 31. Manganese (Mn), Zinc (Zn) and Roanoke River stage at Pollock's Ferry, 31 May to 31 June 1988.

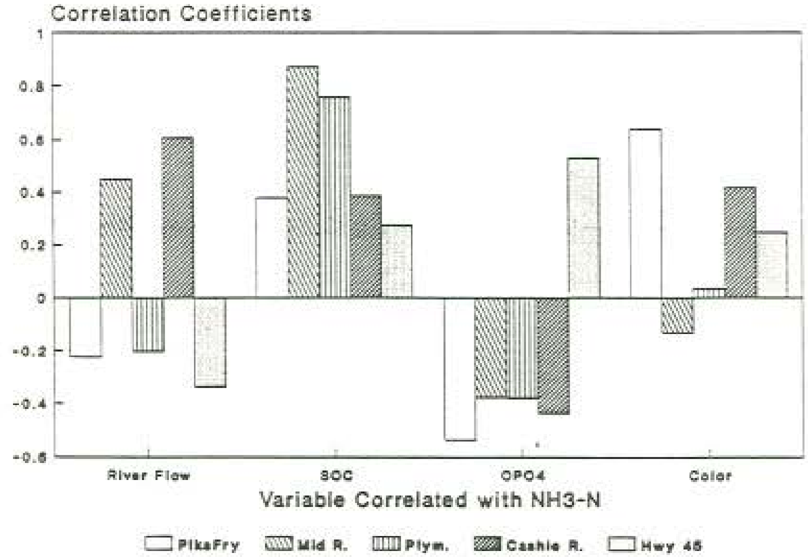


Figure 34. Correlation of ammonia-nitrogen (NH_3-N) with selected environmental variables measured in the lower Roanoke River at Pollock's Ferry and Plymouth area stations during the spring of 1988.

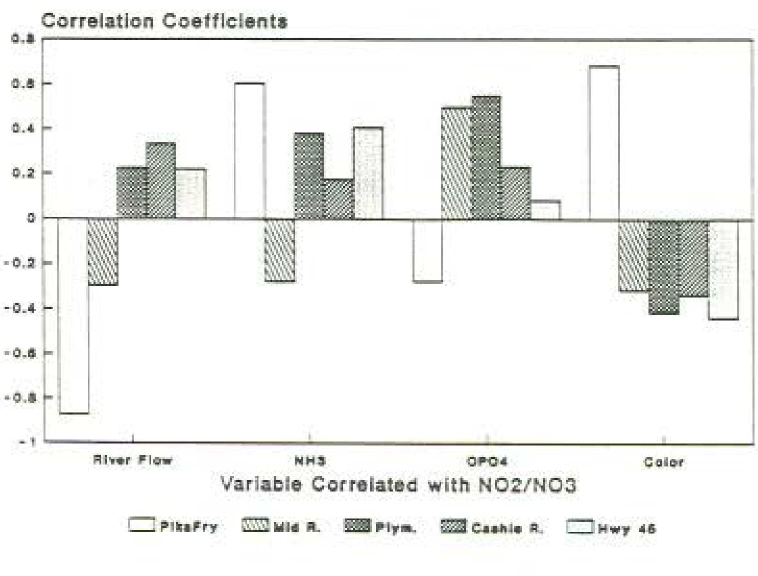


Figure 35. Correlation of nitrate/nitrite-nitrogen (NO_3/NO_2-N) with selected environmental variables measured in the lower Roanoke River at Pollock's Ferry and Plymouth area stations during the spring of 1988.

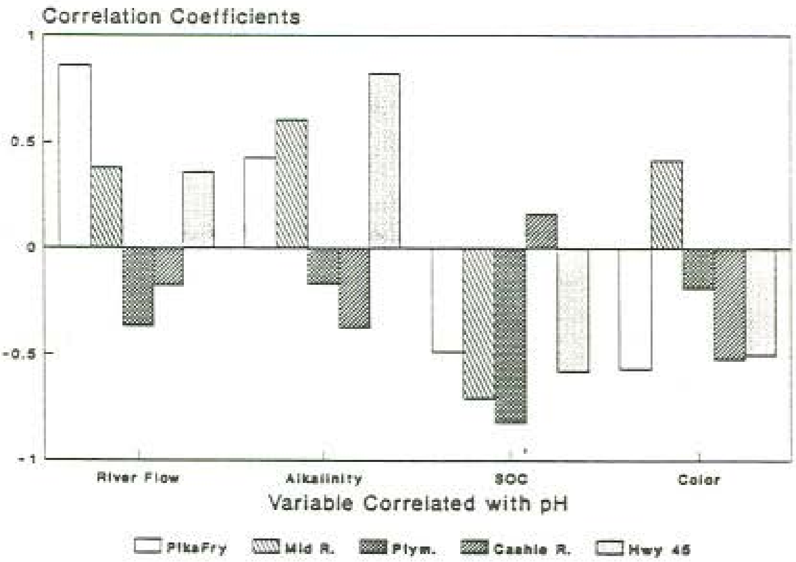


Figure 32. Correlation of field-measured pH with selected environmental variables measured in the lower Roanoke River at Pollock's Ferry and Plymouth area stations during the spring of 1988.

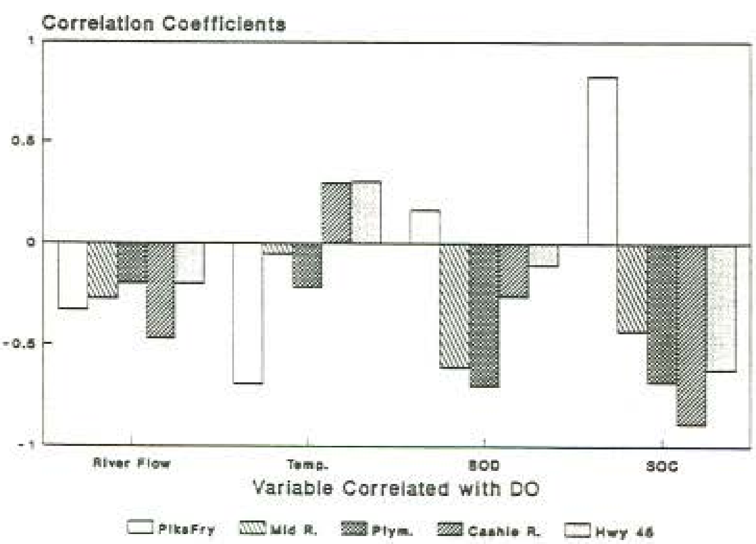


Figure 33. Correlation of dissolved oxygen (DO) with selected environmental variables measured in the lower Roanoke River at Pollock's Ferry and Plymouth area stations during the spring of 1988.

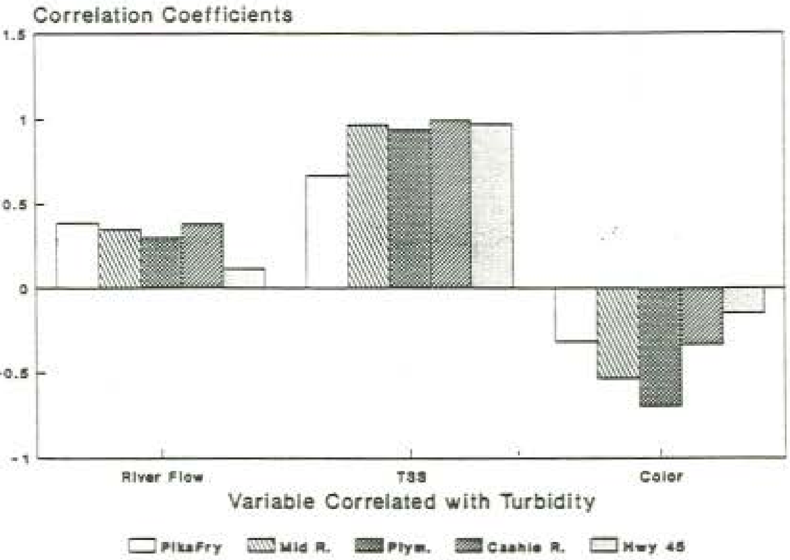


Figure 36. Correlation of turbidity with selected environmental variables measured in the lower Roanoke River at Pollock's Ferry and at Plymouth area stations during the spring of 1988.

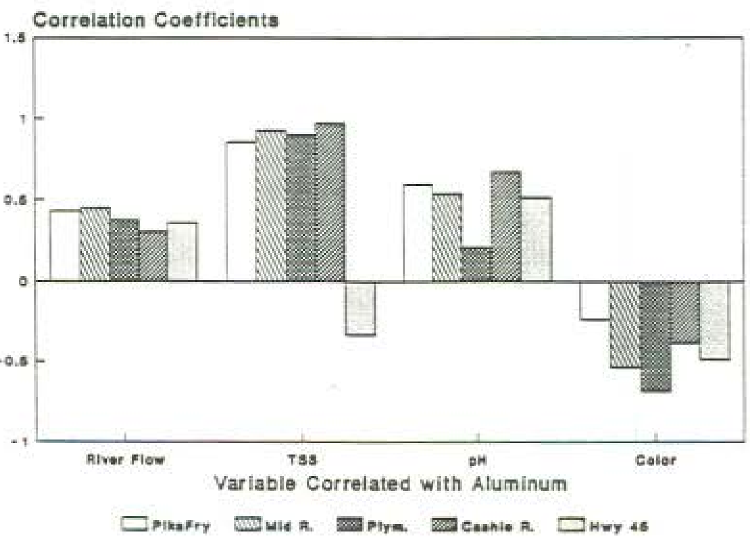


Figure 37. Correlation of aluminum (Al) with selected environmental variables measured in the lower Roanoke River at Pollock's Ferry and at Plymouth area stations during the spring of 1988.

Table 1. **NPDES dischargers to the lower Roanoke River Basin.**

Discharger	Permitted Waste Volume (mgd)	Permitted BOD concentration mg/L		Maximum BOD Loading (lbs/d)		Approximate Location (River Mile)
		Summer (Apr - Oct)	Winter (Nov - Mar)	Summer	Winter	
Champion International Paper Company Mill	28.00	lbs/d	lbs/d	6,850	6,850	137.0
Roanoke Rapids Sanitary Dist.	8.34	30.0	30.0	2,090	2,090	133.5
Weldon Wastewater Treatment Plant	0.12	15.0	15.0	150	150	131.5
N.C. Department of Corrections, Odom	0.08	30.0	30.0	20	20	111.5
N.C. Department of Corrections, Caledonia	0.80	5.2	10.4	35	70	107.0
Rich Square Wastewater Treatment Plant	0.30	30.0	30.0	75	75	102.5
Perdue Farms	3.00	lbs/d	lbs/d	814	814	93.0
Hamilton Wastewater Treatment Plant	0.08	30.0	30.0	20	20	61.3
West Point-Pepperell	1.50	lbs/d	lbs/d	179	179	---
Williamston Wastewater Treatment Plant	2.00	30.0	30.0	501	501	37.0
Liberty Fabrics	0.45	lbs/d	lbs/d	125	125	29.0
Jamesville Wastewater Treatment Plant	2.00	30.0	30.0	38	38	18.0
Weyerhaeuser Company Mill	55.00	lbs/d	lbs/d	9,340	18,680	8.0
Plymouth Wastewater Treatment Plant	0.80	19.0	30.0	126	201	5.0
Cashie Subbasin						
Lewiston-Woodville Wastewater Treatment Plant	0.15	30.0	30.0	38	38	---
Windsor Wastewater Treatment Plant	1.15	10.0	16.0	96	154	---

Table 2. **Water quality sampling schedule for locations on the lower Roanoke River at Pollock's Ferry and the Roanoke delta area near Plymouth, North Carolina.**

	April			May				June	
Location	10-16	17-23	24-30	1-7	8-14	15-21	22-28	29-1	5-11
Pollock's Ferry	one 24 hour composite	six discrete samples	one 24 hour composite	six discrete samples	one 24 hour composite	six discrete samples	one 24 hour composite	six discrete samples	one 24 hour composite
Station 6	composite	composite	composite	composite	composite	composite	composite	composite	composite
Station 7	composite	composite	composite	composite	DISCRETE	composite	DISCRETE	composite	composite
Station 8	composite	composite	composite	composite	composite	composite	composite	composite	composite
Station 10	composite	composite	composite	composite	DISCRETE	composite	DISCRETE	composite	composite
Number of samples	5	10	5	10	9	10	9	10	5
Number of sample bottles	25	50	25	50	45	50	45	50	25

Table 3. **Historial Roanoke River flows (weekly averages), 1912 to 1950, in CFS (at Roanoke Rapids gage, USGS data). Q_1 = 25 percent low flow value; Q_3 = 75 percent high flow value (from Manooch and Rulifson 1989).**

Week number	Approximate dates	Median	Q_1	Q_3
0	1-7 March	8,577	6,127	11,175
1	8-14 March	9,799	7,543	16,029
2	15-21 March	9,090	6,973	14,429
3	22-28 March	8,930	6,626	14,300
4	29 March - 4 April	8,333	6,681	14,186
5	5-11 April	8,476	6,379	13,171
6	12-18 April	8,539	6,810	14,029
7	19-25 April	7,821	5,703	10,800
8	26 April - 2 May	7,260	5,357	9,327
9	3-9 May	6,470	4,829	9,200
10	10-16 May	6,213	4,410	9,490
11	17-23 May	5,896	4,431	9,759
12	24-30 May	5,854	4,329	9,329
13	31 May - 6 June	5,450	*3,983	7,663
14	7-13 June	5,139	*3,701	7,814
15	14-20 June	5,124	*3,871	7,301
16	21-27 June	4,447	*3,394	6,607
17	28 June - 4 July	4,413	*3,058	6,173

*4,000 cfs minimum tentatively agreed to at the Roanoke River Water Flow Committee meeting on 3 May 1988 in Greenville, NC.

Table 4. **Summary water quality analyses of the lower Roanoke River at Pollock's Ferry and Plymouth area stations for the period 14 April to 10 June 1988. Data in mg/L unless specified.**

	Pollock's Ferry		Middle River		Roanoke near Plymouth		Cashie River		Roanoke at Highway 45 Bridge	
Parameter	mean	cv	mean	cv	mean	cv	mean	cv	mean	cv
pH	7.2	4.02	7.2	1.32	7.2	2.40	7.1	4.02	7.2	1.67
Temperature (°C)	18	22.94	17.8	22.00	18.1	23.24	19.3	23.59	19.3	22.75
DO	7.4	16.87	6.3	21.40	6.4	20.99	6.3	21.21	6.3	20.32
Secchi (cm)	81	15.25	-.-	-.-	-.-	-.-	-.-	-.-	-.-	-.-
Water velocity (cm/sec)	85.8	12.27	-.-	-.-	-.-	-.-	-.-	-.-	-.-	-.-
River flow (cfs)	7,821	15.84	-.-	-.-	-.-	-.-	-.-	-.-	-.-	-.-
Conductivity (µmhos)	101	3.00	102	26.78	114	50.12	131	44.49	130	55.17
Alkalinity	27	5.83	26.6	11.66	25.6	6.33	22.2	20.40	26.0	9.96
Color (APHA)	22	36.05	49	62.79	45	42.28	53	52.83	57	44.55
Turbidity (NTU)	12	17.67	20	39.67	18	32.32	22	77.17	17	27.24
TOC	6.3	52.34	13.2	112.00	12.9	98.99	21.7	92.63	14.6	99.97
SOC	3.7	20.02	10.6	135.00	4.6	33.98	16.6	103.00	9.1	105.00
TSS	13.8	29.13	20.6	62.65	16.8	48.93	24.8	98.06	15.5	43.46
VSS	2.5	26.70	3.1	53.57	2.9	24.64	4.5	87.20	3.1	44.23
BOD5	1.3	26.54	1.0	17.30	1.0	14.49	1.3	12.47	1.3	18.40
TKN	0.33	22.32	0.46	23.19	0.42	13.93	0.54	53.40	0.62	15.84
NH_3N	0.06	27.86	0.09	48.39	0.07	31.22	0.08	25.15	0.15	31.71
NO_2N	0.006	37.27	0.006	20.68	0.006	19.87	0.006	134.00	0.007	15.19
NO_3/NO_2N	0.15	16.77	0.20	37.76	0.19	37.45	0.15	53.57	0.18	37.33
TPO_4P	0.15	42.90	0.16	48.66	0.16	49.02	0.17	44.02	0.18	30.73
OPO_4P	0.05	92.70	0.08	59.98	0.06	51.26	0.06	52.90	0.09	55.29
SO_4	11.7	20.08	10.3	27.66	11.4	25.47	6.7	66.81	14.4	24.36
Chlorophyll *a* (µg/L)	2	69.22	-.-	-.-	-.-	-.-	-.-	-.-	-.-	-.-
Metals (µg/L)										
Al	494	43.72	990	85.55	688	62.21	755	74.03	634	32.26
Ba	23	3.91	29	16.65	27	7.67	31	25.61	28	6.31
Ca	6,679	3.06	6,616	4.43	6,561	4.53	6,416	16.71	6,877	4.21
Fe	623	17.38	1,387	34.63	1,117	19.00	1,510	68.28	1,071	19.08
K	2,229	10.22	2,329	18.34	2,286	17.40	2,344	16.11	2,492	16.16
Mg	2,788	2.92	2,777	5.26	2,738	5.33	2,642	11.17	2,797	5.29
Mn	50	23.34	95	34.20	81	23.23	11	76.31	85	20.58
Na	8,987	4.36	9,357	8.09	9,428	7.73	9,077	8.33	13,926	7.06
Sr	47	1.86	47	2.82	47	2.64	46	5.47	49	2.58
Zn	17	46.97	34	104.00	17	50.33	28	105.00	21	59.19

Table 5. **Average total metals concentrations at five Roanoke River stations, April to June 1988, and average soluble metals concentrations at the USGS Roanoke Rapids station (quarterly samples) for the period November 1987 to September 1988.**

Metal	Symbol	Roanoke Rapids (Soluble)	Pollock's Ferry (Total)	Middle River (Total)	Roanoke above Plymouth (Total)	Cashie River (Total)	Roanoke Highway 45 Bridge (Total)
Aluminum	Al	27.5	494	990	689	755	635
Antimony	Sb	-.-	<50	<50	<50	<50	<50
Arsenic	As	*<1	<2	<2	<2	<2	<2
Barium	Ba	21	23	29	27	31	28
Beryllium	Be	<0.5	<5	<5	<5	<5	<5
Bismuth	Bi	-.-	<10	<10	<10	<10	<10
Boron	B	-.-	47	42	45	62	64
Cadmium	Cd	<1	<5	<5	<5	<5	<5
Calcium, mg/L	Ca	7.2	6.7	6.6	6.6	6.4	6.9
Chromium	Cr	3	<5	<5	<5	<5	<5
Cobalt	Co	<3	<10	<10	<10	<10	<10
Copper	Cu	1.5	<10	<10	<10	<10	<10
Iron, mg/L	Fe	0.039	0.6	1.4	1.1	1.5	1.1
Lead	Pb	<5	<50	<50	<50	<50	<50
Lithium	Li	<4	<30	<30	<30	<30	<30
Magnesium, mg/L	Mg	3.0	2.9	2.8	2.7	2.6	2.8
Manganese	Mn	8	50	95	81	119	85
Mercury	Hg	<0.1	-.-	-.-	-.-	-.-	-.-
Molybdenum	Mo	<10	<10	<10	<10	<10	<10
Nickel	Ni	<1	<20	<20	<20	<20	<20
Potassium, mg/L	K	2.2	2.2	2.3	2.3	2.3	2.5
Selenium	Se	<1	<3	<3	<3	<3	<3
Silver	Ag	<1	<10	<10	<10	<10	<10
Sodium, mg/L	Na	8.1	9.0	9.4	9.4	9.1	13.9
Strontium	Sr	50	47	47	47	46	46
Tin	Sn	-.-	<50	<50	<50	<50	<50
Vanadium	V	<6	<10	<10	<10	<10	<10
Zinc	Zn	<3	18	34	17	28	21

*less than detection limit

Table 6. **Comparison between routine NO_2-N determinations by Weyerhaeuser and ECU, and total aluminum (by ICP) and dissolved monomeric aluminum (DAM1, electrometric) performed by ECU labs, on water from the lower Roanoke River. Stations as in Figure 3.**

				NO_2-N (mg/L)		Aluminum (µg/L)	
Date	Station	Sample type	Time	Weyer.	ECU	Total	DMA1
880414	1	Discrete	1000	0.005	0.003	260	8
880414	1	Discrete	1000	0.005	0.003	260	8
880414	1	Discrete	1400	0.005	0.003	330	10
880414	1	Discrete	1800	0.005	0.003	260	14
880414	1	Discrete	2200	-.---	0.003	260	7
880415	1	Discrete	200	0.005	0.002	---	3
880415	1	Discrete	600	-.---	0.002	260	18
880419	1	Discrete	1000	0.005	0.002	360	8
880419	1	Discrete	1400	0.005	0.003	390	16
880419	1	Discrete	1800	0.007	0.002	500	20
880426	1	Composite	----	0.004	0.003	300	5
880503	1	Discrete	600	0.004	0.004	287	1
880503	1	Discrete	1000	0.005	0.004	315	-18
880503	1	Discrete	1400	0.005	0.004	318	10
880503	1	Discrete	1800	0.006	0.003	292	9
880503	1	Discrete	2200	0.004	0.002	242	9
880504	1	Discrete	200	0.005	0.003	342	0
880504	1	Discrete	600	0.005	0.003	432	10
880510	1	Composite	----	0.006	0.002	331	31
880517	1	Discrete	600	0.006	0.003	355	16
880517	1	Discrete	1000	0.005	0.003	560	38
880517	1	Discrete	1400	0.006	0.004	410	25
880517	1	Discrete	1800	0.009	0.003	530	2
880517	1	Discrete	2200	0.006	0.004	700	12
880518	1	Discrete	600	0.005	0.003	460	--
880525	1	Composite	----	0.011	0.004	830	--
880531	1	Discrete	600	0.012	0.008	710	0
880531	1	Discrete	1000	0.012	0.006	580	-2
880531	1	Discrete	1400	0.010	0.009	570	7
880531	1	Discrete	1800	0.010	0.008	760	1
880531	1	Discrete	2200	0.010	0.007	1050	4
880601	1	Discrete	600	0.008	0.003	920	8
880608	1	Composite	----	0.005	0.004	690	11
880414	6	Composite	2400	0.007	-.---	600	8
880421	6	Composite	2300	0.007	0.007	470	20
880428	6	Composite	2050	0.004	0.003	440	18
880505	6	Composite	2255	0.005	0.004	529	12
880512	6	Composite	2050	0.006	0.004	471	16
880518	6	Composite	2324	0.005	0.006	2660	--
880526	6	Composite	2055	0.007	0.003	1760	7
880414	7	Composite	2300	0.008	-.---	550	19
880421	7	Composite	2330	0.008	0.002	420	11
880428	7	Composite	2000	0.005	0.005	450	15
880505	7	Composite	2322	0.006	0.003	501	4
880512	7	Surface	2020	0.006	0.003	341	11
880518	7	Composite	2400	0.005	0.003	1540	--
880526	7	Surface	2028	0.006	0.003	930	7
880415	8	Composite	110	0.008	-.---	360	42

Table 6. *continued*

Date	Station	Sample type	Time	NO_2-N (mg/L)		Aluminum (µg/L)	
				Weyer.	ECU	Total	DMA1
880421	8	Composite	2100	0.006	0.002	380	34
880428	8	Composite	2140	0.006	0.003	360	26
880505	8	Composite	2200	0.006	0.003	445	-1
880512	8	Composite	2200	0.006	0.002	392	12
880518	8	Composite	2215	0.007	0.003	1110	--
880526	8	Composite	2215	0.005	0.004	2020	--
880601	8	Composite	2400	0.006	0.002	1060	4
880609	8	Composite	1940	0.006	0.004	670	7
880415	10	Composite	200	0.009	-.---	550	33
880421	10	Composite	1924	0.007	0.003	530	42
880428	10	Composite	2300	0.006	0.003	450	24
880505	10	Composite	2130	0.009	0.003	593	29
880512	10	Surface	2450	0.008	0.004	557	31
880518	10	Composite	2020	0.008	0.003	1020	--
880526	10	Surface	2445	0.007	0.004	860	2
880601	10	Composite	2455	0.006	0.004	450	21
880609	10	Composite	2005	0.006	0.004	670	11
880601	13	Composite	2330	0.007	0.004	240	14
880601	15	Composite	2235	0.006	0.006	1110	4

APPENDIX

Table A-1. **North Carolina standards and EPA criteria for selected water quality parameters for protection of fresh water aquatic life.**

Parameter	Symbol	NC standard	EPA criteria
Aluminum	Al	--	150 µg/L
Ammonia	NH_3	--	2.1 mg/L
Arsenic	As	50 µg/L	48 µg/L/190 µg/L[5]
Cadmium	Cd	2 µg/L	1.1 µg/L
Chromium	Cr	50 µg/L	11 µg/L/210 µg/L[6]
Copper	Cu	7 µg/L (Al[2])	12 µg/L
Dissolved Oxygen	DO	5 mg/L (4 mg/L[3])	1 mg/L
Iron	Fe	1 mg/L (Al[2])	1 mg/L
Lead	Pb	25 µg/L	3.2 µg/L
Mercury	Hg	0.012 µg/L	0.012 µg/L
Nickel	Ni	88 µg/L	160 µg/L
pH	--	6.0 - 9.0 (4.3[4])	6.5 - 9.0
Selinium	Se	5 µg/L	35 µg/L
Silver	Ag	0.06 µg/L (Al[2])	0.12 µg/L
Turbidity	--	50 NTU	--
Zinc	Zn	50 µg/L (Al[2])	110 µg/L

[1]EPA standards for metals are for soluble form
[2]Action limits
[3]Instantaneous minimum
[4]Minimum for swamp waters
[5]Pentavalient/Trivalient arsenic standards
[6]Hexavalient/Trivalient chronium standards

Table A-2. **Laboratory-tested water quality parameters detection limits (mg/L unless specified, except metals, µg/L).**

Parameter	Detection Limit
pH, units	0.05[1]
Conductivity, µmhos	50
Alkalinity	1
Color, APHA units	3
Turbidity, NTU units	0.1
TOC	1
SOC	1
TSS	0.001
VSS	0.001
BOD	0.5
TKN	<0.03
NH_3-N	<0.01
NO_2-N	0.02
NO_3/NO_2-N	<0.01
TPO_4-P	<0.01
OPO_4-P	<0.01
SO_4	5
Al	50
B	50
Ba	10
Ca	50
Cd	5
Cr	5
Cu	10
Fe	50
K	500
Li	50
Mg	10
Mn	10
Na	100
P	100
Sr	30
V	10
Zn	10

[1]limit of precision for pH

Table A-3. *In-situ* **water quality of the lower Roanoke River at Pollock's Ferry (RM 105) near Scotland Neck, North Carolina, 1988. River stage levels reflect relative change.**

Date	Time	Temperature (°C) Air	Water	pH	Dissolved oxygen (mg/L)	Conductivity (µmhos)	Total dissolved solids	Secchi depth (cm)	Water velocity (cm/sec)	River stage (ft.)
880414	1000	6.0	13.0		10.4	110		75		11.4
880414	1405	14.0	13.0		9.2	120		80	70.85	
880414	1820	15.0	13.5		9.7	120		65		
880414	2200	12.7	13.0		9.4	100			60.00	12.0
880415	200	9.0	12.5		8.0	110				11.0
880415	600	9.3	12.5		7.3	110			54.00	10.0
880419	1000	9.5	14.0	7.0	8.8	140	5	100	77.68	
880419	1400	7.5	13.5	6.8	8.6	140	5	70	88.29	
880419	1800	8.0	13.5	7.0	6.5	140	5	60	95.68	
880419	2200	4.5	12.5	6.8	8.8	140	6			
880426	200	8.0	14.0	7.0	7.9	130	4		92.77	8.8
880426	600	6.0	14.0	7.2	8.4	130	6	80	93.17	8.8
880426	1000	16.0	15.5	7.0	8.0	140	5	85	92.77	8.7
880426	1400	22.5	16.5	6.8	8.6	130	4		93.99	8.7
880426	1800	21.0	16.5	7.2	8.4	140	5	90	93.99	8.7
880426	2200	13.5	15.0	7.0	8.2	140	5		92.77	8.6
880427	200	10.5	14.5	7.0	8.0	130	5		96.98	8.6
880427	600	7.5	14.5	7.2	7.9	140	3	90	94.83	8.4
880427	1000	19.0	16.5	7.4	7.7	140	5	100	93.99	8.5
880503	200	10.5	14.5	7.0	7.1	140	5		87.44	7.8
880503	600	9.0	14.2	7.1	7.2	140	6	80	87.09	7.8
880503	1000	15.5	15.8	7.1	7.5	130	5	85	81.44	7.9
880503	1400	19.0	16.1	7.1	7.6	140	5	90	79.61	8.0
880503	1800	18.0	15.0	7.1	7.7	140	5	90	74.34	8.0
880503	2200	13.0	14.5	7.0	7.2	150	5		104.08	8.0
880504	200	11.0	14.5	7.0	7.1	150	5		102.09	8.0
880504	600	12.0	14.5	6.9	7.0	150	5	65	96.98	8.0
880504	1000	20.0	15.8	6.9	7.3	150	5	75	93.58	8.3
880510	200	17.5	17.3	7.3	8.4	130			93.58	10.2
880510	600	18.5	17.5	7.2	7.6	130	5	80	92.77	10.0
880510	1000		17.1	7.2	7.7	140	4	80	90.41	9.6
880510	1400	22.0	18.0		7.6	130	4	85	88.53	9.3
880510	1800		18.0		6.8	130	4	100	89.65	9.1
880510	2200	17.0	18.0		6.9	140	5		100.17	9.5
880511	200	15.0	18.2	7.0	6.7	130	5		98.78	10.3
880511	600	13.0	18.0	7.2	6.4	140	5	95	79.91	10.1
880511	1000	22.4	18.5	7.0	5.2	140	4	85	87.09	9.8
880517	200	18.0	20.0	7.0	8.6	150	5		95.68	10.8
880517	600	18.5	20.0	6.7	9.0	130	4	80	80.82	10.4
880517	1000	23.0	21.0	7.1	10.0	120	4	87	79.60	10.0
880517	1400	29.0	22.5	7.1	8.8	130	4	95	77.59	9.9
880517	1800	18.0	20.0	7.0	9.0	130	5	95	82.70	10.5
880517	2200	17.0	20.0	7.3	8.3	140	4		101.60	11.0
880518	200	18.0	19.5	7.3	8.0	140	5		96.11	11.1
880518	600	17.0	19.0	6.9		140	3	95	75.13	10.8
880518	1000	21.0	20.2	6.9		130	3	100	74.86	10.3
880525	200	19.0	21.0	7.3	6.0	70	5		86.73	9.8
880525	600		21.0	7.4	6.0	90	4	80	78.44	10.6
880525	1000	16.0	20.5	7.4	6.2	80	4	100	73.57	10.2
880525	1400									

Table A-3. *continued*

Date	Time	Temperature (°C) Air	Temperature (°C) Water	pH	Dissolved oxygen (mg/L)	Conductivity (μmhos)	Total dissolved solids	Secchi depth (cm)	Water velocity (cm/sec)	River stage (ft.)
880525	1800	12.0	19.1	7.4	6.0	100	5	102	82.37	9.3
880525	2200	11.0	19.8	7.1	5.8	100	4		81.75	9.3
880526	200	10.0	19.0	7.1	5.6	110	4		77.87	9.3
880526	600	13.0	19.8	7.1	5.6	110	4	95	90.79	9.3
880526	1000	16.0	20.0	7.1	5.8	110	4	95	82.70	9.3
880531	600	27.0	24.0	7.7	5.6	80	3	75	77.87	7.5
880531	1000	32.0	24.5	7.8	5.6	90	3	90	76.75	7.5
880531	1400	34.0	25.5	7.9	5.4	90	3	86	78.73	7.6
880531	1800	34.5	24.7	7.6	5.4	90	5	75	85.00	9.3
880531	2200	30.1	23.5	7.6	5.4	90	4		81.44	11.3
880601	200									
880601	600	26.5	22.6	7.7	5.6	90	3	70	91.18	13.4
880601	1000	30.0	23.4	7.6	5.0	80	5	80	91.41	13.4
880607	200	24.0	23.0	7.6	6.8	110	2		80.21	7.7
880607	600	21.0	23.0	7.8	6.4	110	1	42	89.65	10.1
880607	1000	32.0	23.5	7.5	7.2	80	3	65	126.25	12.5

Table A-4. ***In-situ* water quality of the lower Roanoke River and western Albemarle Sound, North Carolina, 1988. Station numbers as in Figure 3. Site 1 = surface; site 2 = mid-depth; site 3 = bottom.**

Date	Station	Time	Site	Depth (m)	Temp. (°C)	Dissolved oxygen (mg/L)	Conductivity (μhmos)	Salinity (ppt)	pH
880414	6	2236	1	5.0	11.0	8.6	110		
880414	6	2236	2		11.0	7.8	110		
880414	6	2236	3		11.5	7.8	110		
880421	6	2220	1	5.0	14.9	5.4	140	0.16	
880421	6		2		14.9	5.4	140	0.16	
880421	6		3		14.9	5.2	140	0.16	
880428	6	2050	1	5.0	17.0	4.9	100	0.00	7.1
880428	6		2		17.0	4.9	100	0.00	
880428	6		3		17.0	4.9	100	0.00	
880505	6	2255	1	5.0	17.8	4.9	100	0.10	7.2
880505	6		2		17.8	4.6	200	0.20	
880505	6		3		17.8	4.4	100	0.10	
880512	6	2050	1	4.5	20.6	8.5	80	0.10	7.3
880512	6		2		19.9	7.7	80	0.10	
880512	6		3		19.6	6.1	80	0.14	
880518	6	2324	1	5.0	21.9	7.0	80	0.12	
880518	6		2		21.9	6.8	80	0.12	
880518	6		3		21.9	6.8	80	0.14	
880526	6	2055	1	5.0	22.0	6.6	70	0.14	7.3
880526	6		2		22.2	6.6	70	0.12	
880526	6		3		22.0	6.6	70	0.12	
880414	7	2235	1	6.0	11.0	8.8	100	0.20	
880414	7	2235	2		11.0	8.0	110		
880414	7	2235	3		11.0	8.0	110		
880421	7	2252	1	6.0	15.0		200	0.20	
880421	7		2		14.9		200	0.20	
880421	7		3		14.9		200	0.20	
880428	7	2000	1	5.0	17.2	5.2	50		6.9
880428	7		2		17.0	5.2	50		
880428	7		3		17.0	5.2	50		
880505	7	2232	1	5.5	18.0	4.6	200	0.20	7.3
880505	7		2		17.8	4.7	100	0.10	
880505	7		3		18.0	4.4	100	0.10	
880512	7	2020	1	9.0	21.7	8.5	40	0.14	7.2
880512	7		2		21.0	6.4	40	0.16	
880512	7		3		19.7	4.3	40	0.10	
880518	7	2400	1	6.0	22.4	6.8	160	0.18	
880518	7		2		22.2	7.0	160	0.18	
880518	7		3		22.1	7.0	160	0.20	
880526	7	2028	1	7.0	22.7	7.1	200	0.20	7.2
880526	7		2		22.7	7.1	60	0.12	
880526	7		3		22.5	7.3	60	0.14	
880414	8	100	1	5.0	10.5	8.0	100		
880414	8	100	2		10.5	7.1	100		
880414	8	100	3		10.5	7.1	100		
880421	8	2111	1	6.1	15.2	4.7	100	0.10	
880421	8		2		15.2	4.8	0	0.00	
880601	13	2330	1	1.2	23.9	7.9	160	0.14	7.1
880601	13		2		23.5	7.8	160	0.14	
880601	13		3		23.5	7.7	160	0.14	
880601	15	2235	1	2.5	25.2	8.4	160	0.14	7.3
880601	15		2		25.1	8.2	160	0.14	
880601	15		3		24.0	7.6	160	0.14	

Table A-5. **Water quality analysis for five sites in the lower Roanoke River watershed, North Carolina, in 1988. Sta 1 = Pollocks Ferry, 6 = Middle River, 7 = Roanoke above Weyerhaeuser, 8 = Cashie River, 10 = Roanoke above Highway 45 bridge. D = discrete sample, C = composite, S = surface, M = mid-depth, B = bottom, * = sample lost.**

Date	Sta	Time	pH	Cond (µmhos)	Alk	Color (APHA)	Turb (NTU)	TOC	SOC	TSS	VSS	BOD	TKN	NH_3-N	NO_2-N	NO_3-NO_2-N
880414	1 D	1000	7.71	100	25	25	10	4.0		10.393	1.966	1.6	0.34	0.077	0.005	0.129
880414	1 D	1400	7.71	100	27	24	11	3.1	2.7	12.425	2.806	1.0	0.11	0.061	0.005	0.135
880414	1 D	1800	7.53	100	26	25	10	4.7	3.3	10.241	1.606	1.0	0.15	0.077	0.005	0.129
880414	1 D	2200	7.61	100	23	30	11	3.3	8.3	10.200	1.400	1.0	0.34	0.090	0.005	0.135
880415	1 D	200	7.63	100	23	25	11	9.1	3.4	9.697	2.222	1.1	0.28	0.085	0.005	0.140
880419	1 D	1000	7.76	100	29	30	11	4.1	3.0	8.200	2.000	1.8	0.33	0.062	0.005	0.176
880419	1 D	1400	7.58	100	24	33	17	4.4	3.5	12.525	1.392	2.0	0.19	0.069	0.005	0.188
880419	1 D	1800	7.63	100	29	34	17	3.8	3.6	13.527	1.825	1.9	0.33	0.096	0.007	0.174
880426	1 C	9999	7.65	100	28	22	10	11.2	4.4	9.722	1.984	1.4	0.24	0.088	0.004	0.177
880503	1 D	600	7.65	100	32	27	9	8.0	2.7	11.178	2.196	1.1	0.46	0.070	0.004	0.169
880503	1 D	1000	7.64	100	24	29	10	3.4		9.820	2.204	1.0	0.30	0.063	0.005	0.163
880503	1 D	1400	7.63	100	33	31	10	7.0	3.2	10.822	2.405	1.5	0.32	0.039	0.005	0.157
880503	1 D	1800	7.52	100	23	39	10	3.1		11.200	2.400	1.4	0.37	0.061	0.006	0.154
880503	1 D	2200	7.54	100	26	32	9	4.4	2.7	10.159	2.390	1.3	0.28	0.068	0.004	0.169
880504	1 D	200	7.64	100	28	26	12	5.0	4.9	18.759	5.219	2.6	0.59	0.050	0.005	0.167
880504	1 D	600	7.58	100	22	35	13	7.1	3.1	16.146	4.872	2.8	0.32	0.053	0.005	0.168
880510	1 C	9999	7.56	100	25	14	11	4.3	3.1	11.687	2.530	0.9	0.32	0.044	0.006	0.151
880517	1 D	600	7.61	100	24	15	10	3.7	2.7	10.240	1.517	0.8	0.22	0.050	0.006	0.117
880517	1 D	1000	7.66	105	28	19	10	57.7	16.4	11.697	1.950	0.9	0.35	0.049	0.005	0.125
880517	1 D	1400	7.67	105	23	32	12	3.0		13.102	2.128	1.0	0.34	0.054	0.006	0.140
880517	1 D	1800	7.62	110	25	18	14	8.5	3.5	13.441	2.202	1.4	0.44	0.061	0.009	0.142
880517	1 D	2200	7.64	110	24	16	13	4.3	2.4	12.108	1.906	1.4	0.40	0.064	0.006	0.106
880518	1 D	200	7.72	120	33	16	11	3.4	2.3	11.269	1.751	1.2	0.38	0.046	0.006	0.126
880518	1 D	600	7.69	110	23	16	12	2.9	2.1	10.843	1.643	1.1	0.39	0.089	0.005	0.122
880525	1 C	9999	7.54	100	26	30	12			17.600	3.400	1.5	0.45	0.064	0.011	0.152
880531	1 D	600	7.41	100	25	13	13	2.9	3.4	13.373	1.996	0.8	0.23	0.048	0.012	0.132
880531	1 D	1000	7.45	110	26	15	12	3.5	2.5	15.170	2.794	0.9	0.35	0.049	0.012	0.112
880531	1 D	1400	7.49	100	29	15	10	2.5	2.4	11.928	2.386	0.9	0.33	0.040	0.010	0.122
880531	1 D	1800	7.45	110	27	15	14	6.1	2.5	18.962	2.994	0.7	0.40	0.070	0.010	0.121
880531	1 D	2200	7.45	100	25	23	19	5.7	2.6	26.587	4.564	0.9	0.69	0.076	0.010	0.139
880601	1 D	600	7.40	100	28	12	16	3.8	3.9	19.145	3.527	1.0	0.41	0.074	0.008	0.096
880608	1 C	9999	7.65	100	30	10	16	4.2	3.3	21.463	3.180	1.3	0.29	0.032	0.005	0.113
880414	6 C	2400	7.71	110	27	58	18	12.8	6.3	17.000	1.972	1.1	0.48	0.072	0.007	0.153
880421	6 C	2300	7.59	95	23	60	17	42.7	39.7	8.871	1.200	1.1	0.48	0.185	0.007	0.152
880428	6 C	2050	7.42	100	22	40	15			14.571	2.595	1.1	0.32	0.084	0.004	0.199

Table A-5. *continued*

Date	Sta	Time	pH	Cond (μmhos)	Alk	Color (APHA)	Turb (NTU)	TOC	SOC	TSS	VSS	BOD	TKN	NH_3-N	NO_2-N	NO_3-NO_2-N
880505	6 C	2255	7.30	100	30	27	17	6.0	5.3	18.316	2.808	1.3	0.39	0.078	0.005	0.359
880512	6 C	2050	7.31	100	29	111	14	4.3	4.9	14.257	2.574	0.7	0.36	0.055	0.006	0.174
880518	6 C	2324	7.44	99	29	22	37	8.2	3.4	48.139	6.204	1.0	0.60	0.119	0.005	0.150
880526	6 C	2055	7.42	100	26	28	21	5.0	3.8	22.754	4.192	1.0	0.57	0.060	0.007	0.186
880414	7 C	2300	7.32	100	25	61	16	37.1	6.4	13.710	1.613	1.0	0.48	0.092	0.008	0.148
880421	7 C	2230	7.57	95	25	58	16	6.6	6.7	8.400	2.400	1.0	0.47	0.101	0.008	0.144
880428	7 C	2000	7.31	100	25	46	15			14.571	2.994	1.2	0.32	0.075	0.005	0.199
880505	7 C	2322	7.10	100	23	29	18	16.5	3.5	18.495	3.349	1.2	0.38	0.073	0.006	0.178
880512	7 S	2020	7.45	110	28	152	11	16.3	3.8	10.002	2.836	0.7	0.55	0.040	0.006	0.173
880512	7 M	2020	7.42	110	25	32	12	5.6		11.911	2.703	1.0	0.41	0.063	0.006	0.168
880512	7 B	2020	7.37	110	29	39	14	4.6		13.069	2.574	0.9	0.45	0.045	0.006	0.172
880518	7 C	2400	7.47	98	28	26	30	3.9	3.0	33.903	3.704	1.0	0.43	0.040	0.005	0.135
880526	7 S	2028	7.34	100	26	30	17	4.3	3.5	12.354	1.836	0.8	0.47	0.109	0.005	0.330
880526	7 M	2028	7.37	100	29	25	17	4.6	3.7	17.505	3.823	0.9	0.38	0.078	0.006	0.233
880526	7 B	2028	7.41	100	22	23	21	4.0	5.3	21.200	4.400	0.8	0.34	0.104	0.007	0.455
880415	8 C	110	7.41	92	15	106	10	50.6	15.1	8.283	2.020	1.4	0.53	0.084	0.008	0.089
880421	8 C	2100	7.44	88	16	93	13	35.2	38.3	8.800	2.000	1.3	0.48	0.098	0.006	0.097
880428	8 C	2140	7.15	94	24	56	10			9.200	2.200	1.2	0.31	0.121	0.006	0.167
880505	8 C	2200	7.29	100	28	37	13	50.1	43.5	11.558	1.818	1.3	0.43	0.070	0.006	0.149
880512	8 C	2200	7.25	92	27	45	11	5.5	4.8	9.514	2.227	1.0	0.38	0.054	0.006	0.139
880518	8 C	2215	7.26	97	20	35	41	7.5		51.143	6.854	1.5	0.62	0.075	0.007	0.098
880526	8 C	2215	7.15	98	22	44	57	8.7	5.6	74.895	13.479	1.4	1.25	0.090	0.005	0.363
880601	8 C	2400	7.35	100	25	40	29	8.0	4.9	38.228	7.089	1.2	0.55	0.062	0.006	0.131
880609	8 C	1940	7.46	120	23	22	13	8.2	3.7	11.881	3.168	1.1	0.30	0.072	0.006	0.163
880415	10 C	200	7.31	130	27	80	16		7.9	13.138	2.811	1.6	0.82	0.191	0.009	0.162
880421	10 C	1924	7.51	120	23	71	17	9.9	8.1	12.600	2.600	1.6	0.68	0.066	0.007	0.101
880428	10 C	2300	7.21	110	25	60	13			11.222	2.204	1.2	0.46	0.143	0.006	0.192
880505	10 C	2130	7.32	120	26	51	15	26.3	32.2	14.954	2.511	1.4	0.55	0.180	0.009	0.147
880512	10 S	2450	7.26	130	27	83	15	7.2	6.1	12.903	2.419	0.8	0.62	0.171	0.007	0.147
880512	10 M	2450	7.35	120	26	86	16	7.2	6.8	13.846	3.162	1.0	0.65	0.174	0.008	0.141
880512	10 B	2450	7.34	130	29	151	18	8.2	5.3	17.878	3.166	0.9	0.74	0.170	0.010	0.126
880518	10 C	2020	7.36	120	21	37	16	5.8	4.5	12.181	2.550	1.1	0.61	0.187	0.008	0.337
880526	10 S	2445	7.39	120	32	42	15	5.5	4.4	12.151	2.988	1.1	0.60	0.166	0.006	0.150
880526	10 M	2445	7.40	120	27	42	16	7.4	4.8	14.571	2.595	1.2	0.60	0.151	0.007	0.194
880526	10 B	2445	7.43	120	25	37	17	5.6		14.653	3.366	1.1	0.51	0.163	0.007	0.133
880601	10 C	2455	7.41	135	28	43	29	5.8	5.4	33.253	6.747	1.3	0.65	0.136	0.007	0.178
880609	10 C	2005	7.59	140	29	25	15	4.9	3.7	13.828	2.806	1.4	0.62	0.076	0.006	0.173

Table A-5. *continued*

Date	Sta	Time	pH	Cond (μmhos)	Alk	Color (APHA)	Turb (NTU)	TOC	SOC	TSS	VSS	BOD	TKN	NH_3-N	NO_2-N	NO_3-NO_2-N
880601	13	C2330	7.43	110	27	45	9	5.3	4.2	6.494	2.597	1.0	0.47	0.076	0.006	01.24
880601	15	C2235	7.44	120	28	31	5	8.9	5.1	3.777	2.187	1.6	0.60	0.037	0.006	0.112

Table A-5. *continued*

Date	Sta	Time	TPO_4-P	OPO_4-P	SO_4^{2-}	(µg/L)	Al	B	Ba	Ca	Cd	Cr	Cu	Fe	K	Li
880414	1 D	1000	0.085	0.029			260	<50	21	6440	<5	<5	<10	530	2000	<20
880414	1 D	1400	0.072	0.018	12.26		330	<50	22	6430	<5	<5	<10	630	2000	<20
880414	1 D	1800	0.115	0.063	10.00		260	<50	23	6830	<5	<5	<10	470	2000	<20
880414	1 D	2200	0.084	0.038	12.21		260	<50	22	6670	<5	<5	<10	520	2000	<20
880415	1 D	200	0.070	0.025	9.27		260	<50	22	6750	<5	<5	<10	530	2000	<20
880419	1 D	1000	0.119	0.026	*	0.9	360	<50	20	6590	<5	<5	<10	610	2000	<20
880419	1 D	1400	0.292	0.036	22.38	1.6	390	<50	22	6320	<5	<5	<10	690	2000	<20
880419	1 D	1800	0.062	0.019	12.70	2.2	500	<50	23	6350	<5	6	<10	840	2000	<20
880426	1 C	9999	0.188	0.020	11.85	0.9	300	<50	22	6590	<5	<5	<10	570	2000	<20
880503	1 D	600	0.173	0.015	11.23	0.9	287	34	21	7020	<5	<5	<10	490	2000	<30
880503	1 D	1000	0.299	0.026	10.83	2.0	315	48	21	6980	<5	<5	<10	520	2000	<30
880503	1 D	1400	0.260	0.014	10.81	28.0	318	17	21	7200	<5	<5	<10	490	3000	<30
880503	1 D	1800	0.047	0.013	*	1.0	292	28	21	7130	<5	<5	<10	500	2000	<30
880503	1 D	2200	0.221	0.020	12.08	0.9	242	29	21	7130	<5	<5	<10	400	2000	<30
880504	1 D	200	0.128	0.013	*	2.2	342	44	23	7130	<5	<5	<10	510	3000	<30
880504	1 D	600	0.187	0.018	*	0.9	432	35	23	7120	<5	<5	<10	620	2000	<30
880510	1 C	9999	0.292	0.172	11.04	1.3	331	39	22	6900	<5	<5	<10	590	2000	<30
880517	1 D	600	0.113	0.082	10.73	3.0	355	<50	21	6510	<5	<5	<10	350	2700	<30
880517	1 D	1000	0.115	0.054	10.70	1.4	560	<50	23	6540	<5	<5	<10	580	2300	<30
880517	1 D	1400	0.113	0.104	11.76	3.1	410	<50	23	6480	<5	<5	<10	430	2200	<30
880517	1 D	1800	0.130	0.048	11.71	1.6	530	<50	23	6610	<5	<5	<10	510	2300	<30
880517	1 D	2200	0.138	0.060	*	0.9	700	<50	23	6670	<5	<5	<10	600	2400	<30
880518	1 D	200	0.139	0.110	10.42	0.9	650	<50	23	6620	<5	<5	<10	580	2400	<30
880518	1 D	600	0.112	0.096	12.36	1.0	460	<50	21	6430	<5	<5	<10	380	2200	<30
880525	1 C	9999	0.070	0.017	9.67		830	<50	23	6590	<5	<5	<10	700	2400	<30
880531	1 D	600	0.112	0.051	12.18	3.8	710	<50	23	6700	<5	<5	<10	610	2500	<30
880531	1 D	1000	0.115	0.105	12.38	1.2	580	<50	21	6560	<5	<5	<10	480	2500	<30
880531	1 D	1400	0.100	0.045	13.14	0.9	570	<50	23	6740	<5	<5	<10	550	2500	<30
880531	1 D	1800	0.141	0.025	11.55	0.9	760	<50	26	6780	<5	<5	<10	810	2500	<30
880531	1 D	2200	0.150	0.081	11.53	0.9	1050	70	27	6890	<5	6	<10	1040	2600	<30
880601	1 D	600			8.63	0.9	920	<50	24	6620	<5	<5	<10	790	2500	<30
880608	1 C	9999	0.161	0.053	11.74	2.3	690	<50	27	6710	<5	7	<10	980	2400	<30
880414	6 C	2400	0.325	0.036	11.58		600	<50	30	6620	<5	<5	<10	1520	2000	<20
880421	6 C	2300	0.089	0.025	5.59		470	50	25	6230	<5	<5	<10	950	2000	<20
880428	6 C	2050	0.198	0.031	7.66		440	50	28	6450	<5	<5	<10	1140	2000	<20
880505	6 C	2255	0.156	0.139	12.41		529	22	25	7160	<5	<5	<10	1080	3000	<30
880512	6 C	2050	0.125	0.093	13.81		471	21	25	6780	<5	<5	<10	1010	2000	<30
880518	6 C	2324	0.102	0.128	9.85		2660	50	38	6500	<5	<5	<10	2260	2600	<30

Table A-5. *continued*

Date	Sta	Time	TPO_4-P	OPO_4-P	SO_4^{2-}	(µg/L)	Al	B	Ba	Ca	Cd	Cr	Cu	Fe	K	Li
880526	6 C	2055	0.153	0.120	11.48		1760	50	32	6570	<5	<5	<10	1740	2700	<30
880414	7 C	2300	0.142	0.030	9.23		550	60	29	6500	<5	<5	<10	1380	2000	<20
880421	7 C	2230	0.068	0.028	8.91		420	50	25	6060	<5	<5	<10	900	2000	<20
880428	7 C	2000	0.313	0.028	9.52		450	50	28	6600	<5	<5	<10	1180	2000	<20
880505	7 C	2322	0.119	0.069	12.23		501	30	25	6920	<5	<5	<10	1080	2000	<30
880512	7 S	2020	0.195	0.086	10.83		341	24	23	6880	<5	<5	<10	810	3000	<30
880512	7 M	2020	0.143	0.079	13.30		340	23	24	6960	<5	<5	<10	860	3000	<30
880512	7 B	2020	0.128	0.073	28.20		430	25	25	6880	<5	<5	<10	1000	3000	<30
880518	7 C	2400	0.188	0.081	10.00		1540	50	29	6400	<5	6	<10	1400	2400	<30
880526	7 S	2028	0.137	0.146	11.76		930	50	27	6530	<5	<5	<10	940	2700	<30
880526	7 M	2028	0.136	0.115	13.07		920	50	27	6490	<5	<5	<10	990	2500	<30
880526	7 B	2028	0.093	0.044	12.04		1120	50	27	6610	<5	<5	<10	1030	2600	<30
880415	8 C	110	0.118	0.027	1.51		360	50	32	5290	<5	<5	<15	1230	2000	<20
880421	8 C	2100	0.147	0.030			380	50	28	5530	<5	<5	<10	1070	2000	<20
880428	8 C	2140	0.081	0.026	2.79		360	50	27	6150	<5	<5	<10	1010	2000	<20
880505	8 C	2200	0.220	0.115	11.13		445	28	25	6680	<5	<5	<10	990	2000	<30
880512	8 C	2200	0.134	0.037	10.68		392	87	24	6650	<5	<5	<10	900	3000	<30
880518	8 C	2215	0.260	0.087	7.59		1110	50	29	6080	<5	<5	<10	1220	2500	<30
880526	8 C	2215	0.314	0.081	3.35		2020	70	38	6200	<5	6	<10	2490	2400	<30
880601	8 C	2400	0.113	0.076	3.58		1060	90	49	9010	<5	7	<10	3910	2800	<30
880609	8 C	1940	0.182	0.064	13.16		670	80	27	6160	<5	<5	<10	770	2400	<30
880415	10 C	200	0.118	0.043	9.05		550	50	30	6900	<5	<5	<10	1390	2000	<20
880421	10 C	1924	0.117	0.051	9.71		530	50	27	6450	<5	<5	<10	1040	2000	<20
880428	10 C	2300	0.196	0.037	12.18		450	50	27	6810	<5	<5	<10	1100	2000	<20
880505	10 C	2130	0.296	0.177	17.58		593	74	26	7390	<5	<5	<10	1050	3000	<30
880512	10 S	2450	0.215	0.187	16.48		557	82	26	7250	<5	<5	<10	1030	3000	<30
880512	10 M	2450	0.241	0.082	18.61		458	31	26	7230	<5	<5	<10	950	3000	<30
880512	10 B	2450	0.181	0.114	20.72		556	63	26	7250	<5	<5	<10	1080	3000	<30
880518	10 C	2020	0.193	0.111	14.76		1020	90	27	6630	<5	<5	<10	850	2600	<30
880526	10 S	2445	0.144	0.062	15.05		860	50	29	6880	<5	<5	<10	960	2600	<30
880526	10 M	2445	0.152	0.128	14.22		820	90	29	6810	<5	<5	<10	990	2600	<30
880526	10 B	2445	0.161	0.110	14.71		1100	50	29	6800	<5	<5	<10	1070	2700	<30
880601	10 C	2455	0.173	0.078	14.75		450	50	31	6910	<5	<5	<10	1390	2600	<30
880609	10 C	2005	0.154	0.046	18.23		670	90	28	6730	<5	<5	<10	800	2600	<30
880601	13 C	2330	0.126	0.122	12.94		240	50	27	6130	<5	<5	<10	720	2400	<30
880601	15 C	2235	0.125	0.103	12.41		1110	50	25	6230	16	<5	<10	550	2400	<30

Table A-5. *continued*

Date	Sta	Time	Mg	Mn	Na	P	Sr	V	Zn
880414	1 D	1000	2660	46	8000	<100	46	<10	<10
880414	1 D	1400	2690	52	8300	<100	46	<10	<10
880414	1 D	1800	2740	50	8400	<100	48	<10	25
880414	1 D	2200	2720	46	8900	<100	47	<10	<10
880415	1 D	200	2700	46	8100	<100	47	<10	<10
880419	1 D	1000	2710	35	9000	<100	47	<10	20
880419	1 D	1400	2640	41	8800	<100	46	<10	13
880419	1 D	1800	2660	42	9100	<100	46	<10	63
880426	1 C	9999	2720	42	9200	<100	48	<10	<10
880503	1 D	600	2890	42	9200	<100	46	<10	<10
880503	1 D	1000	2880	45	9300	<100	46	<10	<10
880503	1 D	1400	2920	44	9100	<100	46	<10	17
880503	1 D	1800	2900	43	9500	<100	46	<10	<10
880503	1 D	2200	2890	37	9300	<100	46	<10	11
880504	1 D	200	2950	42	9300	140	46	<10	33
880504	1 D	600	2950	47	9500	150	46	<10	51
880510	1 C	9999	2860	51	8900	<100	46	<10	24
880517	1 D	600	2730	41	8400	120	46	<10	16
880517	1 D	1000	2770	48	8300	140	46	<10	<10
880517	1 D	1400	2730	39	8300	130	46	<10	55
880517	1 D	1800	2780	41	8800	120	47	<10	34
880517	1 D	2200	2790	43	9200	120	46	<10	<10
880518	1 D	200	2780	44	9700	120	46	<10	<10
880518	1 D	600	2690	32	8400	100	45	<10	15
880525	1 C	9999	2790	55	8600	110	46	<10	<10
880531	1 D	600	2810	41	9400	150	47	<10	<10
880531	1 D	1000	2770	37	9400	160	46	<10	15
880531	1 D	1400	2850	43	9500	150	48	<10	21
880531	1 D	1800	2870	60	9300	150	48	<10	44
880531	1 D	2200	2930	70	9500	130	49	<10	<10
880601	1 D	600	2820	71	8300	130	47	<10	<10
880608	1 C	9999	2840	77	9600	180	47	<10	<10
880414	6 C	2400	2650	98	11000	130	49	<10	54
880421	6 C	2300	2570	45	8800	<100	47	<10	46
880428	6 C	2050	2660	93	8900	<100	49	<10	9
880505	6 C	2255	2940	92	9300	130	47	<10	9
880512	6 C	2050	2860	76	9300	110	46	<10	10
880518	6 C	2324	2900	152	9300	160	47	<10	10

Table A-5. *continued*

Date	Sta	Time	Mg	Mn	Na	P	Sr	V	Zn
880526	6 C	2055	2860	110	8900	180	47	<10	97
880414	7 C	2300	2610	79	11000	100	49	<10	15
880421	7 C	2230	2510	46	9000	<100	46	<10	9
880428	7 C	2000	2690	91	8800	<100	49	<10	9
880505	7 C	2322	2930	90	9500	<100	47	<10	11
880512	7 S	2020	2850	61	9300	<100	47	<10	13
880512	7 M	2020	2870	66	9200	110	46	<10	9
880512	7 B	2020	2880	74	9400	110	47	<10	73
880518	7 C	2400	2770	99	9300	150	46	<10	22
880526	7 S	2028	2780	65	9100	170	47	<10	9
880526	7 M	2028	2770	69	9000	160	47	<10	27
880526	7 B	2028	2810	152	9200	160	48	<10	19
880415	8 C	110	2090	77	9000	110	43	15	10
880421	8 C	2100	2270	63	9000	<100	43	<10	24
880428	8 C	2140	2520	74	8600	140	47	<10	9
880505	8 C	2200	2820	81	9100	<100	46	<10	9
880512	8 C	2200	2820	65	8600	120	45	<10	87
880518	8 C	2215	2680	105	8800	130	45	<10	9
880526	8 C	2215	2740	200	8500	160	47	<10	26
880601	8 C	2400	2990	327	9100	240	51	11	69
880609	8 C	1940	2850	83	11000	120	48	<10	9
880415	10 C	200	2640	91	15000	170	50	<10	17
880421	10 C	1924	2550	58	14000	<100	48	<10	32
880428	10 C	2300	2680	87	13000	<100	51	<10	9
880505	10 C	2130	2980	94	15000	110	49	<10	40
880512	10 S	2450	2920	78	15000	130	48	<10	80
880512	10 M	2450	2910	77	15000	130	48	<10	12
880512	10 B	2450	2910	84	15000	130	48	<10	22
880518	10 C	2020	2770	76	13000	120	47	<10	12
880526	10 S	2445	2820	74	13000	160	49	<10	12
880526	10 M	2445	2810	76	12000	140	49	<10	27
880526	10 B	2445	2810	76	12000	170	49	<10	22
880601	10 C	2455	2910	122	14000	160	50	<10	9
880609	10 C	2005	2920	81	14000	140	50	<10	12
880601	13 C	2330	2880	82	10000	150	48	<10	21
880601	15 C	2235	3020	67	10000	150	48	<10	75