EFFECTS OF WATER-CONTROL STRUCTURES ON HYDROLOGIC AND WATER-QUALITY CHARACTERISTICS IN SELECTED AGRICULTURAL DRAINAGE CANALS IN EASTERN NORTH CAROLINA

by M.W. Treece, Jr., and M.L. Jaynes

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	*By*	*To obtain*
	Length	
inch (in.)	25.4	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
	Area	
acre	4,047	square meter
square mile (mi^2)	2.590	square kilometer
	Flow	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
cubic foot per second per square mile [$(ft^3/s)/mi^2$]	0.01093	cubic meter per second per square kilometer

Temperature: Temperature is given in degrees Celsius (°C), which can be converted to degrees Fahrenheit (°F) by the following equation:

$$°F = 1.8\ (°C) + 32$$

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

Abbreviations:
in/yr, inch per year
mg/L, milligram per liter
mL, milliliter
mi/hr, mile per hour
ppt, part per thousand
µS/cm, microsiemens per centimeter at 25 °Celsius
lb/d, pound per day
lbs/acre, pound per acre

EFFECTS OF WATER-CONTROL STRUCTURES ON HYDROLOGIC AND WATER-QUALITY CHARACTERISTICS IN SELECTED AGRICULTURAL DRAINAGE CANALS IN EASTERN NORTH CAROLINA

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ABSTRACT

Movement of water into and out of tidally affected canals in eastern North Carolina was documented before and after the installation of water-control structures. Water levels in five of the canals downstream from the water-control structures were controlled primarily by water-level fluctuations in estuarine receiving waters. Water-control structures also altered upstream water levels in all canals. Water levels were lowered upstream from tide gates, but increased upstream from flashboard risers. Both types of water-control structures attenuated the release of runoff following rainfall events, but in slightly different ways. Tide gates appeared to reduce peak discharge rates associated with rainfall, and flashboard risers lengthened the duration of runoff release.

Tide gates had no apparent effect on pH, dissolved oxygen, suspended-sediment, or total phosphorus concentrations downstream from the structures. Specific conductance measured from composite samples collected with automatic samples increased downstream of tide gates after installation. Median concentrations of nitrite plus nitrate nitrogen were near the minimum detection level throughout the study; however, the number of observations of concentrations exceeding 0.1 milligram per liter dropped significantly after tide gates were installed. Following tide-gate installation, instantaneous loadings of nitrite plus nitrate nitrogen were significantly reduced at one test site, but this reduction was not observed at the other test site. Loadings of other nutrient species and suspended sediment did not change at the tide-gate test sites after tide-gate installation.

Specific conductance was lower in the Beaufort County canals than in the Hyde County canals. Although there was a slight increase in median values at the flashboard-riser sites, the mean and maximum values declined substantially downstream from the risers following installation. This decline of specific conductance in the canals occurred despite a large increase of specific conductance in the tidal creek.

Flashboard risers had no significant effect on concentrations of dissolved oxygen, suspended sediment, total ammonia plus organic nitrogen, or phosphorus. Maximum concentrations of ammonia nitrogen were smaller at both test sites after riser installation. In addition, concentrations of nitrite plus nitrate nitrogen exceeding 1.0 milligram per liter rarely occurred at the flashboard-riser test sites following installation of the risers. Median loadings of nitrite plus nitrate nitrogen and total nitrogen decreased at one riser test site following flashboard-riser installation.

Tide gates and flashboard risers were associated with reductions in concentrations and export of nitrite plus nitrate nitrogen; however, these changes should be interpreted cautiously because reductions were not observed consistently at every site. The hydrology and baseline water-quality characteristics of the two study areas differ, making comparisons of the effectiveness of the two types of water-control structures difficult to interpret.

The effects of water-control structures on the hydrology of the drainage canals are more meaningful than the changes in water quality. Tide gates and flashboard risers altered the hydrologic characteristics of the drainage canals and created an environment favorable for nutrient loss or transformation. Both structures retained agricultural drainage upstream, which increased potential storage for infiltration and reduced the potential for surface runoff, sediment, and nutrient transport, and higher peak outflow rates.

INTRODUCTION

North Carolina has more than 2 million acres of estuarine waters that provide a myriad of ecological and economic benefits. Protection of these waters is a high priority in the State. However, recent estimates indicate that nonpoint sources account for approximately 80 percent of the degradation of the State's coastal waters that do not fully support their designated uses (North Carolina Department of Environment, Health, and Natural Resources, 1990c).

Nonpoint sources of contamination have contributed to the degradation of surface waters in the Albemarle-Pamlico (A-P) estuarine system (Jones and Sholar, 1981; North Carolina Department of Natural Resources and Community Development, 1982; North Carolina Department of Environment, Health, and Natural Resources, 1990c). In this region, water-quality degradation is caused most often by eutrophication, which can result in undesirable algal blooms, oxygen depletion, and fish kills. Eutrophication is caused by excessive inputs of nutrients, such as nitrogen and phosphorus. Agricultural runoff can contribute to eutrophication by increasing nutrient loadings to estuarine waters (Evans and others, 1991).

Agricultural practices can alter levels of constituents carried by runoff and affect the quantity and movement of freshwater that flows into estuaries. Croplands in eastern North Carolina typically are drained by an array of small ditches that feed larger collector canals that, in turn, empty into estuarine creeks or other receiving waters. Artificial drainage systems increase the rate and can increase the volume of land-surface runoff (Daniel, 1981; Gilliam and Skaggs, 1986). Agricultural runoff into the receiving estuarine waters can adversely affect biological productivity. Nutrient loads are of concern because of potential eutrophic effects, and freshwater intrusion can upset the salinity balance required to sustain certain biota.

Water-control structures can help mitigate the adverse effects of agricultural drainage on sensitive estuarine waters (Gilliam, 1987) when used in draining cropland in the Coastal Plain of North Carolina. Water-control structures provide on-site benefits to the farmer; for example, flashboard risers allow the farmer to exert some control over field soil-moisture conditions. Also, water-control structures reduce the upstream movement of saline water onto fields, which can damage crops and jeopardize the productivity of the soil.

Flashboard risers and tide gates are two primary types of water-control structures used in the State's coastal counties (fig. 1). Flashboard risers, which allow landowners to control drainage from ditches upstream from these structures, are a widely accepted "best-management practice" in the A-P region. A flashboard riser consists of a vertical frame (the riser) constructed to hold a series of boards which extend across the width of the canal providing a barrier to water movement in the ditch or canal (fig. 1A). The crest elevation of flashboard risers can be changed at any time by removing or adding boards to the structure.

Tide gates allow landowners limited control in regulating water level or flow, and are commonly used in agricultural drainage canals throughout eastern North Carolina. A tide gate consists of an aluminum culvert with a hinged cover that opens solely in response to a minimum difference between water levels upstream and downstream from the structure (fig. 1B). According to the design used most often in North Carolina, the tide gates open and allow drainage from upstream fields when the upstream water level exceeds downstream water level by more than 0.2 foot (ft) (R. Woolard, U.S. Soil Conservation Service, oral commun., 1989). When a tide gate is functioning properly, flow through the gate is in one direction (downstream) and the tide gate prohibits upstream backflows.

In 1984, the North Carolina Division of Soil and Water Conservation implemented the North Carolina Agricultural Cost Share Program (ACSP) (North Carolina Department of Environment, Health, and Natural Resources, 1990c). An objective of this program is to protect coastal waters by applying best-management practices to reduce the delivery of agricultural nonpoint-source contaminants into the State's surface waters by application of best-management practices. The ACSP provides funding for the installation of flashboard risers in ditches and canals that drain agricultural lands. Despite widespread use, tide gates are not an ACSP-approved best-management practice because the benefits of tide gates to downstream water quality have not been well documented.

In 1988, the U.S. Geological Survey (USGS), in cooperation with the North Carolina Department of Environment, Health, and Natural Resources, began a 4-year investigation to address issues concerning artificial drainage of cropland, water-control structures, and estuarine receiving-water quality. The objective of the investigation was to evaluate the effects of two types of water-control structures--tide gates and flashboard risers--on the hydrology and water quality of drainage canals and downstream receiving waters.

Study sites were established in two locations in the Coastal Plain of North Carolina. Tide gate study sites were located on three canals in Hyde County, and flashboard riser study sites were located on three canals in Beaufort County (fig. 2). Data also were collected in

A

B

Figure 1. Photographs of a (A) flashboard riser and (B) tide gate at study sites in eastern North Carolina.

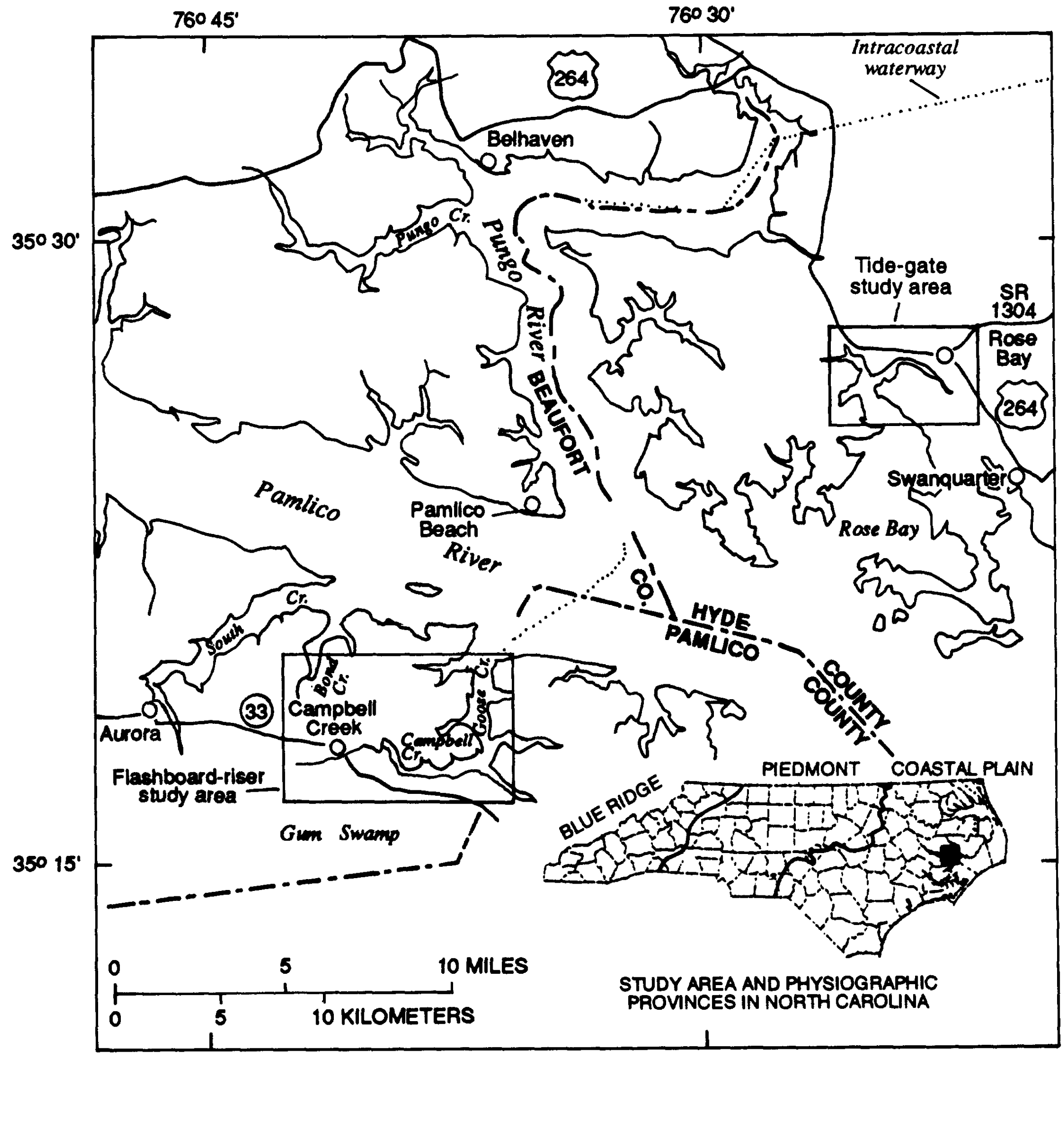

Figure 2. General location of study areas.

Campbell Creek, a tidal creek that receives drainage from two of the Beaufort County canals. In this report, the tide-gate sites are often referred to as the Hyde County sites, and the flashboard-riser sites are referred to as the Beaufort County sites.

Purpose and Scope

This report presents the results of the study to evaluate the effects of tide gates and flashboard risers on the hydrologic and water-quality characteristics in selected agricultural drainage canals. Data are evaluated to quantify hydrologic and water-quality changes that occurred in each canal upstream and downstream from the water-control structures following their installation. Changes measured at the test sites are compared to conditions at reference sites to determine if the changes resulted from the effects of water-control structures or from natural variations. Hydrologic and water-quality conditions in a tidal creek receiving cropland drainage also are compared before and after installation of flashboard risers in canals draining to the creek.. Analyses are based on data collected from May 1988 through April 1992.

Movement of water into and out of tidally affected canals was documented before and after the installation of water-control structures. Hydrologic data include continuous records of water levels in canals upstream and downstream from the water-control structures and stream velocities downstream from water-control structures. Discharge was computed from water-level and velocity measurements made downstream from water-control structures. Specific conductance, pH, water temperature, and dissolved-oxygen concentrations were recorded biweekly in the canals and the tidal creek. Suspended-sediment and nutrient concentrations (total nitrite plus nitrate, total ammonia plus organic nitrogen, total ammonia, total phosphorus, and total orthophosphate) were analyzed in samples collected at biweekly intervals. Continuous records of specific conductance also were obtained in the canals and in the tidal creek.

Approach

The effects of water-control structures on downstream water quality and hydrologic conditions were characterized before and after the installation of water-control structures. In each study area (fig. 2), two canals were established as test sites and one canal was established as a reference site. At the reference sites, water-control structures were installed at the beginning of the investigation so that changes recorded at the test sites could be related to conditions at the reference sites. This information was used to determine whether changes at the test sites resulted from the effects of the water-control structures or were simply due to natural environmental variability. At the test sites, water-control structures were installed about midway through the investigation.

Water-levels and flows were evaluated with particular emphasis on mean water levels and peak flows. Any changes in hydrology that potentially could alter water-quality concentrations and loadings to receiving waters were identified. Water-quality and hydrologic data were analyzed graphically using time-series plots and box plots. The Wilcoxon rank-sum test was used to determine if the distributions of concentrations and instantaneous loads for before and after water-control structure installation were statistically different. Kendall rank-order correlations were used to examine relations of nutrient fractions to physical and hydrologic properties.

Hydrologic and water-quality data collected at the tide-gate sites were compared to data collected at the flashboard-riser sites. The Kruskal-Wallis analysis of variance was used to determine if differences between sites within each study area were statistically significant. The effects of freshwater drainage from the upland agricultural drainage canals on water quality in the receiving waters of the tidal creek were evaluated by relating rainfall, water level, and concurrent measurements of water quality in the drainage canals and the creek. The effects of drainage from the canals with flashboard risers on the water quality in the creek were evaluated by graphical displays of the water-quality data and by analysis of variance procedures.

Previous Investigations

The effects of land-use change on runoff and water quality in the North Carolina Coastal Plain have been studied by numerous investigators, including Heath (1975), Kirby-Smith and Barber (1979), Skaggs and others (1980), Daniel (1981), and Gregory and others (1983). Most of these studies focused on the conversion of undisturbed land to agriculture. Because of relatively high rainfall, low topographic relief, and a shallow water table, extensive artificial-drainage systems are required for agricultural development, as well as for most other types of land use, in many areas of the Coastal Plain. These drainage systems increase the rate and can increase the volume of the land-surface runoff relative to undrained systems, thereby potentially increasing nonpoint-source loadings to receiving waters (Skaggs and others, 1980; Daniel, 1981).

Results of previous studies indicate that proper use of some types of water-control structures in field ditches improves the quality of water immediately downstream from the structure. Flashboard risers have been shown to decrease nitrate loads to downstream surface waters (Gilliam and others, 1978). Results from an investigation of the effects of controlled surface and subsurface drainage on runoff and water quality at field ditch outlets indicate that field-ditch drainage volume is the most important factor affecting nutrient efflux (Evans and others, 1987). Computer modeling of nutrient concentrations in field ditches also has been performed for a variety of soil types and subsurface and surface-drainage conditions (Deal and others, 1986).

Acknowledgments

The authors gratefully acknowledge the landowners who provided access to study sites located on their property, farming-practice data, and valuable assistance throughout the investigation. Cooperating landowners are Mr. Sydney Credle, Mr. Charlie Godley, Mr. David O'Neal, Mr. Hiram Paul, and Mr. Kelly Williams. Mr. David O'Neal was particularly instrumental in identifying Hyde County sites and in maintaining local support for the investigation. Mr. Rufus Croom, Mr. James T. Etheridge, Mr. Michael W. Harriett, and Mr. Rodney Woolard, of the U.S. Soil Conservation Service, assisted in identifying sites, developing and maintaining local contacts, and providing technical guidance. The Hyde County Soil and Water Conservation District also was responsible for blocking a ditch to hydraulically separate two of the basins. Mr. James R. Cummings and Ms. Patricia Hooper of the North Carolina Division of Soil and Water Conservation; Ms. Elizabeth McGee, Mr. David Harding, and Mr. Jimmie R. Overton of the North Carolina Division of Environmental Management; and Mr. Thomas W. Ellis of the North Carolina Department of Agriculture were instrumental in initiating and developing continuing support for the investigation. This study began in cooperation with the Albemarle-Pamlico Estuarine Study, North Carolina Department of Environment, Health, and Natural Resources, and has continued in cooperation with the Division of Environmental Management.

State funds were appropriated for the installation of the tide gates, which was accomplished by the landowners with assistance from the Pamlico Soil and Water Conservation District. Installation of flashboard risers was funded cooperatively by the landowners and the ACSP and was conducted by each landowner with assistance from the Beaufort Soil and Water Conservation District.

DESCRIPTION OF STUDY AREAS

The Hyde and Beaufort County study areas, including Campbell Creek, lie near the mouth of the Pamlico River (fig. 2). The Pamlico River is a drowned river-valley estuary characterized by daily mean tidal fluctuations of less than a foot and salinity concentrations from near zero to about 20 parts per thousand (ppt) (Bales, 1990). Because of the proximity of the agricultural basins to the Pamlico River and Pamlico Sound, and because the bottom of the canal that drains each basin is near or below mean sea level, water levels and water quality in the canals are almost always affected by downstream estuarine conditions.

The climate of the region is mild and moderately moist. The mean annual temperature is about 60 °F, and the mean annual precipitation is about 52 inches (in.) (Hardy and Hardy, 1971). Although annual precipitation varies from 35 to 80 in., average monthly precipitation is relatively uniform throughout the year, with slightly higher amounts typically occurring during July, August, and September. Evapotranspiration rates average about 34 inches per year (in/yr) and exhibit much less variability from year to year than precipitation (Wilder and others, 1978). Average wind speeds are about 10 miles per hour (mi/hr). Winds typically blow from south to southwest between April and August and from north to northwest between September and February. There is no consistently prevailing wind direction during March (Garrett and Bales, 1991).

Hyde County Study Area

The Hyde County study area is drained by three adjacent, parallel drainage canals (fig. 3) located near the community of Rose Bay. This area was selected because the basins which drain to the canals have many similar characteristics, such as drainage area, land use, soil type, and degree of tidal interaction. Tide gates are used extensively in Hyde County.

All of the data-collection sites are less than 2,000 ft from the confluence of the drainage canals with Rose Bay Creek, a tidal creek draining to Rose

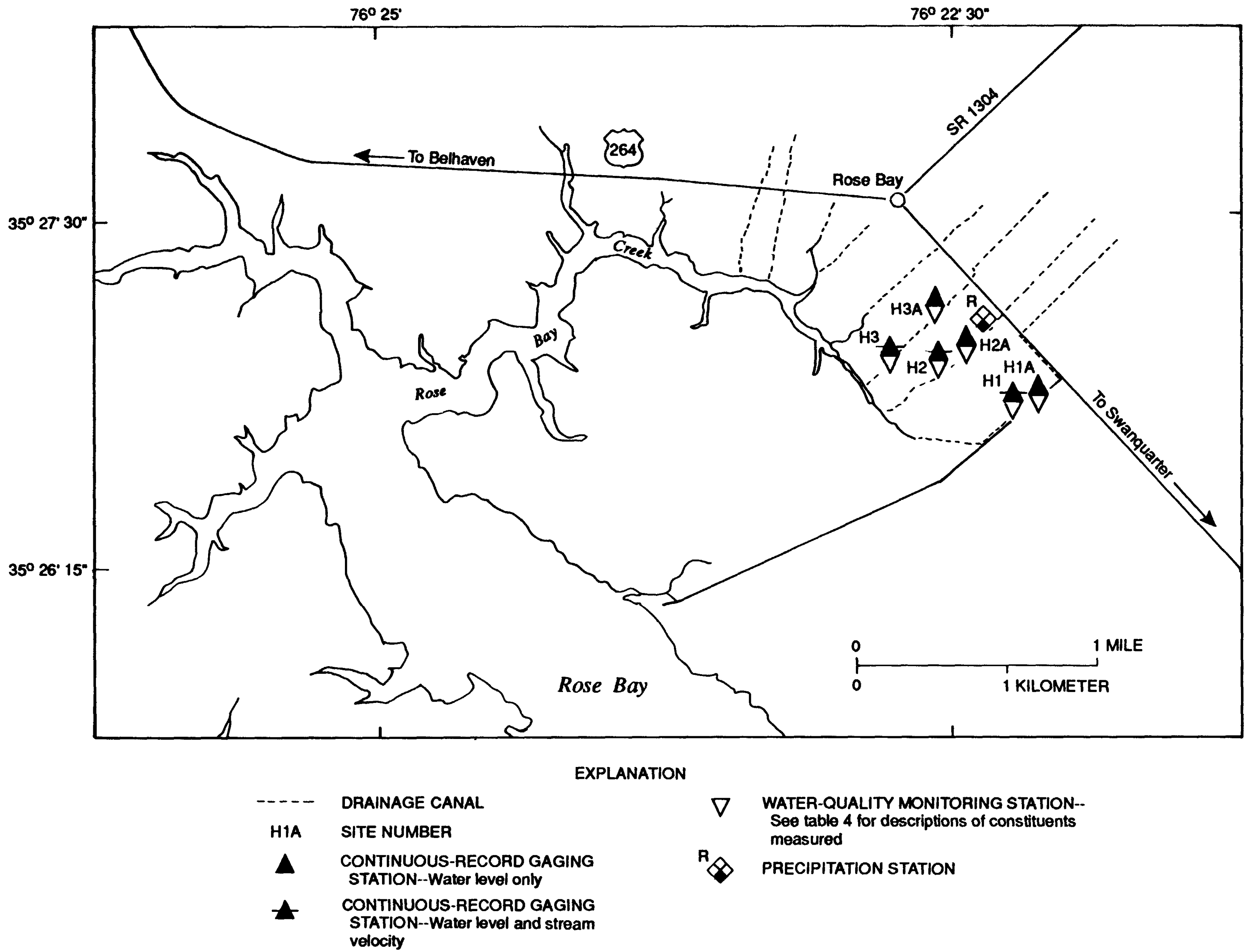

Figure 3. Location of Hyde County data-collection sites for tide-gate study area, North Carolina.

Bay. The drainage areas range in size from 70 to 140 acres (table 1) and are characterized by highly productive mineral soils used to grow winter wheat and soybeans in rotation (R. Woolard, U.S. Soil Conservation Service, oral commun., 1988). All surface runoff in the basin is by way of surface drainage to ditches and subsequently to the canals where the data-collection sites are located.

The canals at test sites H2 and H3 (fig. 3) are about 13 ft wide and about 4 ft deep. Both canals are straight and free of obstructions to flow. The drainage canal at site H1 (fig. 3), the reference canal site, is about 9 ft wide and 2 ft deep and is not as well maintained as the other canals. Vegetation and debris in the H1 canal, along with its asymmetrical geometry, tend to obstruct the free flow of water.

Beaufort County Study Area

The Beaufort County study area is located near the community of Campbell Creek, 5 miles (mi) east of Aurora (fig. 4) and about 20 mi southwest of the Hyde County study area. The drainage areas of the Beaufort County sites average about 70 acres, which are smaller than those of the Hyde County sites (table 1). Soils within the basins are loams and fine, sandy loams. Agriculture in the basins is devoted exclusively to row crops (corn, milo, soybeans, potatoes, and winter wheat). All runoff in the basins is by way of surface drainage, but there is a more extensive network of surface-drainage ditches in the Beaufort County study area than in the Hyde County study area.

The network of agricultural drainage ditches and canals upstream from site B1 (fig. 4) forms the headwaters of Bond Creek. Site B1, the reference site, is about 4,000 ft from the mainstem of Bond Creek, but the land between site B1 and Bond Creek is entirely forested. At this site, the flow channel is about 7 ft wide and 2 ft deep. The maintained canal, which ends just upstream from site B1A, is about 7 ft wide and 8 ft deep.

Table 1. Description of data-collection sites

[NA, not available]

Site number (figures 3 and 4)	USGS station number[1]	Latitude	Longitude	Drainage area (acres)	Description
			Tide-gate sites in Hyde County		
H1	0208458600	35°26'44"	76°22'25"	70	Drainage canal, downstream from tide gate.
H1A	0208458600	35°26'48"	76°22'18"	70	Drainage canal, upstream from tide gate.
H2	0208458700	35°26'57"	76°22'37"	140	Drainage canal, downstream from tide gate.
H2A	0208458700	35°26'59"	76°22'34"	140	Drainage canal, upstream from tide gate.
H3	0208458800	35°27'01"	76°22'45"	104	Drainage canal, downstream from tide gate.
H3A	0208458800	35°27'06"	76°22'43"	104	Drainage canal, upstream from tide gate.
			Flashboard-riser sites in Beaufort County		
B1	0208455130	35°18'41"	76°43'28"	93	Drainage canal, downstream from flashboard riser.
B1A	0208455130	35°18'44"	76°43'35"	93	Drainage canal, upstream from flashboard riser.
B2	0208455143	35°17'20"	76°41'45"	47	Drainage canal, downstream from flashboard riser.
B2A	0208455143	35°17'23"	76°41'46"	47	Drainage canal, upstream of flashboard riser.
B3	0208455141	35°17'10"	76°41'50"	68	Drainage canal, downstream from flashboard riser.
B3A	0208455141	35°17'08"	76°41'50"	68	Drainage canal, upstream from flashboard riser.
C1	0208455145	35°17'13"	76°41'13"	5,120	Receiving stream for sites B2 and B3.
			Other sites		
GC	0208455600	35°19'34"	76°36'35"	NA	Tide gage near mouth of Goose Creek.
PB	0208455500	35°23'37"	76°36'22"	NA	Tide gage on north side of Pamlico River near Pamlico Beach.

[1]U.S. Geological Survey downstream order identification number.

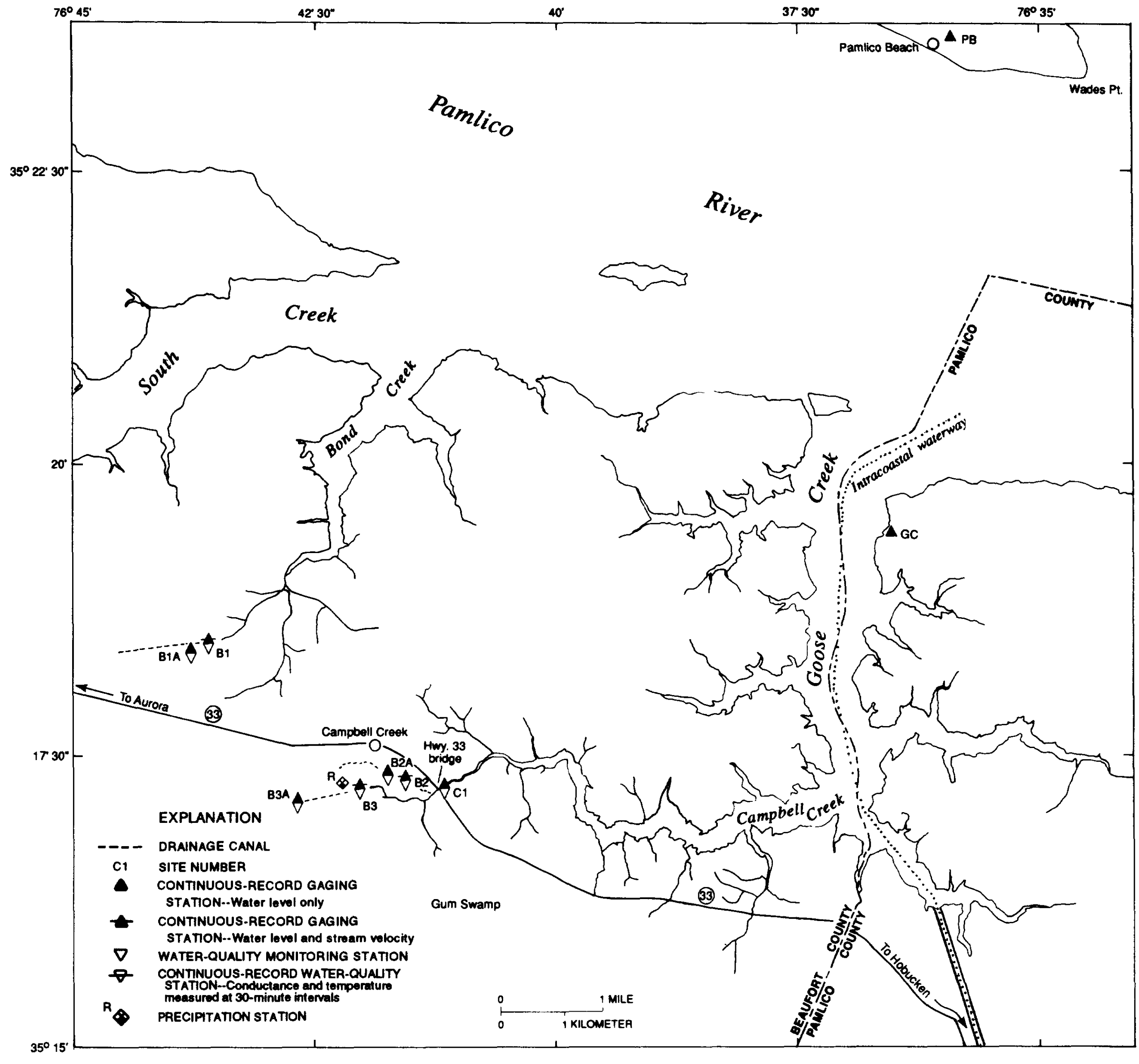

Figure 4. Location of Beaufort County data-collection sites for flashboard-riser study area, Campbell Creek, Pamlico Beach, and Goose Creek, North Carolina.

Test sites B2 and B3 (fig. 4) are on adjacent canals that drain directly to Campbell Creek and are about 2,000 ft upstream from Campbell Creek. The area between the data-collection sites and Campbell Creek is forested, and no additional ditches or canals drain into the two canals between the data-collection sites and Campbell Creek. The canals at sites B2 and B3 are each about 12 ft wide. The canal is 3 ft deep at site B2, and 4 ft deep at site B3.

Campbell Creek

Upstream from the State Highway 33 bridge (site C1), Campbell Creek drains a 5,120-acre (8-square-mile (mi^2)) wetland area known as Gum Swamp (fig. 2; table 1). There is very little agricultural land in this part of the Campbell Creek watershed, and with the exception of the canals that drain sites B2 and B3, only one other agricultural drainage canal is known to drain into Campbell Creek.

Downstream, between the State Highway 33 bridge and the confluence of Campbell Creek with Goose Creek (fig. 4), an additional 7,610 acres (11.9 mi^2) drain into Campbell Creek. Thus, the watershed for Campbell Creek covers a total of 12,700 acres (19.9 mi^2). The distance along the axis of the creek from the State Highway 33 bridge to the mouth of the creek is about 5 mi. Land use in the lower part of the Campbell Creek basin is a mixture of agriculture (primarily row crops) and forested wetlands.

DATA COLLECTION

In the summer of 1988, a tide gate was installed in the Hyde County canal about 100 ft upstream from site H1 (fig. 3), and a continuous-record water-level gage was installed upstream from the tide gate at site H1A. Following more than 2 years of data collection at sites H1, H1A, H2, and H3, tide gates were installed in the canals upstream from sites H2 and H3 in August 1990. Water-level gages were then installed at sites H2A and H3A (fig. 3) about 15 ft upstream from the tide gates. Following tide-gate installation at sites H2 and H3, data were collected through April 1992, at all six sites.

At the beginning of the investigation in 1988, a support structure for a flashboard riser was installed in the canal upstream from site B1 (fig. 4), and a continuous-record water-level gage was installed about 75 ft upstream from the structure at site B1A. Prolonged dry periods resulted in frequent periods of no flow in the canal, and during periods of flow, an unstable channel resulted in severe streambed scouring. Moreover, the structure was never used to regulate flow in the canal. The hydrologic conditions precluded the collection of meaningful data, therefore water-quality data collection was discontinued at the site on September 30, 1990, and water-level monitoring ended in March 1991.

In April 1991, following about 3 years of data collection, flashboard risers were installed in the canals upstream of sites B2 and B3 (fig. 4). Continuous-record water-level gages were then installed upstream from flashboard risers at sites B2A and B3A (fig. 4). Site B2A was located about 15 ft upstream from the riser, and site B3A was located about 45 ft upstream from the riser. Data collection at sites B2, B2A, B3, and B3A continued through April 30, 1992.

At Campbell Creek site C1, a continuous-record water-level gage was installed in May 1988. Beginning in April 1989, the site was included in the biweekly water-quality sampling schedule. The site also was equipped with a monitoring device in October 1990 to record water temperature and specific conductance at 15-minute intervals. Data collection continued at site C1 until April 30, 1992.

Continuous-record water-level gages were installed at sites GC (Goose Creek) and PB (Pamlico Beach) (fig. 4) in March 1988. Site GC was discontinued in October 1991, and data collection at site PB continued throughout the study period. These sites were part of another USGS investigation, but water-level data from these sites were useful for hydrologic comparison with the study sites.

Hydrologic and water-quality data for the study period were reported by Treece and Bales (1992) and Treece (1993). Detailed documentation of data-collection methods are also given in these reports.

Hydrologic Data

Precipitation was measured at 15-minute intervals at sites H2 and B3 (table 2). Precipitation data from the nearest National Weather Service station to site H2, located at New Holland 12 mi east of the site, were used to compare observations at site H2 with long-term averages and to estimate missing daily totals at this site. Likewise, data from the nearest National Weather Service station to site B3, located at New Bern 25 mi southwest of the site, were used to compare observations at site B3 with long-term averages and to estimate missing daily totals at this site.

Table 2. Hydrologic data-collection network for sites in Hyde and Beaufort Counties, North Carolina

[---, no data]

Site (figures 3 and 4)	Measurement type and recording interval			
	Precipitation (minutes)	Water level (minutes)	Stream velocity (minutes)	Discharge
H1	---	15	15	Periodically.
H1A	---	15	---	---
H2	15	15	15	Periodically.
H2A	15	15	---	---
H3	---	15	15	Periodically.
H3A	---	15	---	---
B1	---	15	15	Periodically.
B1A	---	15	---	---
B2	---	15	15	Periodically.
B2A	---	15	---	---
B3	15	15	15	Periodically.
B3A	15	15	---	---
C1	---	15	---	---
GC	---	15	---	---
PB	---	15	---	---

Water levels were recorded at 15-minute intervals in each of the six drainage canals, in Campbell Creek at site C1, in Goose Creek at site GC, and in the Pamlico River at site PB. Prior to the installation of water-control structures, water levels were recorded at one site (base gage) on each canal downstream from where the structures were to be installed. Following installation of the water-control structures, water levels also were recorded upstream from the control structures. All water levels were referenced to sea level, and gage datums were checked annually.

Standard stream-gaging techniques using a weir and a stage-discharge relation to compute discharge were not feasible for most of the study sites for three reasons: (1) movement of water in these canals occurs in two directions--downstream as a result of land-surface drainage, and upstream as a result of tidal action; (2) typically, a weir will become submerged and nonfunctional during periods of extremely high water levels resulting from streamflow or increases in tidal elevation; and (3) the weir itself can act as a water-control structure by storing water in the canal upstream from the weir. Consequently, discharges were computed by using ratings of water level and channel area relations and the measured stream velocities.

Sites H1, H2, H3, and B3 are regularly affected by water-level fluctuations in the downstream estuary. Stream velocity (magnitude and direction) was recorded at 15-minute intervals in these canals using Marsh-McBirney bidirectional electromagnetic-velocity meters. The meter sensor, which is about 10 in. long and 1 in. in diameter, was mounted to extend horizontally and perpendicular to the flow. The meter was controlled by an electronic datalogger, which was programmed to make 30 measurements within a 15-minute interval. These measurements were averaged to provide a mean velocity for the interval, which was stored in the datalogger. During biweekly visits to the sites, the dataloggers were downloaded and field measurements of velocity were made with a Price AA optic current meter or a Marsh-McBirney MDL 201 current meter and compared to the electromagnetic velocity meter readings to ensure meter calibration and to determine appropriate data corrections.

Discharge was computed for these four canals by first determining the relation between water-level and cross-sectional area. The water-level area relation was for the cross section where the velocity meter probe was located. Next, discharge measurements (about 15 at each canal) were made for different flow and water-level conditions. By comparing the average flow velocity for the cross section (measured flow divided by total area) determined from the discharge measurement with the point velocity measured by the bidirectional electromagnetic-velocity meter at the time of the discharge measurement, a relation between measured point velocity and cross-sectional average velocity was developed for each canal.

Instantaneous discharge was then computed by (1) using measured water level to obtain a cross-sectional area, (2) using measured point velocity to obtain a cross sectionally averaged velocity, and (3) multiplying cross-sectional area by cross sectionally averaged velocity. Instantaneous discharges were calculated at 15-minute intervals and averaged for a 24-hour period to obtain daily mean discharges.

Determination of discharge was dependent on accurate water-level data accompanied by concurrently measured stream velocity. Water levels occasionally dropped below the velocity sensor; consequently, flow could not be computed for these periods. Moreover, prolonged exposure of the meter sensor to air usually altered the calibration, resulting in lost record while the meter was being recalibrated.

Net discharges for a given time period were calculated as the difference between the total upstream discharges and the total downstream discharges. Hence, net discharges were sometimes near zero even when large fluctuations in flow occurred.

Site B1 was not tidally affected, and flow at site B2 was rarely affected by downstream conditions. Consequently, a small (v-notch 4 in. above the streambed) weir was installed at site B2 in 1988 at the onset of the investigation, and at site B1 in November 1989, to stabilize the channels and possibly simplify the procedure for obtaining accurate records of discharge. Discharge at these sites was determined by using a standard relation between water level and discharge at the weir.

Water-Quality Data

Water-quality data (table 3) were collected using standard USGS procedures. Procedures for field-data collection, instrumentation maintenance, and data processing were developed for the specific instrumentation and conditions of this study. These procedures are documented in an unpublished quality-assurance manual that was prepared as part of this investigation (R.G. Garrett, U.S. Geological Survey, written commun., 1990).

Field meters were calibrated at the beginning of each day of use. Field instruments used were the Yellow Springs Instrument Company Model 33 S-C-T specific-conductance meter, the Beckman 11 pH meter, the Yellow Springs Instrument Company Model 54 dissolved-oxygen meter, and the Thommen barometer.

Specific-conductance standards were used to develop a calibration curve for the conductance meter. Field meter readings were within 5 percent of the standards after calibration. The pH meter was calibrated using standard solutions at pH 4, 7, and 10. After calibration, meter readings were always within 0.2 pH unit, and more than 90 percent of the readings were within 0.1 pH unit of the standards. Temperature thermistors were calibrated against an American Society for Testing Materials thermometer at two temperatures. All values were within 0.5 °C after calibration. Barometers were calibrated annually against a National Weather Service barometer. The dissolved-oxygen meter was calibrated in water-saturated air and adjusted for barometric pressure. After calibration, the meter readings were within 0.1 milligram per liter (mg/L) of the saturation value at the measured temperature and pressure. The dissolved-oxygen calibration was for freshwater. Quality-control samples, prepared by the USGS Ocala Water-Quality Laboratory, were analyzed semi-annually for pH and specific conductance to ensure field meter accuracy.

Table 3. Number of water-quality samples and measurements collected for selected physical properties and constituents at study sites in Hyde and Beaufort Counties, North Carolina, November 1988 through April 1992

[$NO_2 + NO_3$, nitrite plus nitrate; N, nitrogen; P, phosphorus]

	Composite samples[1]	Biweekly measurements										
Site (figures 3 and 4)	Specific conductance	Specific conductance	pH	Water temperature	Dissolved oxygen	Total $NO_2 + NO_3$ as N	Total ammonia as N	Total ammonia + organic nitrogen	Total phosphorus	Total orthophosphorus as P	Suspended sediment	Storm-event samples[2]
H1	1,278	81	82	82	80	82	44	81	81	81	82	28
H1A	0	75	0	75	0	0	0	0	0	0	0	1
H2	1,012	79	80	80	79	80	43	79	79	79	80	24
H2A	0	35	0	35	0	0	0	0	0	0	0	0
H3	1,228	79	80	80	79	79	44	79	79	79	80	28
H3A	0	34	0	34	0	0	0	0	0	0	0	0
B1	292	27	26	27	26	27	2	27	27	27	25	0
B1A	0	26	0	26	0	0	0	0	0	0	0	0
B2	1,019	72	71	72	72	72	40	72	72	72	72	27
B2A	0	22	0	22	0	0	0	0	0	0	0	0
B3	1,034	78	77	78	77	78	42	78	78	78	77	32
B3A	0	22	0	22	0	0	0	0	0	0	0	0
C1	0	69	69	66	70	71	43	71	71	71	70	0

[1] A composite sample consisting of five discrete samples collected at about 3-hour intervals.
[2] Storm-event samples analyzed for total nutrient and suspended-sediment concentrations.

Water-quality samples were collected biweekly beginning in November 1988 at the canal sites and beginning in April 1989 at Campbell Creek. Samples were collected manually using the equal-width increment (EWI) method (Edwards and Glysson, 1988), which requires equal spacing of subsamples throughout the cross section of the canal or creek and an equal vertical-transit sampling rate, up and down, for all subsamples.

Specific conductance and pH were measured in the field from hand-collected samples. Dissolved oxygen and water temperature were measured in the canals or creek at 1 ft below the water surface. Suspended-sediment concentrations were determined in the sediment laboratory at the North Carolina District USGS office in Raleigh, using procedures documented by Guy (1969).

After nutrient samples were collected in glass bottles, they were stored in opaque brown bottles, preserved with mercuric chloride, and placed on ice. The nutrient samples were analyzed for concentrations of total nitrite plus nitrate, total ammonia plus organic nitrogen (TKN), total phosphorus, and total orthophosphate. Nutrient analyses were performed in the USGS National Water-Quality Laboratory in Denver using methods described by Fishman and Friedman (1985). Analysis of total ammonia nitrogen was added in May 1990 to allow calculation of the organic-nitrogen part of total ammonia plus organic nitrogen. Initially, samples were analyzed for total and dissolved nutrient concentrations, but because dissolved concentrations were nearly equal to total concentrations in most cases (and funding was limited), only total concentrations were analyzed after May 15, 1990.

Specific conductance was measured from composite samples collected automatically in each of the drainage canals using the Instrumentation Specialty Company (ISCO) Model 2700 automatic water sampler. Each 500-milliliter (mL) sample was the composite of five 100-mL samples collected at approximately 3-hour intervals during a 14-hour period. During biweekly visits to the sites, the sample bottles were replaced with clean empty bottles. The samples were then returned to the laboratory for measurement of specific conductance. Salinity was determined from specific conductance using the relation given by Miller and others (1988) and summarized in table 4.

Table 4. Conversion table for specific conductance to salinity (Miller and others, 1988)

[μS/cm, microsiemens per centimeter at 25 degrees Celsius; ppt, parts per thousand]

Specific conductance (μS/cm)	Salinity (ppt)	Specific conductance (μS/cm)	Salinity (ppt)
0	0.00	15,000	8.71
500	.23	15,500	9.03
1,000	.47	16,000	9.34
1,500	.74	16,500	9.65
2,000	1.00	17,000	9.97
2,500	1.27	17,500	10.29
3,000	1.55	18,000	10.62
3,500	1.82	18,500	10.94
4,000	2.10	19,000	11.26
4,500	2.38	19,500	11.59
5,000	2.67	20,000	11.91
5,500	2.95	20,500	12.23
6,000	3.24	21,000	12.56
6,500	3.54	21,500	12.89
7,000	3.83	22,000	13.21
7,500	4.13	22,500	13.54
8,000	4.42	23,000	13.87
8,500	4.71	23,500	14.20
9,000	5.01	24,000	14.53
9,500	5.31	24,500	14.86
10,000	5.62	25,000	15.19
10,500	5.92	25,500	15.53
11,000	6.23	26,000	15.86
11,500	6.54	26,500	16.20
12,000	6.84	27,000	16.54
12,500	7.15	27,500	16.87
13,000	7.45	28,000	17.21
13,500	7.77	28,500	17.54
14,000	8.08	29,000	17.88
14,500	8.40	29,500	18.22

At site C1 in Campbell Creek (fig. 4), a USGS minimonitor equipped with two sensors was used to record temperature and specific conductance at 15-minute intervals beginning in September 1990. The minimonitor consisted of (1) a water-tight can (about 14.5 in. high by 10.5 in. in diameter) containing signal conditioners, (2) cables with waterproof connectors, (3) water-quality sensors, and (4) a 12-volt battery (Garrett and Bales, 1991). The minimonitor also was controlled by a datalogger, which was programmed to turn on the minimonitor at 15-minute intervals, receive data from the sensors, record the time, and turn off the minimonitor. The datalogger stored the data, which were downloaded biweekly during routine field visits.

Specific conductance and temperature were measured at site C1 near the water surface and at 1-ft intervals over the full depth. Measurements made with calibrated portable field meters near the minimonitor sensors were used to check minimonitor readings and to determine correction factors. The minimonitor sensors were fixed at 2 1/2 ft above the bottom of the channel, and the depth of water was typically about 6 ft deep.

Storm-event water-quality samples were collected using the ISCO model 2700 pumping sampler with fixed intake. The sampler intake was located near the center of each canal at about 0.5 ft above the bottom of the canal. Depth-integrated samples also were collected and compared to point samples to ensure that the ISCO samples were representative of conditions throughout the canal cross section. Event samples were retrieved from the sampler within 24 hours after sample collection and split for analyses of nutrient and suspended-sediment concentrations. Nutrient samples were stored in opaque bottles, preserved with mercuric chloride, placed on ice, and analyzed for the same constituents as the biweekly manually collected samples.

EFFECTS OF WATER-CONTROL STRUCTURES ON WATER LEVEL AND FLOW

The hydrology of artificially drained areas is profoundly affected by the drainage systems. Water-control structures can modify artificial drainage systems and, thus, affect the movement of freshwater and contaminants into receiving waters.

Movement of water into and out of tidally affected canals was documented before and after the installation of water-control structures. Although earlier studies documented flow to compute loadings in nontidally affected drainages, previous attempts to quantify streamflow for drainage canals with this degree of tidal influence have been limited.

Tide Gates

The hydrology of the Hyde County study area is complex; it is influenced by prevailing winds, precipitation, and hydrologic conditions in the Pamlico River, as well as the artificial drainage system. Conditions before and after tide gates were installed at sites H2 and H3 (fig. 3) were compared to assess the effects of the water-control structures on canal hydrology. Water level and flow data collected at a reference site (H1) were used to determine whether changes at sites H2 and H3 could have resulted from natural hydrologic variations or the presence of tide gates. In addition, USGS water-level data in the Pamlico River provided a frame of reference for interpretations of the canal data. This site, located at Pamlico Beach 10 mi west of the mouth of Rose Bay (site PB, fig. 4), was part of a large network of estuarine stations monitored by the USGS in North Carolina. Water-level and flow characteristics at the Hyde County sites are described in the following sections.

Water Level

Seasonal water levels in canals in the Hyde County study area respond to prevailing wind patterns. During the 4-year study, monthly mean water levels in the canals were highest from August through October, and lowest from December through February (fig. 5). The southwesterly winds of summer and fall acting on Pamlico Sound tend to elevate water levels on the northeastern part of the Pamlico estuary. When winds shift to become northerly in the winter months, estuarine waters are pushed to the south, or away from the Hyde County canals which allowed more rapid drainage from field ditches during months when the fields are typically the wettest.

The monthly mean of daily water-level ranges in canals (the monthly mean of the daily differences between daily minimum and daily maximum water levels) also varied seasonally with greater fluctuations occurring in spring and summer (fig. 5). Daily water-level ranges were between zero and 1.0 ft at site H1 and between 0.24 and 2.4 ft at sites H2 and H3. The minimum instantaneous water level of -1.01 ft was measured at site H2 on January 21, 1992 (table 5). High water levels in the drainage canals corresponded to storm-runoff events as well as to high water levels in the Pamlico River estuary.

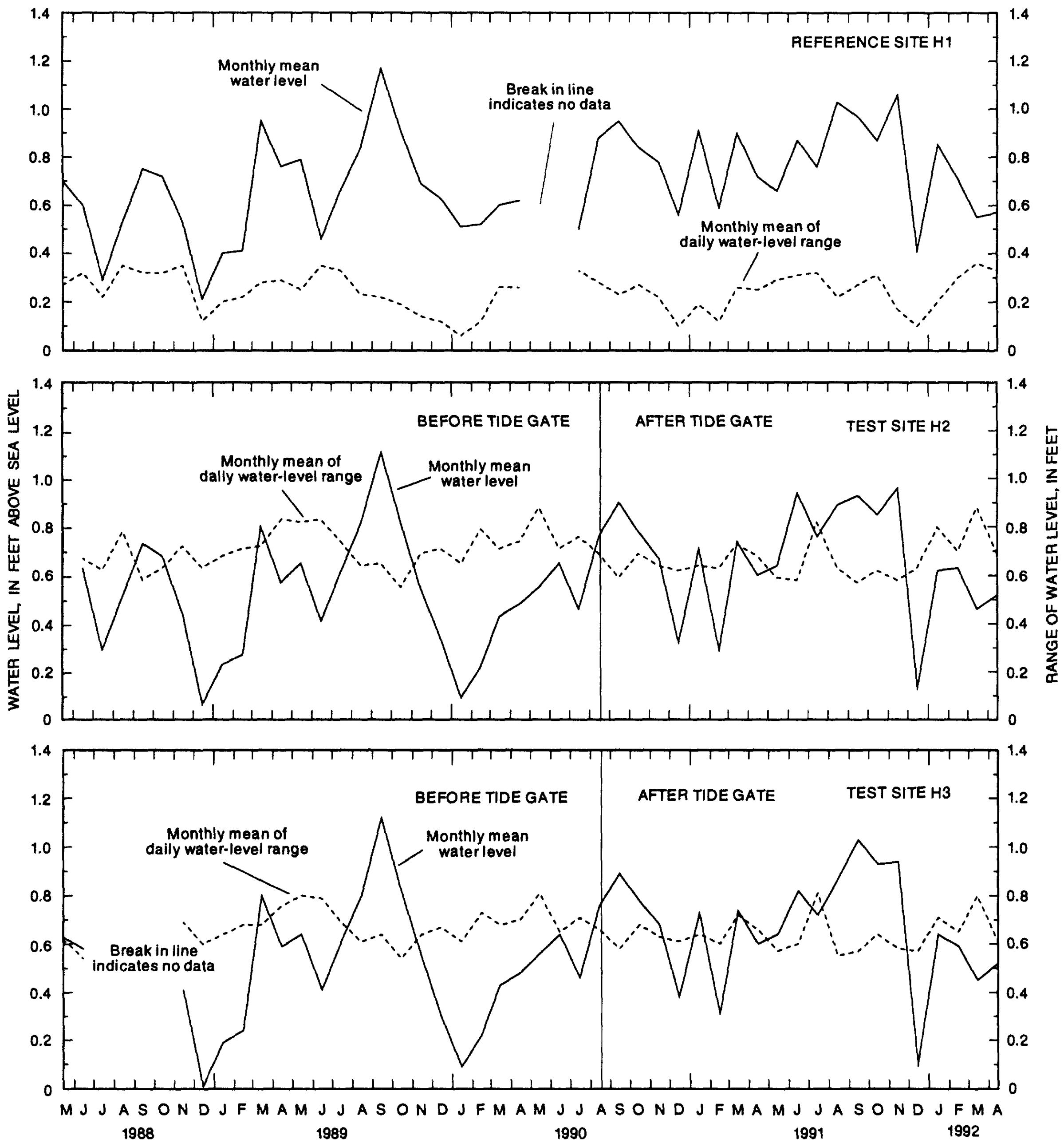

Figure 5. Monthly water-level statistics at sites H1, H2, and H3, May 1988 through April 1992, Hyde County, North Carolina.

Table 5. Summary of water-level statistics for Hyde County (H) sites before and after water-control structures were installed at sites H2 and H3, May 1988 through April 1992

[NA, not applicable]

Site (figure 3)	Values are in feet above or below (-) sea level										Values are in feet	
	Mean		Maximum recorded		Minimum recorded		Mean daily maximum		Mean daily minimum		Mean daily range	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
H1	0.64	0.79	1.96	2.07	-0.20	0.13	0.77	0.91	0.53	0.67	0.25	0.24
H1A	.65	.76	1.87	1.93	.14	.03	.75	.83	.56	.69	.19	.14
H2	.52	.67	2.29	2.50	-.70	-1.01	.86	.98	.15	.32	.71	.66
H2A	NA	.22	NA	1.42	NA	-.90	NA	.35	NA	.11	NA	.23
H3	.51	.67	2.31	2.49	-.55	-.49	.84	.98	.17	.34	.67	.64
H3A	NA	.40	NA	2.24	NA	-.52	NA	.44	NA	.25	NA	.20

Although monthly mean and maximum water levels at sites H2 and H3 were similar, monthly minimum water levels were usually lower at site H2 than at site H3 (fig. 6). The elevation of the channel bottom is 0.5 ft lower at site H2 than at site H3, which probably accounts for the differences in extreme minimum water levels. Water levels at site H1 generally were lower during high water-level periods and higher during low water-level periods than those concurrently measured at sites H2 and H3. These differences can be attributed to the geometry, size, elevation of canal bottom, and management of the canals. The H2 and H3 canals are similar in size and cross section. Moreover, these two canals are straight and clear of debris and, thus, free of obstructions to flow. The H1 canal is very shallow and laden with thick vegetation and debris. There is less upstream tidal movement of estuarine water into the H1 canal; thus, monthly maximum water levels at site H1 generally were low compared to sites H2 and H3. In addition, monthly mean and minimum water levels at the H1 canal were consistently higher, and the daily mean range tended to be less than at the H2 and H3 canals (fig. 6) because water in the H1 canal does not drain freely.

In general, changes in water levels downstream from the tide gates from pre-installation conditions could not solely be attributed to the installation of tide gates. Although mean water levels at sites H2 and H3 increased from about 0.5 ft to 0.67 ft after tide gates were installed, an increase of similar magnitude was recorded at the reference site (table 5). Mean daily maximum water levels downstream from the tide gates increased by about 0.14 ft at all sites (H1, H2, and H3) after tide gates were installed (table 5). Mean daily minimum water levels also increased slightly, by 0.14 ft at site H1, and by 0.17 ft at sites H2 and H3. Mean daily ranges declined by 0.05 and 0.03 ft at sites H2 and H3, respectively, and by 0.01 ft at site H1 (table 5) after tide gates were installed at the test sites. The difference in monthly mean water levels between sites H2 and H3 was greater after tide gates were installed than before (fig. 6); however, this difference never exceeded 0.12 ft. Before tide gates were installed, the greatest difference between monthly mean water levels at these two sites was 0.05 ft.

Water-level data recorded on the Pamlico River at site PB (fig. 4) were used to evaluate the relation between water levels in the river and those in the drainage canals (fig. 7). On average, water levels at the PB site tended to be 0.1 to 0.2 ft higher than in the Hyde County canals. Mean and maximum water levels at site H2 were strongly related to water levels in estuary, as indicated by the near-zero differences between monthly mean and maximum water levels at sites H2 and PB (fig. 7). The close relation between water levels at sites H2 and PB persisted throughout the study (fig. 7) with no evidence of seasonal differences (fig. 8). However, because the PB site is about 20 mi from the Hyde County canal sites and 10 mi upriver from the mouth of Rose Bay (fig. 2), it is likely that some of the difference in water levels at PB relative to the Hyde County sites is due to a slight difference in gage-datum elevation between PB and the Hyde County sites. Therefore, exact numerical comparisons of water levels between the sites should be made with caution.

Data collected during the last week of May 1990, before tide gates were installed, illustrate the tidal influence of the Pamlico River and precipitation on canal water levels (fig. 9). Throughout the week, water levels at sites H2 and PB followed similar (12-hour) tidal cycles, with lower water levels and greater fluctuations at H2, which agrees with general trends in figure 7. Prior to the rainfall event on May 28-29, water-level fluctuations at site H2 were entirely in response to water-level changes in the Pamlico River.

Occasionally, the water level at site H2 exceeded that at the PB site. For example, when water level at site PB fell below 0.8 ft on May 26, the water-surface slope changed (fig. 9). Water level in the canal exceeded water level in the Pamlico River. Similar results were observed at other times during the study, indicating that when water levels in the estuary fall below a critical elevation (approximately 0.6 to 0.8 ft), there is a pronounced change in slope between the canals and the estuary. This shift would presumably enhance downstream movement of water in the canals, thus providing an opportunity for better drainage.

On May 27 and 28, the water levels in the canal and the estuary rose in response to southwesterly winds. Water level in the canal also rose in response to more than 2.5 in. of rainfall (fig. 9) and, for a brief time, exceeded that at site PB on the evening of May 28. For the most part, water levels at site PB remained higher than water levels in the canals throughout most of the storm event. Following the storm on May 29, water-level fluctuations in the canal on May 30-31 again became dominated by and mirrored conditions in the Pamlico River (fig. 9).

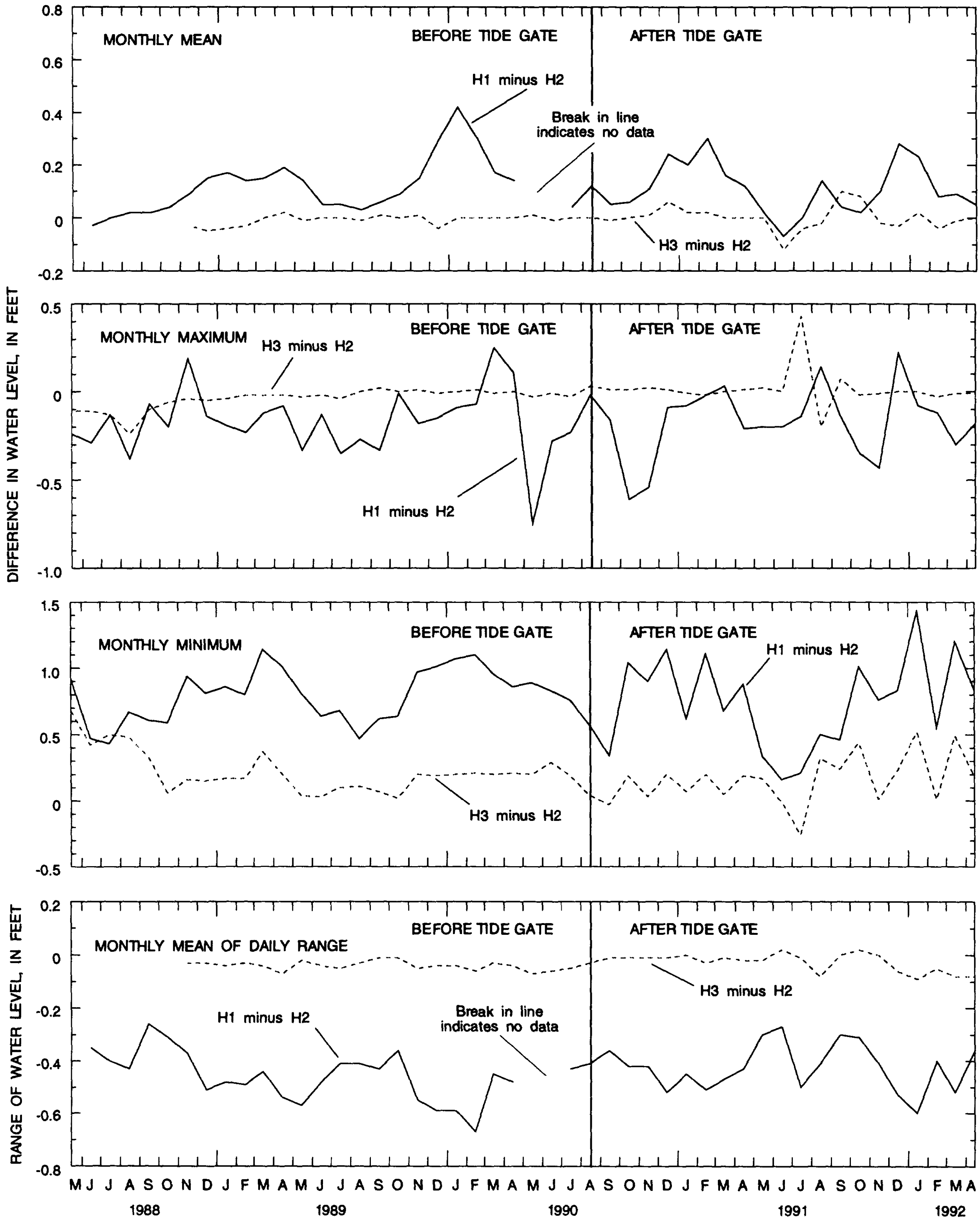

Figure 6. Difference between monthly water-level statistics at sites H1 and H2, and at sites H2 and H3, May 1988 through April 1992, Hyde County, North Carolina.

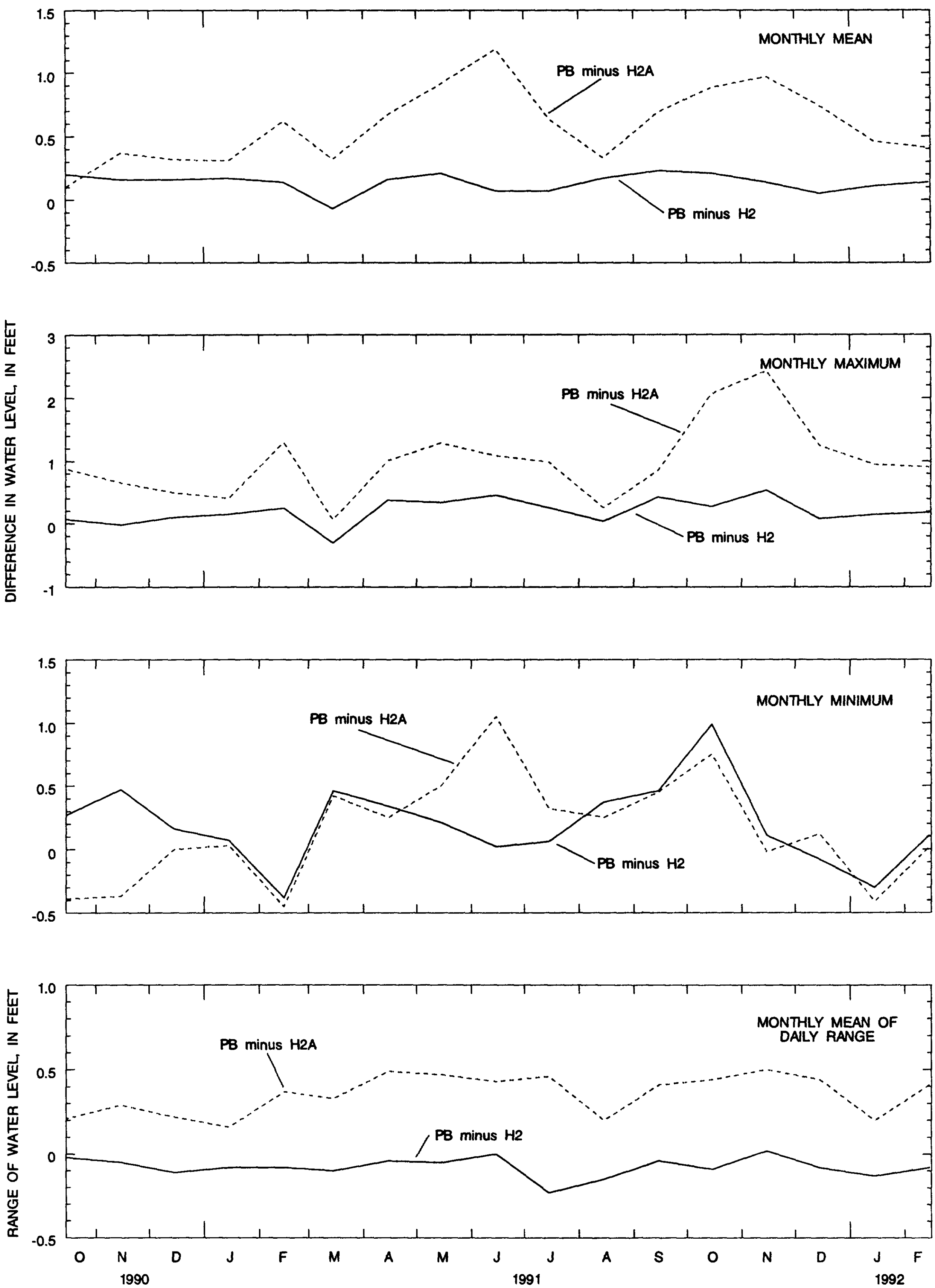

Figure 7. Difference between monthly water-level statistics at sites H2 and PB, and at sites H2A and PB, October 1990 through February 1992, Hyde and Beaufort Counties, North Carolina.

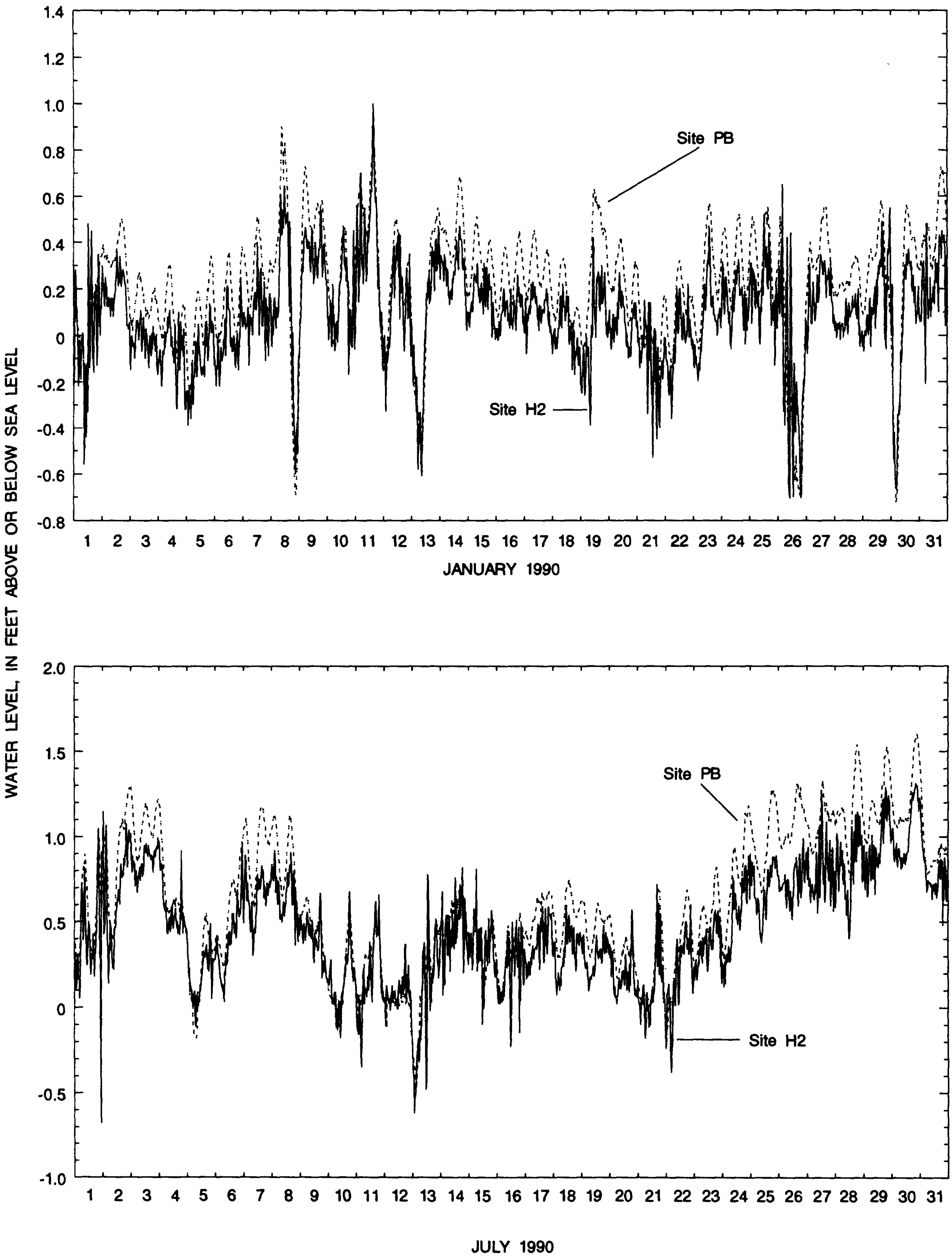

Figure 8. Water levels at sites H2 and PB for January and July 1990, Hyde and Beaufort Counties, North Carolina.

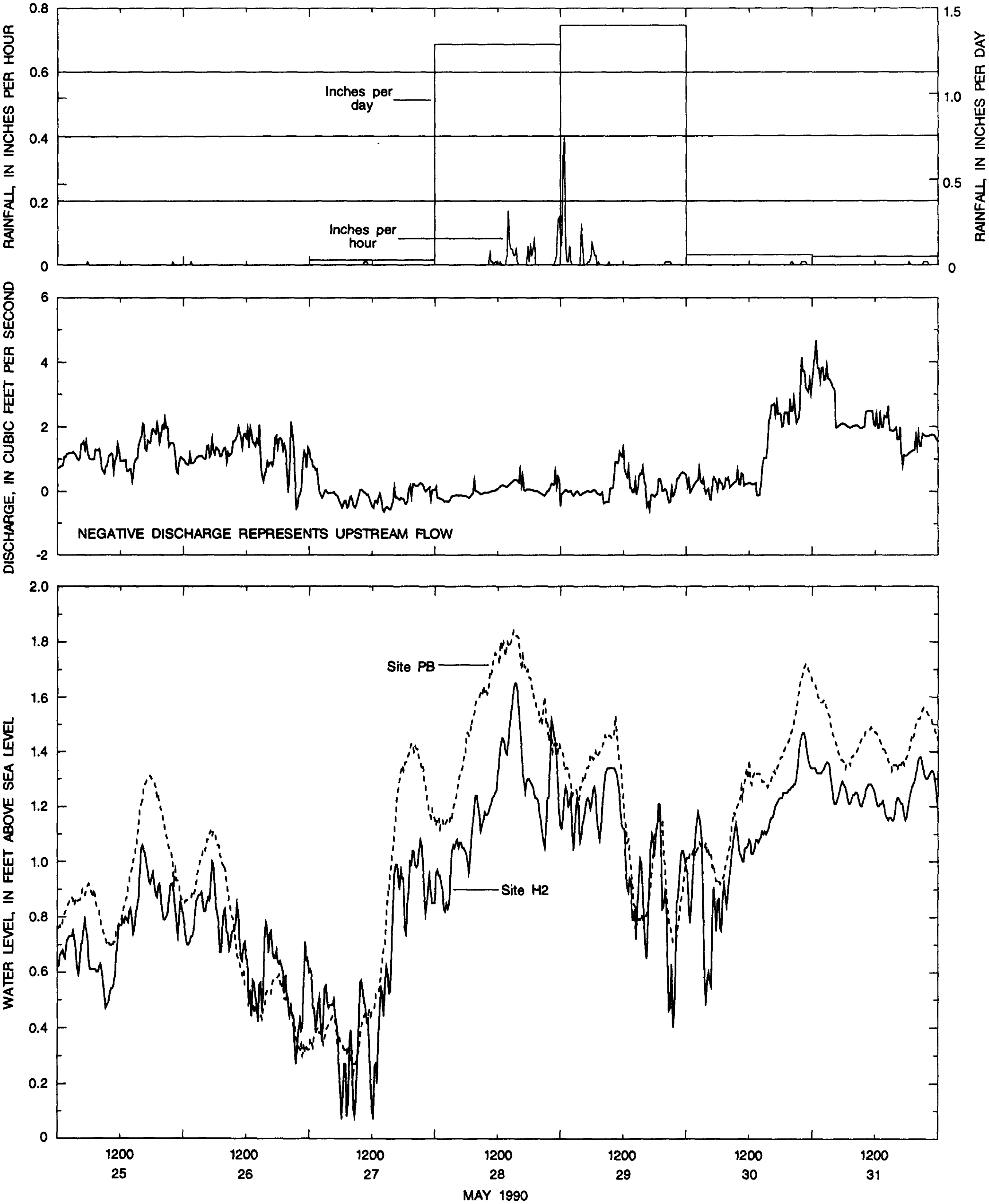

Figure 9. Rainfall and discharge at site H2 and water levels at sites H2 and PB, May 25-31, 1990, Hyde and Beaufort Counties, North Carolina.

Although tide gates had little effect on downstream water levels, water levels upstream from the tide gates changed relative to conditions before the tide gates were installed. Differences between upstream and downstream water levels are evident when viewed in relation to water levels in the Pamlico River at site PB (fig. 7). Upstream from the tide gate at site H2A, mean and maximum water levels were lower than at site H2 and did not closely follow water-levels in the estuary. Moreover, the daily water level range and the minimum water levels generally were lower upstream from the tide gate relative to downstream because, in part, the upper canal was physically separated from the receiving waters and, therefore, was no longer replenished with tidal inflows (fig. 7).

The relation between minimum water levels at site PB and H2A exhibited a seasonal pattern (fig. 7). The minimum water levels at site H2A typically were higher than at site PB during late fall and winter because of higher runoff and lower water level in the estuary, resulting from northerly winds. During the spring and summer, minimum water levels at site H2A were lower than at site PB because of lower runoff and high water level in the estuary, resulting from southerly winds.

The tide gate protected the upper canal from upstream flow and from the influence of water-level fluctuations in the Pamlico River. Prior to the installation of tide gates, most of the water in the canal originated from the estuary rather than from upland sources. High-frequency (short-term) oscillations in water level at site H2A were often similar to water-level changes at site H2 (fig. 10, August 8), suggesting that there may have been minor leakage of water around the tide gates.

Water-level data from October 1990 through April 1992 indicate that tide gates at sites H1, H2, and H3 were open 3.7, 0.2, and 2.1 percent of the time, respectively, assuming that the tide gates were open only when upstream water level exceeded downstream water level by more than 0.2 ft (table 6). Tide gates were open more often during winter months when water levels in the estuary were lowest and rainfall was greatest. The duration for which tide gates remained open depended on existing water-level conditions upstream and downstream from the tide gates and the intensity of storm events.

Drainage sometimes occurred immediately following rainfall. At other times, drainage was significantly delayed when water levels in the Pamlico River and, hence, in Rose Bay were high enough to prevent the tide gates from opening. On August 7, 1991, for example, the water level rose at site H2 partially because of tidal influence and partially because of a runoff resulting from a 1-in. rainfall (fig. 10). A comparison of water levels at sites H2 and H2A indicates that the tide gate never opened on August 7. However, on August 10, 1991, almost 4 in. of rain fell. As a result, the water level at site H2A exceeded that at site H2 by more than 0.2 ft, and the tide gate remained open for about 3 consecutive hours to allow discharge of land-surface runoff from the fields.

Precipitation had a relatively minor, short-term effect on water levels in the Hyde County canals as indicated by the fact that tide gates were rarely open. Water levels in the canals were more strongly influenced by water levels in the Pamlico River estuary than by precipitation, even during large rainfall events, before and after tide gates were installed. Pre-existing conditions in the canals, particularly upstream from the tide gates, were an important factor in how runoff rates responded to storm events. During periods of dry weather (especially when evapotranspiration rates were high) cropland drainage from many rainfall events only temporarily raised the upstream water levels in the canals, but not enough to open tide gates.

Flow

As previously described, flow data at the tide-gate sites are limited, resulting in limited summary statistics to describe overall flow conditions during the study. Although many downstream flows were recorded in the canals while the tide gates were closed, these downstream flows did not represent drainage from upland areas. Rather, downstream flows reflected the back and forth flux of water between Rose Bay Creek and the canals as a result of changing winds and water levels in the estuary. Following tide-gate installation, water levels provided a fairly complete and accurate record of when tide gates were open and when discharge record actually represented freshwater drainage from upland fields.

Peak-flow events, no-flow periods, and upstream-flow periods illustrate the complex hydrology of the Hyde County study area. Seasonal patterns of flow are difficult to discern because of missing data and high variability in the flow data. In general, monthly mean discharge tends to increase in the winter and early spring and decrease in the summer months and early fall (Treece and Bales 1992; Treece, 1993).

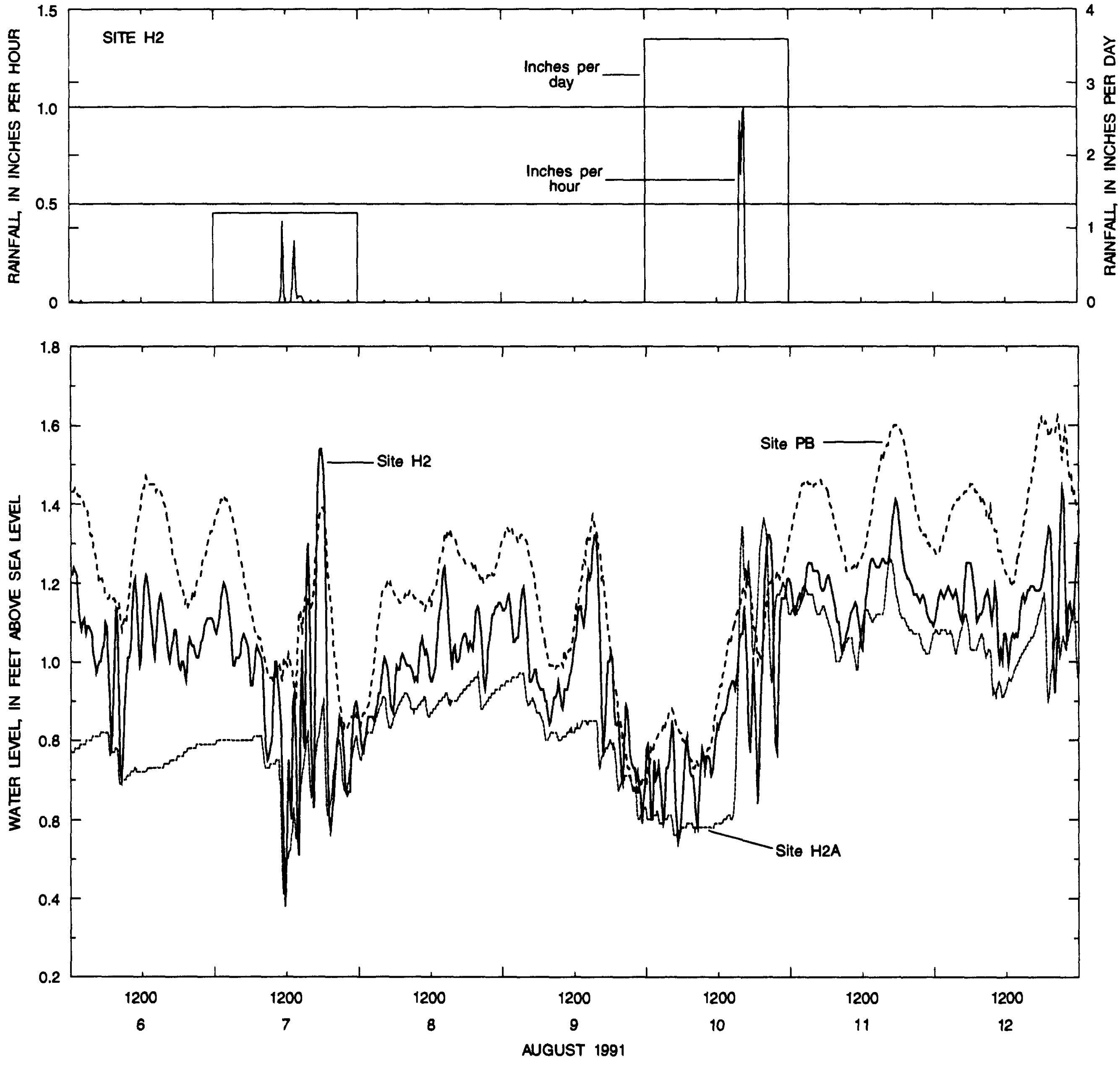

Figure 10. Rainfall at site H2, and water levels at sites H2A, H2, and PB, August 6-12, 1991, Hyde and Beaufort Counties, North Carolina.

Table 6. Percentage of time, by month, that the difference between water level upstream and downstream from tide gate was within specified range at sites H1, H2, and H3, October 1990 through April 1992, Hyde County, North Carolina

[Sites are shown in figure; ---, no data]

	Downstream water level is greater than upstream water level			Upstream water level is greater than downstream water level by less than 0.2 ft			Upstream water level is greater than downstream water level by more than 0.2 ft		
	Tidegates closed at site			Tidegates closed at site			Tidegates open at site		
Month	H1	H2	H3	H1	H2	H3	H1	H2	H3
October 1990	76.0	94.8	---	24.0	5.0	---	0.0	0.2	---
November	42.1	96.9	---	51.7	3.1	---	6.2	.0	---
December	16.9	89.4	---	50.1	10.0	---	33.0	.6	---
January 1991	64.1	86.8	54.0	17.0	13.2	45.5	18.9	.0	0.5
February	31.3	97.1	65.9	67.7	2.9	32.7	1.0	.0	1.4
March	57.5	99.3	85.6	42.5	.7	12.8	.0	.0	1.6
April	23.6	98.5	88.0	76.4	1.5	11.5	.0	.0	.5
May	63.0	100.0	97.7	37.0	.0	2.3	.0	.0	.0
June	47.4	96.3	94.7	52.6	3.7	4.8	.0	.0	.5
July	23.4	96.2	89.1	76.6	3.8	10.5	.0	.0	.4
August	20.3	90.3	80.3	79.7	8.9	17.8	.0	.8	1.9
September	59.6	97.4	98.0	40.4	2.6	2.0	.0	.0	.0
October	60.5	99.6	99.9	39.5	.3	.1	.0	.1	.0
November	47.6	95.0	77.2	52.4	5.0	21.8	.0	.0	1.0
December	71.3	97.6	66.1	28.7	2.4	28.0	.0	.0	5.9
January 1992	43.6	78.9	55.5	53.6	20.3	41.5	2.8	.8	3.0
February	54.6	87.6	71.0	37.0	11.9	28.5	8.4	.5	.5
March	53.5	83.3	68.6	46.5	15.2	15.4	.0	1.5	16.0
April	50.2	97.1	84.1	49.8	2.8	14.9	.0	.1	1.0
Average:	47.7	93.8	79.9	48.6	6.0	18.1	3.7	.2	2.1

Precipitation in the Hyde County study area was 9.5 in. below the long-term (30-year) average during April 1989 through August 1990, before tide gates were installed, and 14 in. below the long-term average from September 1990 through April 1992, after tide-gate installation. Therefore, results of this study could underestimate discharge rates from the canals that might be observed during more typical periods.

Flow at site H1 was generally lower than flows at sites H2 and H3, before and after tide gates were installed at the H2 and H3 sites. As previously noted, flow at site H1 was somewhat obstructed by the canal's geometry and debris in the canal.

Similar ranges of flow were observed at sites H2 and H3 during the study. However, concurrently measured flows at sites H2 and H3 often differed considerably, even though water levels in these two canals were usually very similar (fig. 6). At times, water flowed upstream in one canal while water flowed downstream in the other canal. Reasons for this phenomenon were not clear, but it may have been related to the different storage capacities of the two canals. The drainage area and network of field ditches for the H2 canal are larger than for the H3 canal; therefore, more water can be stored upstream from the H2 tide gate. At times, high downstream water levels prevented freshwater runoff from draining completely at site H2, resulting in the gradual release of water over a longer period of time. This drainage could account for some downstream discharge at the H2 site when none was observed at site H3.

Flow characteristics changed at sites H2 and H3 after tide-gate installation, but the changes were not consistent at the two sites. Daily mean discharge declined from 0.4 to 0.2 cubic feet per second (ft^3/s) at site H2 while a slight increase was recorded at site H3. At the control site (H1), the daily mean discharge decreased from 0.1 to 0.05 ft^3/s for the before-to-after tide-gate periods at the test sites. It is important to note that mean monthly precipitation declined by about 0.4 in. from before to after tide-gate installation.

High estuarine water level is capable of lessening the magnitude of flow and delaying runoff from the field ditches and drainage canals. The relations among flow, water level, and rainfall are revealed by examining data from specific storm events. For example, during the last week of May 1990, before tide-gate installation, runoff from 2.7 in. of rainfall increased discharge from the H2 canal, but the timing and intensity of this effect was mediated by water-level interactions between the canal and its receiving waters (fig. 9). The initial runoff period was very brief, because high water level in the Pamlico River and Rose Bay Creek attenuated runoff. During the week, daily mean discharge ranged from about -0.1 to 2.2 ft^3/s, and specific conductance decreased from around 10,000 to less than 6,000 microsiemens per centimeter (µS/cm) in response to the continued flushing. The maximum discharge recorded during this period was greater than 4 ft^3/s, and it occurred approximately 36 hours after the rainfall event (fig. 9).

As previously noted, after tide gates were installed, discharge records usually represented the back and forth motion of water between Rose Bay Creek and the canals. Short-term oscillations in discharge tended to be smaller than those recorded before tide gates were installed, even in conjunction with large changes in water level. Also, after tide-gate installation, discharge rates following storms generally were lower than those measured during storms before tide-gate installation because runoff was derived solely from freshwater drainage (no estuarine backflows) after the tide gates were in place.

Data collected during April 18-22, 1991, illustrates the effects of tide gates on interactions between discharge, water level, and precipitation (fig. 11). On April 20 at 1630 hours, following almost 2 in. of rainfall during the previous 8 hours, the H2 tide gate could have opened for about 1 hour when the downstream water level was extremely low. Water level upstream from the tide gate at site H2A dropped 0.15 ft during this 1-hour period, even though records indicate that water level at site H2A exceeded that at site H2 by only 0.06 to 0.12 ft. Discharge increased at site H2 immediately after the tide gate apparently opened. However, discharge rates increased slowly and consistently even though water level was not rising. This suggests that runoff was gradually released for several days following the rainfall event and that the tide gates possibly leaked. Thus, the tide gate at site H2 appeared to decrease the magnitude of the discharge rate and increase the duration of freshwater drainage from the cropland.

Similar results were observed during other rainfall events at sites H2 and H3. Not all precipitation resulted in increased flow; in fact, the flow at downstream canal sites declined or became negative following some rainfall events, before and after tide gates were installed. The response of flows to rainfall depended on many factors, particularly on existing water levels in the estuary and the canals.

Peak discharges resulting from runoff were smaller after tide gates were installed. The maximum daily mean discharge associated with rainfall after tide-gate installation was 0.82 and 1.5 ft^3/s at sites H2 and H3, respectively. In contrast, before tide-gate installation, the maximum daily mean discharge associated with precipitation events at sites H2 and H3 was 4.2 and 1.6 ft^3/s, respectively. However, the maximum daily mean discharge associated with rainfall was higher at site H1 for August 1991 through April 1992 (after tide-gate installation at sites H2 and H3), indicating that the decline in peak flows at H2 and H3 was not the result of natural variation, and supporting the conclusion that tide gates lower peak discharge rates. With tide gates in place, the largest 24-hour rises in daily mean discharge associated with high rainfall were 0.39 ft^3/s at site H2 (April 23, 1992) and 0.53 ft^3/s at site H3 (September 2, 1991) (Treece, 1993). Before tide gates were installed, daily mean discharge at sites H2 and H3 often increased more than 2.0 ft^3/s in a 24-hour period following rainfall (Treece and Bales, 1992).

Throughout the study, peak discharge rates from the canals tended to occur following intense rainfall when water levels in the canals were greater than in the estuary. When estuarine water levels were high, precipitation caused no notable increase in flow in the canals, further supporting the conclusion that water-level interactions between the canals and their receiving waters are the dominant factor regulating discharge of runoff from the Hyde County agricultural canals.

Flashboard Risers

Data collection and hydrologic conditions at site B1 (fig. 4) differed from those at the other Beaufort County sites. The B1 canal, unlike the other two canals, is not tidally influenced and drains to Bond Creek, a tributary of the Pamlico River (fig. 4). At the onset of the investigation, a riser frame was installed at site B1, the reference site for the Beaufort County study area. However, flashboards were not used in the riser until the fall of 1990. Data collection for water level and flow was discontinued at site B1 after March 1991, because hydrologic conditions at the site prevented its use as a reference site for the other canals and because

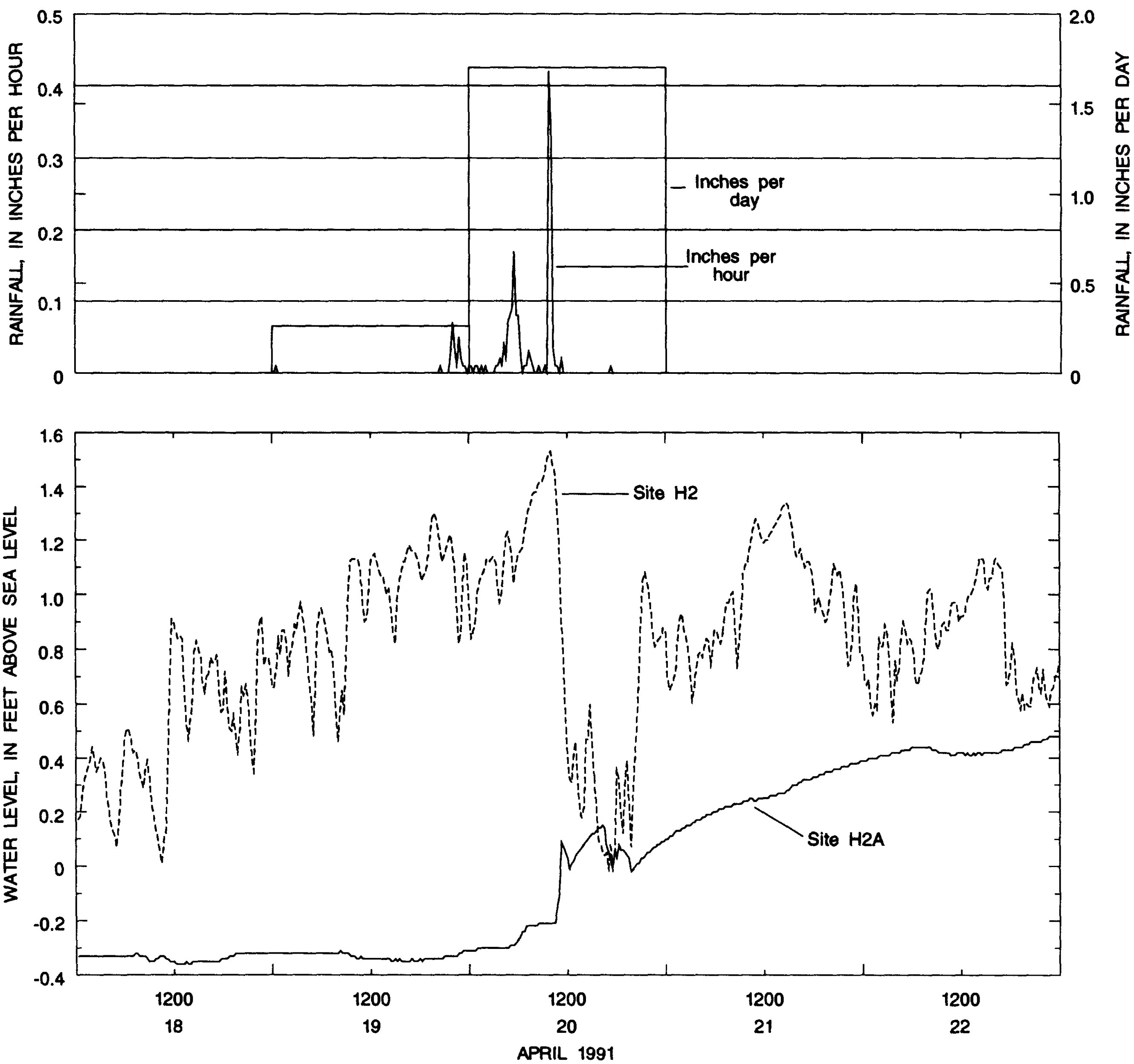

Figure 11. Response of water level to rainfall at sites H2 and H2A following tide-gate installation, April 18-22, 1991, Hyde County, North Carolina.

dry conditions resulted in frequent periods of no flow and missing record.

No upstream flows were recorded, and no seasonal patterns for monthly mean flows were evident at site B1. Water level and flow were directly related to climatic conditions, and highest flows were associated with precipitation events. The maximum daily flow of 4.7 ft^3/s was recorded at site B1 on September 26, 1989, following 3 in. of rainfall (Treece and Bales, 1992). The subsequent discussion focuses on sites B2 and B3 only.

Data were collected at sites B2 and B3 for the entire study period, before and after flashboard risers were installed. Both canals drain into Campbell Creek, a tidal creek that is tributary to Goose Creek (fig. 4). Water levels also were recorded at Campbell Creek (site C1, fig. 4) so that hydrologic relations between the canal sites and their receiving waters could be examined.

Water Level

Comparisons of water-level data for Campbell Creek (site C1) and Goose Creek (site GC) indicate that the water level of Campbell Creek is affected by downstream hydrologic conditions (fig. 12). Water level in Goose Creek occasionally exceeded that in Campbell Creek (for example, July 3-4, 1990, fig. 12) when high water levels in the Pamlico River forced water upstream.

Monthly mean water-level elevations in Campbell Creek tended to be highest in late summer and early fall and lowest in winter (fig. 13), corresponding to seasonal water-level patterns in the Pamlico River. Seasonality is less pronounced at canal sites B2 and B3, but mean water levels generally were lowest in the summer at both sites.

Conditions in the tidal creek occasionally influenced water levels in the canals at sites B2 and B3, but to a much lesser extent than was observed in the Hyde County canals. Concurrently measured water level in Campbell Creek exceeded water levels at sites B2 and B3 8 percent and 19 percent of the time, respectively. This slope of water surface from the creek to the canal usually resulted in upstream flow of water in the canals, accompanied by an increase in specific conductance. Moreover, the water-level data indicate that downstream flow occurred 94 and 81 percent of the time at sites B2 and B3, respectively.

Water level at site B2 was less affected by conditions in Campbell Creek than at site B3 partly because site B2 is at a higher elevation than site B3. The bottom of the canal at site B2 is 0.68 ft higher in elevation than the streambed at site B3. The influence of tidal backflows from Campbell Creek on water-level elevations also was lessened by a weir which was installed immediately downstream from site B2. Upstream flows from Campbell Creek were measured at site B2 only when the water level downstream from the weir was higher than the bottom of the v-notch (at 1.08 ft). In addition, when water level upstream of the weir was lower than 1.08 ft, periods of zero flow were recorded at site B2.

Water levels at site B2 were consistently higher than at site B3 (fig. 13). Daily water-level ranges were consistently lower at site B2 than at site B3 and were highest at site C1. The higher elevation of the channel bottom and the presence of the weir at site B2 could account for the different water-level characteristics of the two canal sites. Monthly mean water levels at sites B3 and C1 were closely related (fig. 13).

Because tidal influences were less at site B2 than at site B3, rainfall had a more pronounced effect on water level at site B2 than at B3. For example, during August 1991 (post-riser installation), water levels at the B2 and B3 sites increased following rainfall on August 15, while water level at site C1 showed a minimal response (fig. 14). The maximum water level was usually higher at site B2 than at site B3. Water levels at site B3 were very similar to those at site C1 for much of the month. At site B2, declines in water level following rainfall were slower and steadier than at site B3 (fig. 14). On August 18, the water-level rise at sites B2 and B3 was solely in response to the water-level rise at site C1.

Water-levels at downstream canal sites increased slightly after flashboard-riser installation (table 7). Water levels at sites B2 and B3 before flashboard-riser installation averaged 1.33 and 0.88 ft above sea level, respectively. Maximum water levels of 5.04 ft at site B2 and 3.73 ft at site B3 occurred in March 1991. After riser installation, mean water levels increased to 1.39 ft at site B2 and 1.02 ft at site B3. However, a similar increase in mean water level was observed at site C1, suggesting that water-level fluctuations in the receiving waters accounted for the slight increase in canal water levels.

Because the flashboard risers retained agricultural drainage water, water levels upstream from these control structures were higher than without risers in place (table 7). Mean water levels after riser installation were 2.54 ft at site B2A compared to 1.39 ft at site B2, and 1.25 ft at site B3A, compared to 1.02 ft

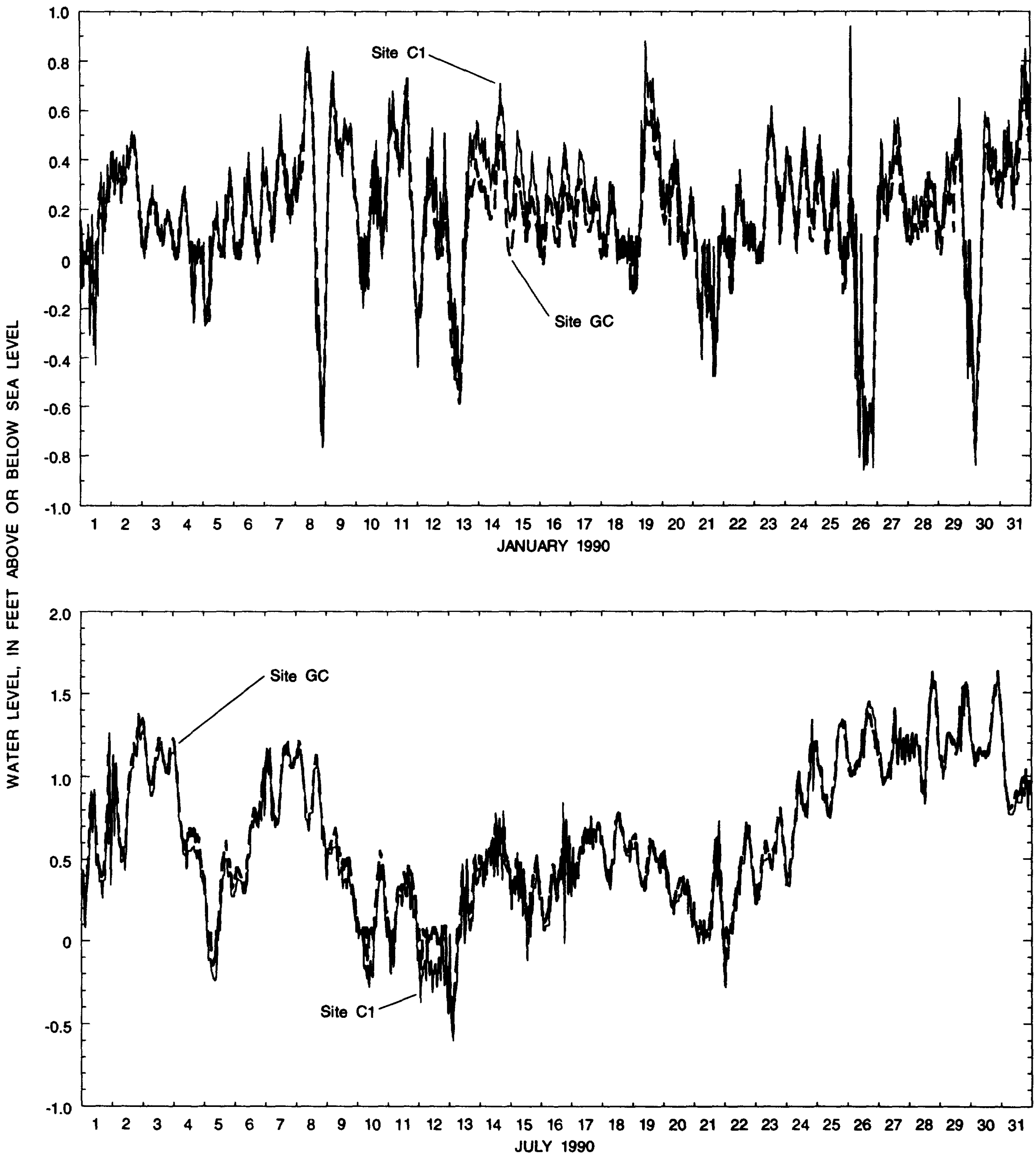

Figure 12. Water levels at sites C1 and GC for January and July 1990, Beaufort County, North Carolina.

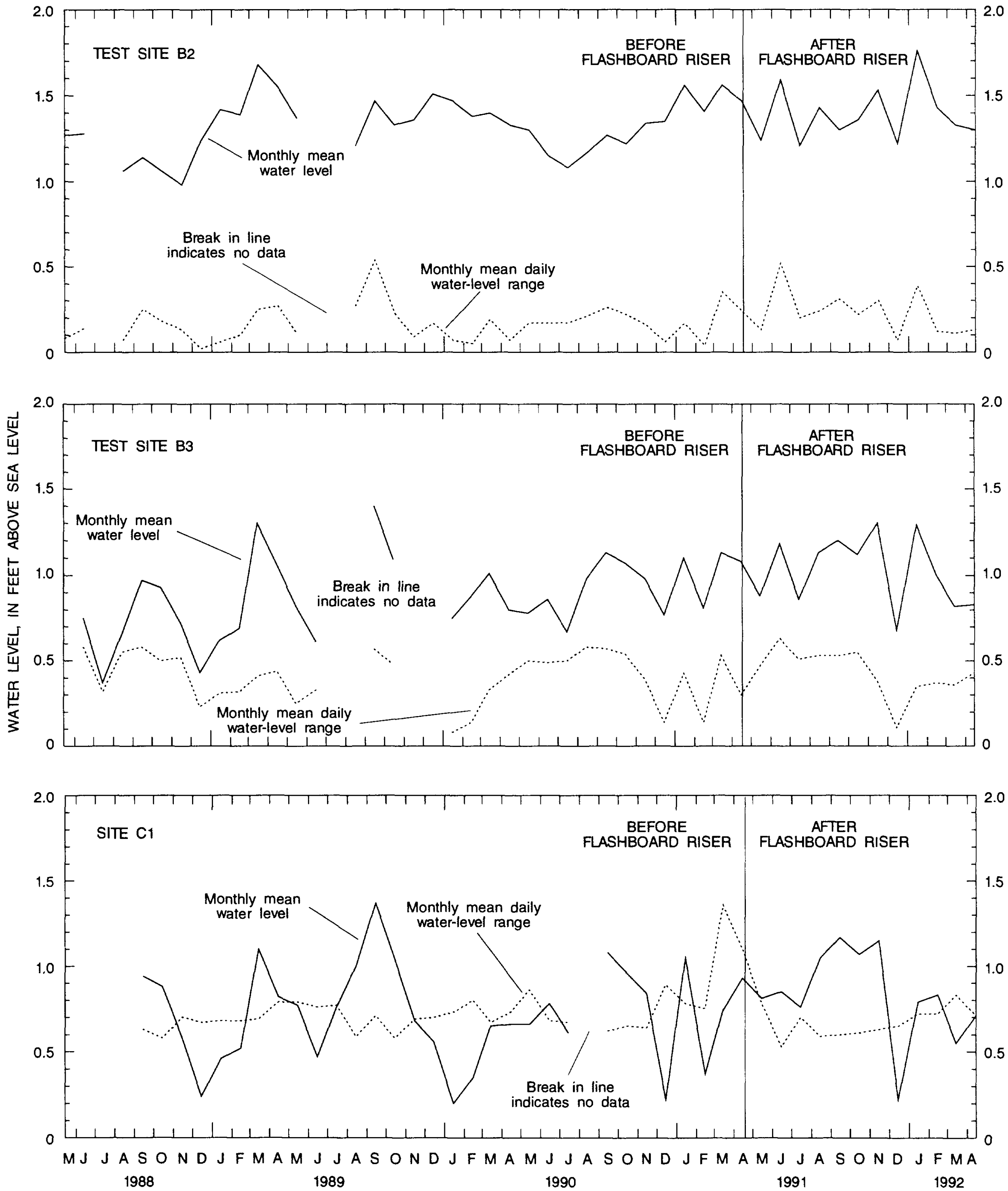

Figure 13. Monthly water-level statistics at sites B2, B3, and C1, May 1988 through April 1992, Beaufort County, North Carolina.

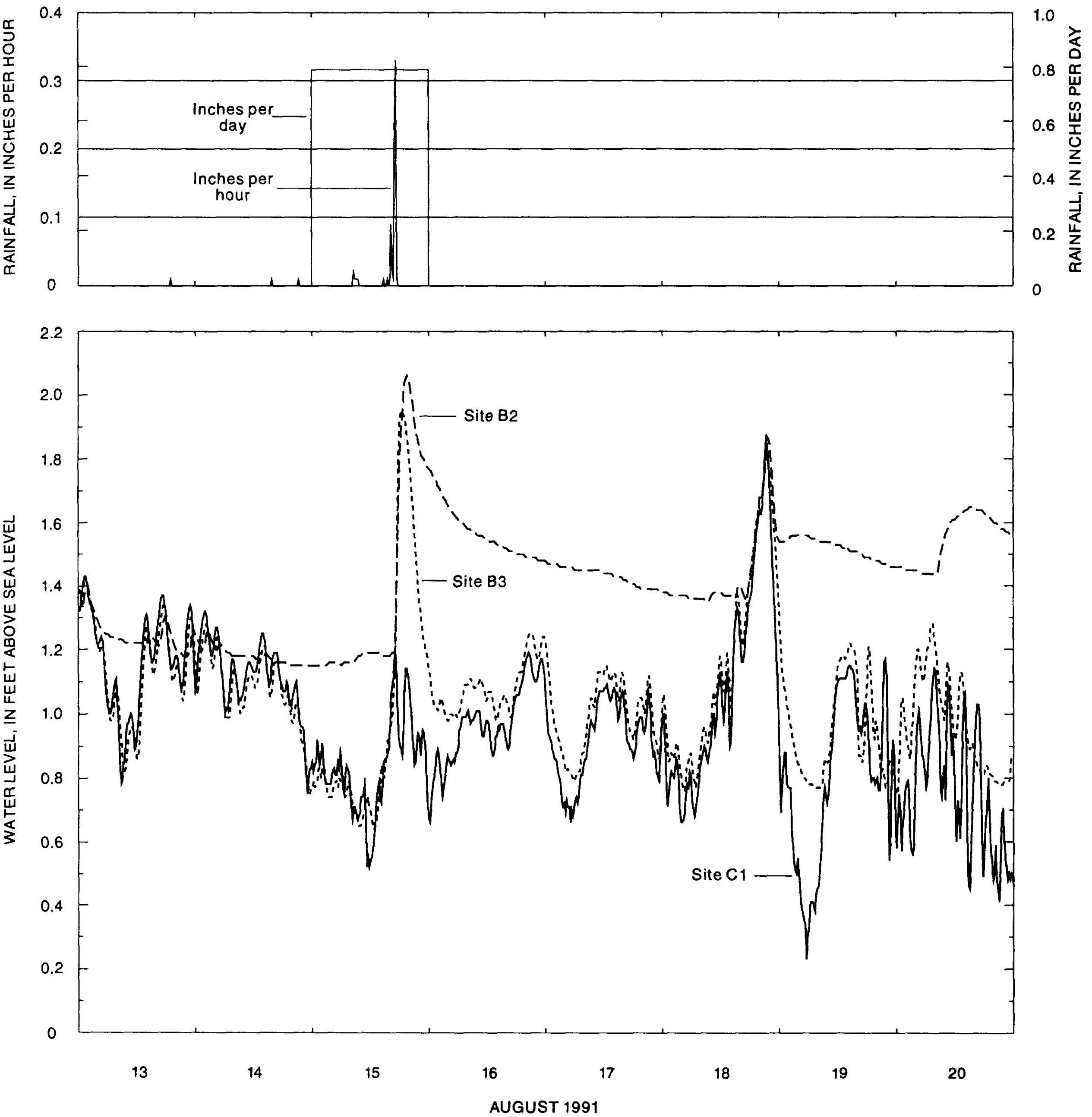

Figure 14. Rainfall at site B3, and water levels at sites B2, B3, and C1, August 13-20, 1991, Beaufort County, North Carolina.

Table 7. Summary of water-level statistics for Beaufort County sites before and after water-control structures were installed at sites B2 and B3, May 1988 to April 1992

[---, no data; NA, not applicable]

Site (figure 4)	Values are in feet above or below (-) sea level										Values are in feet	
	Mean		Maximum recorded		Minimum recorded		Mean daily maximum		Mean daily minimum		Mean daily range	
	Before	After	Before	After	Before	After	Before	After	Before	After	Before	After
B1	2.50	---	4.14	---	1.93	---	2.55	---	2.36	---	0.09	---
B1A	2.52	---	4.55	---	1.24	---	2.58	---	2.47	---	.11	---
B2	1.33	1.39	5.04	4.64	.79	1.04	1.43	1.53	1.26	1.30	.17	0.23
B2A	NA	2.54	NA	4.67	NA	1.68	NA	2.58	NA	2.51	NA	.08
B3	.88	1.02	3.73	3.55	-.11	.36	1.10	1.27	.70	.84	.40	.43
B3A	NA	1.25	NA	4.05	NA	.47	NA	1.41	NA	1.13	NA	.28
C1	.72	.83	3.48	3.47	-1.94	-.95	1.07	1.16	.34	.49	.74	.67

at site B3. Water levels upstream from the flashboard riser at site B2A were higher than those downstream 99 percent of the time, and water levels at site B3A exceeded those at site B3 80 percent of the time. This indicates that without the risers in place, tidal creek water would have been forced up into the canal at site B3 about 20 percent of the time.

Flow

Because upstream flows were not common at site B2, the velocity meter was removed at this site prior to flashboard-riser installation. Discharge at site B2 was then computed using a stage-discharge relation rather than area-velocity calculations. As a result, even though water was observed moving upstream on two occasions, no upstream flow was recorded at site B2 during the latter part of the study.

The flow record in the flashboard-riser canals is somewhat easier to interpret than the flow record from the Hyde County canals. Downstream flow usually represented exclusive drainage of upland water, especially at sites B1 and B2 where there was little tidal influence.

Sites B2 and B3 had distinct flow characteristics, which were influenced to different degrees by precipitation and downstream water level. Flow at site B2 was consistently higher than at site B3. Rainfall events typically resulted in a higher peak runoff at site B2 than at site B3 before and after risers were installed (for example, fig. 15), because tidal effects were less at B2 than at B3 and runoff could drain more freely at B2.

Monthly averages of daily mean discharge increased from 0.08 to 0.12 ft^3/s at site B3. The amount of time that water surface sloped upstream from site C1 to the canals did not change after risers were installed. However, at site B2, dry, no-flow conditions that occurred frequently before the installation of the flashboard riser did not occur after installation despite lower mean monthly precipitation during the post-installation period. The changes in flow cannot be attributed necessarily to the presence of flashboard risers because the period of data collection after the installation of flashboard risers was inadequate to assess hydrologic conditions. The period of study after water-control structures were installed was only one-third as long as the period before installation of risers. The mean monthly precipitation was about 1 in. less for the post-installation period (May 1991 through April 1992) than for the previous 24 months (April 1989 through March 1991), the pre-installation period for which flow was recorded.

The presence of the flashboard risers appeared to affect the timing of runoff in the canals. Before risers were in place, rainfall caused immediate increase in discharge at site B2 (fig. 16a). Upland drainage of field ditches usually was complete within 1-2 days. With the flashboard riser in place (fig. 16b), discharge of runoff at site B2 was extended, sometimes taking several days before returning to pre-storm conditions.

Pre-existing upstream water levels and the height of the riser boards were factors controlling the release of upland drainage into the canals downstream. When water levels upstream were below the crest of the riser boards and rainfall amounts were not large enough to raise the upstream water level above the boards, no increase in flow at site B2 was observed. However, if rainfall occurred when upstream water levels were at or near the top of the riser boards, immediate runoff

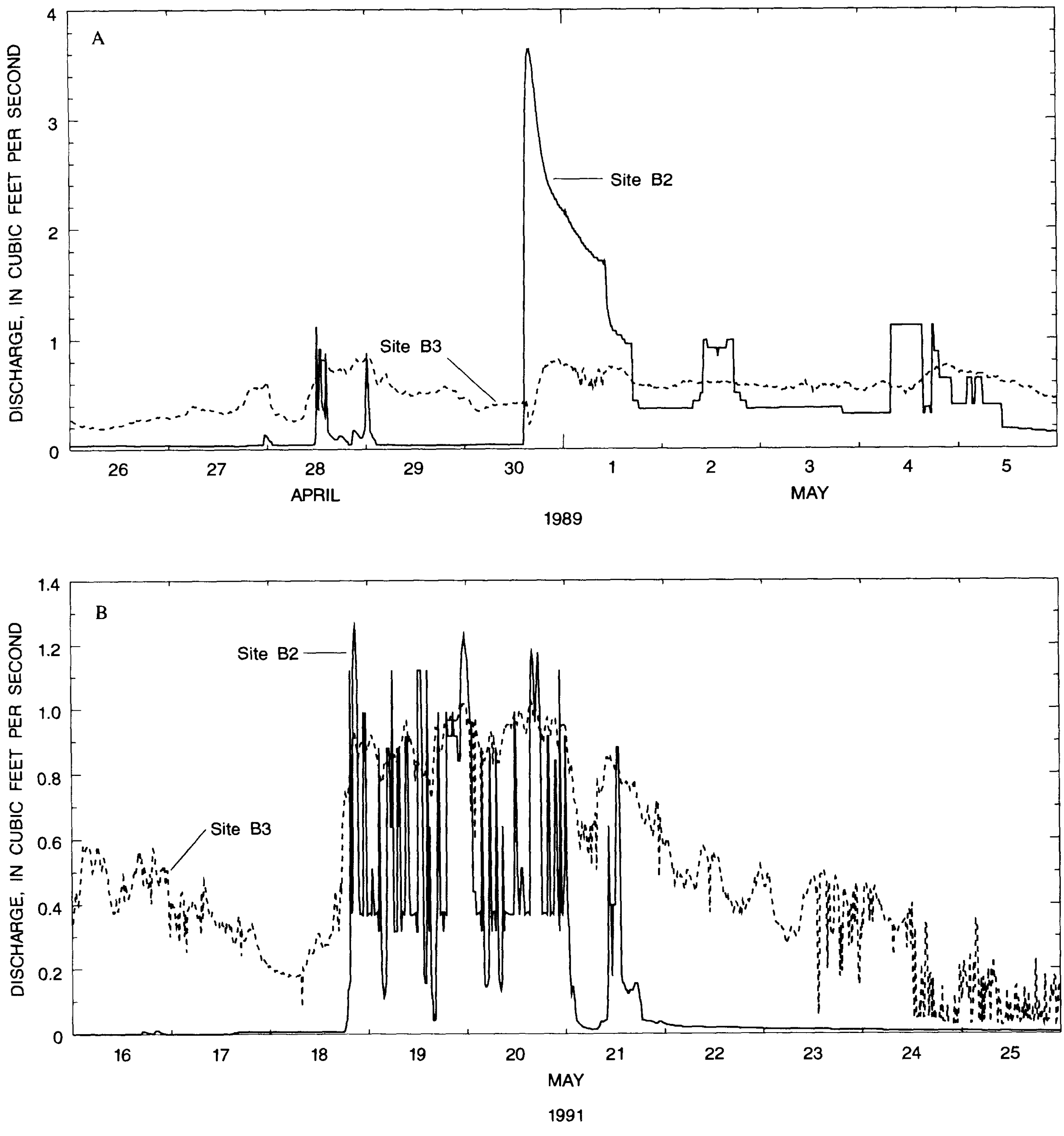

Figure 15. Flow at sites B2 and B3 (A) before flashboard-riser installation, April 26 - May 5, 1989, and (B) after flashboard-riser installation, May 16-25, 1991, Beaufort County, North Carolina.

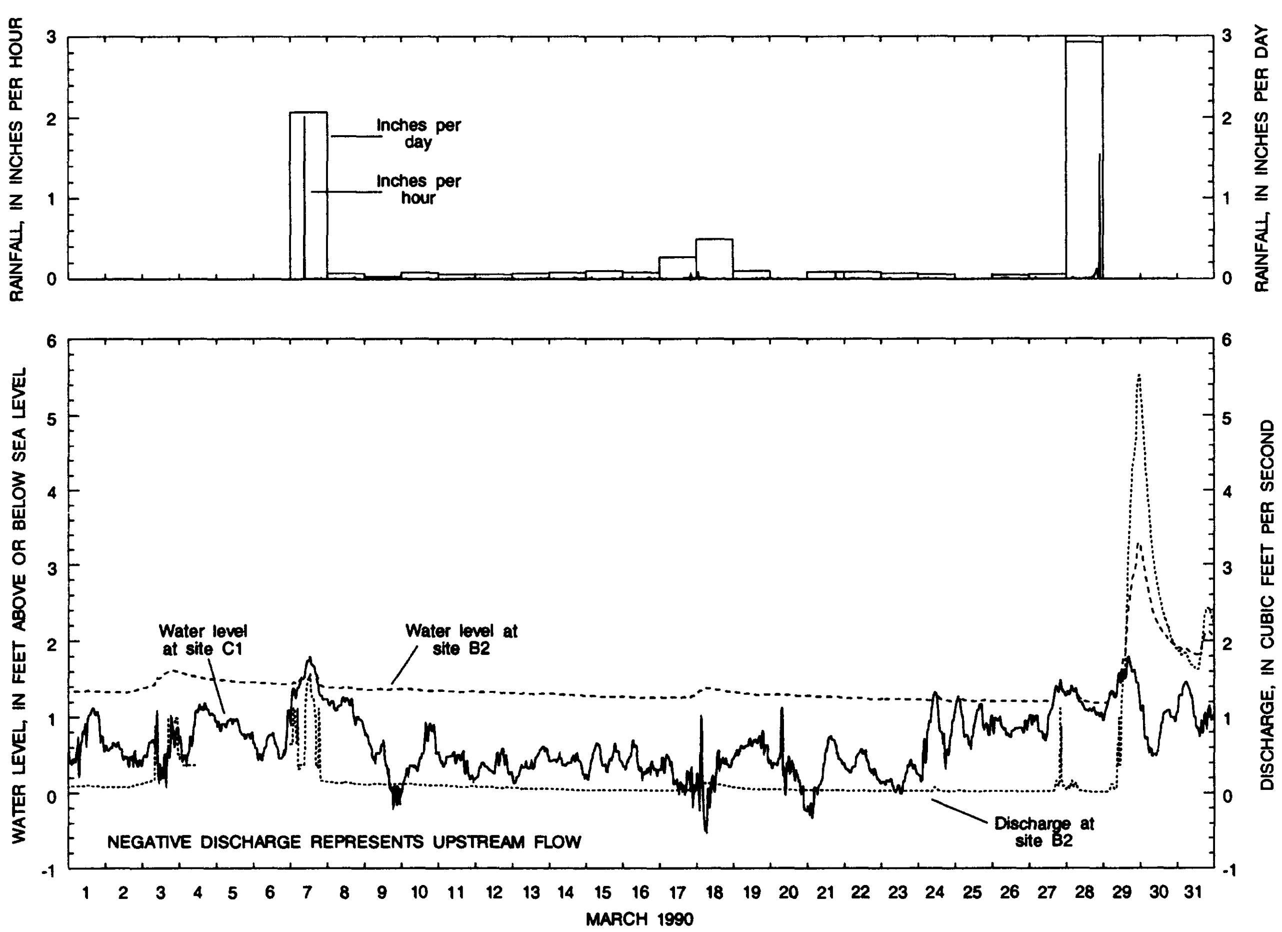

Figure 16a. Relation of flow at site B2 to rainfall and water levels at sites B2 and C1 before flashboard-riser installation, Beaufort County, North Carolina.

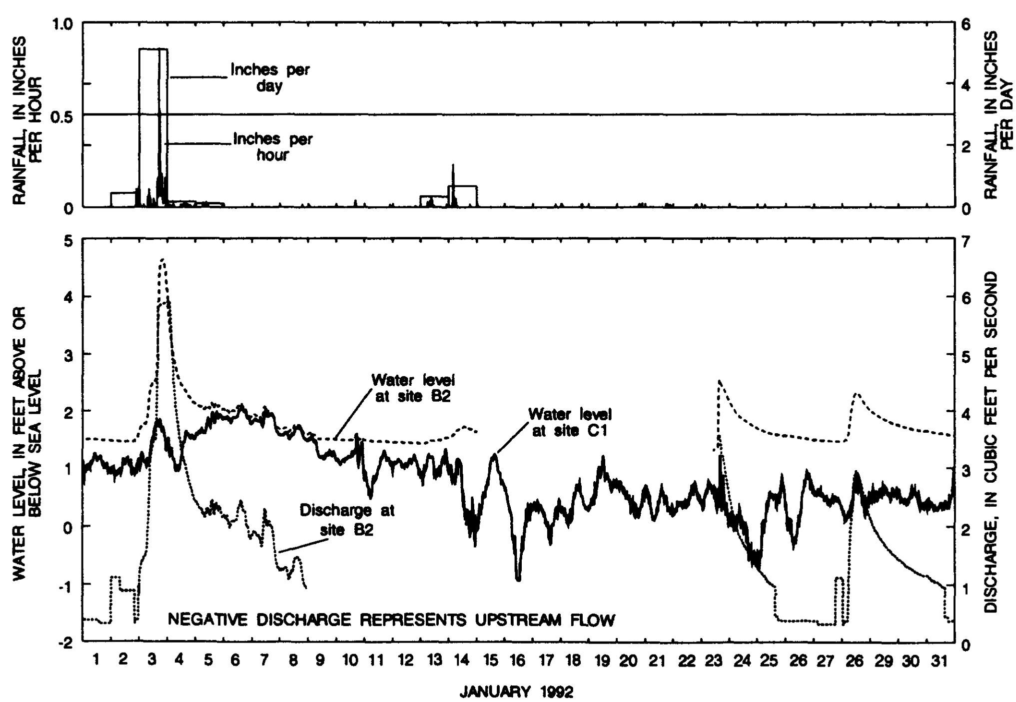

Figure 16b. Relation of flow at site B2 to rainfall and water levels at sites B2 and C1 after flashboard-riser installation, Beaufort County, North Carolina.

resulted. When water level at C1 was much less than in the canals, land-surface drainage of runoff was more rapid (fig. 16a, March 29-30, compared to fig. 16b, January 3-9).

Comparison of Effects of Tide Gates and Flashboard Risers on Water Level and Flow

Tide gates and flashboard risers alter water levels in canals upstream from the structures. Tide gates generally result in lower upstream water levels relative to conditions before tide gates were installed because the canals upstream from the tide gates are no longer replenished with tidal inflows of estuarine water. In contrast, flashboard risers cause an increase in upstream water levels because the boards act as a dam to retain runoff. The use of flashboard risers provides greater potential to manipulate upstream water level than tide gates because the height of riser boards can be adjusted, but tide gates operate passively.

Both types of water-control structures stabilize upstream water levels, as indicated by the smaller ranges of water levels that were observed upstream from the structures after installation. Tide gates can occasionally leak, allowing small amounts of saltwater to move upstream. Saltwater intrusion rarely occurred upstream from flashboard risers because tidal backflows were less of an occurrence at the Beaufort County sites.

Neither tide gates nor flashboard risers had a significant effect on water levels downstream from the structures. Water-control structures had less effect on downstream water levels in Hyde County because water levels in the canals are largely controlled by water-level fluctuations in the estuary. At more upland sites, such as B1 and B2 in Beaufort County, tidal backflows are minor or lacking altogether. At site B2, the flashboard riser eliminated periods of dry, no-flow conditions in the canal by releasing drainage water over an extended time; partly as a result of slow leakage of drainage water through the riser boards.

Small amounts of precipitation often caused no notable change in water level or flow in these agricultural drainage canals. However, maximum discharge recorded during the study was associated with intense rainfall events in the Hyde and Beaufort County canals. Maximum discharge rates associated with rainfall decreased at the Hyde County canals after tide gates were installed. At the Beaufort County sites, the duration of runoff was increased as a result of the presence of flashboard risers. Discharge following rainfall could still be high with flashboard risers in place if upstream water levels were above or near the top of the riser boards when rainfall began. Under these conditions, there was little storage capacity for runoff, and discharge responded quickly to rainfall. However, if pre-existing water levels were low upstream, runoff was retained until the upstream water level exceeded the crest of the riser boards. Water levels were below the crest of the riser boards usually during summer and early fall, which corresponds to a critical period in the growing season when the need for soil-moisture retention is greatest.

Discharge over and through risers occurred about 95 percent of the time. In contrast, discharge through tide gates occurred only about 2 percent of the time. This difference is a function of the design of these two types of water-control structures. Tide gates open to allow drainage and to maintain a particular water-level ratio between upstream and downstream. The flashboard risers simply attenuate or retain land-surface drainage.

EFFECTS OF WATER-CONTROL STRUCTURES ON RECEIVING WATER QUALITY

Water-quality conditions and constituent loadings before and after the installation of water-control structures were compared for each study area. Physical characteristics (specific conductance, pH, water temperature, dissolved oxygen, and suspended sediment), followed by a discussion of nutrients, are presented. Time-series plots show constituent concentrations in chronological sequence; box plots illustrate overall concentration distributions and selected statistics for water-quality constituents.

Concurrent measurements of discharge were used to estimate instantaneous loadings of sediment and nutrients. Conventional methods using instantaneous values to calculate annual nutrient and sediment loads, such as regression equations relating discharge and concentration, could not be used because relations between concentrations and flow were weak, and because of intermittent reverse flow periods. Only sediment and nutrient concentrations associated with downstream flows were used to estimate loadings. Instantaneous loadings of nutrients and sediment were estimated using discharge measurements and constituent concentrations obtained during biweekly and storm-event sampling. Instantaneous export quantities for each constituent were calculated by multiplying discharge by concentration. The values were then converted to daily loads in pounds per day using appropriate conversion factors.

Tide Gates

Water quality in the Hyde County canals could have been influenced by the different morphometries of the canals. The H2 and H3 canals were straight, nearly symmetric in cross section, and clear of debris. Banks were mown regularly at these canals, and the water averaged 3-4 ft in depth. In contrast, the H1 canal was approximately 1 ft deep, with debris and overgrown banks.

There were also appreciable differences in water quality between these canals and those in the Beaufort County study area. Water in the canals in Hyde County was more saline than in the Beaufort County canals. Furthermore, water levels and discharge measurements indicated that water samples from the Hyde County sites often did not represent agricultural drainage waters. Rather, water at these sites often was dominated by backflows from Rose Bay Creek. These distinctions are important for the interpretation of the water-quality results.

Physical Water-Quality Characteristics

Biweekly specific-conductance values recorded during the study were extremely variable, ranging from freshwater (<0.5 ppt salinity) to mesohaline (5 to 18 ppt salinity) conditions (table 8). At site H1, the interquartile range for specific conductance was from 930 to 10,700 μS/cm (0.4 to 6.1 ppt salinity) during the study period (fig. 17). Interquartile ranges at sites H2 and H3 were higher, approximately 6,000 to 16,000 μS/cm or 3.2 to 9.3 ppt salinity (fig. 17).

Because the canal downstream from site H1 was smaller and more overgrown with vegetation than the canals downstream from sites H2 and H3, the daily water-level range at site H1 was significantly smaller than at sites H2 and H3 (Treece and Bales, 1992; Treece, 1993). These characteristics in addition to the lower specific conductance indicate that the volume of tidal exchange was smaller at site H1 than at sites H2 and H3.

The installation of tide gates had no discernible effect on the specific conductance of downstream receiving waters which were measured biweekly. Median conductance was approximately 11,000 μS/cm (6.2 ppt) at sites H2 and H3 before tide gates were installed and 13,000 μS/cm (7.4 ppt) after installation (table 8); however, this slight increase was not statistically significant based on a 95-percent confidence level (fig. 17), nor could it be attributed to the water-control structures because a similar increase in specific conductance was observed at site H1. The higher specific-conductance values after tide-gate installation coincide with lower precipitation and flow for the post-installation period.

The median specific conductance measured from automatically collected composite samples changed significantly after the installation of tide gates. At site H1 the specific conductance was 3,450 μS/cm (1.8 ppt) for the period before tide gates were installed at the test sites and 6,450 μS/cm (3.5 ppt) after tide gates were installed at those sites. Because a tide gate was in place throughout the data-collection period at site H1, this difference was a result of external factors, including variations in precipitation, wind, and estuarine-flow patterns. Median specific conductance at site H2 was 8,560 μS/cm (4.8 ppt) before and 12,600 μS/cm (7.2 ppt) after tide-gate installation. At site H3, median specific conductance was 8,750 μS/cm (4.9 ppt) before and 13,100 μS/cm (7.5 ppt) after tide-gate installation. The distribution of concentrations between the before and after sample populations were significantly different at a 95-percent confidence level using the Wilcoxon rank-sum test (table 9). However, because a statistically significant difference in concentrations for the two periods also occurred at site H1, the increase in salinity at sites H2 and H3 cannot be solely attributed to the presence of the tide gates nor to their ability to lessen freshwater drainage to downstream waters.

The analyses of the composite samples are probably more meaningful than that of the biweekly measurements. The composite samples provided a nearly continuous record of specific conductance (salinity), whereas the biweekly measurements provided a snapshot of the conditions. The composite samples were representative of conditions at the fixed intake point over time, but they were not representative of the entire water column and cross section of the canals at any one time.

Specific conductance also was measured biweekly upstream from each tide gate. Conductance values upstream from the tide gates were almost always lower than values downstream (87 percent of the time at site H1, 97 percent of the time at site H2, and 91 percent of the time at site H3). This indicates that tide gates can prohibit saltwater intrusion into cropland drainage canals. Infrequent occurrences of higher specific conductance upstream from the tide gates relative to downstream seemed to be associated with

Table 8. Summary of physical properties before and after water-control structures were installed at Hyde County (H) and Beaufort County (B) agricultural sites and Campbell Creek (C), November 1988 through May 1992

[µS/cm, microsiemens per centimeter at 25 °C; °C, degrees Celsius; mg/L, milligrams per liter; Max, maximum; Min, minimum; Med, median; Std dev, standard deviation; ---, no data]

Site	Number of samples	Specific conductance (µS/cm)					pH (standard units)					Water temperature (°C)					Dissolved oxygen (mg/L)					Suspended sediment (mg/L)				
		Mean	Max	Min	Med	Std dev	Mean	Max	Min	Med	Std dev	Mean	Max	Min	Med	Std dev	Mean	Max	Min	Med	Std dev	Mean	Max	Min	Med	Std dev
H1[1]	44	5,910	19,000	138	2,940	5,740	6.6	8.2	5.7	6.5	0.5	17.4	28.5	2.0	17.7	8.2	5.5	12.2	0.8	4.9	3.5	23	136	0	15	26
H1[2]	39	6,210	17,600	385	4,780	5,430	6.7	9.1	5.4	6.6	.7	17.0	31.0	5.5	16.5	6.9	5.6	15.2	.5	4.5	4.1	24	189	0	11	42
H1-all[3]	83	6,050	19,000	138	4,000	5,560	6.7	9.1	5.4	6.6	.6	17.2	31.0	2.0	17.0	7.6	5.6	15.2	.5	4.7	3.7	23	189	0	13	34
H1A[1]	39	5,430	18,400	325	2,220	5,800	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
H1A[2]	36	5,470	21,100	253	3,540	5,340	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
H2-before	42	11,900	28,800	1,300	11,400	7,250	7.0	9.0	6.3	6.8	.5	19.4	31.0	6.0	19.2	7.6	7.3	12.8	2.0	6.8	3.1	29	211	2	11	47
H2-after	38	12,600	24,500	719	13,600	6,860	7.2	9.0	5.6	7.1	.7	18.7	32.0	7.0	18.7	6.7	7.9	16.0	2.1	7.3	3.4	17	51	0	15	12
H2-all[3]	80	12,200	28,800	719	12,900	7,000	7.1	9.0	5.6	7.0	.6	19.1	32.0	6.0	19.2	7.2	7.6	16.0	2.0	7.0	3.2	23	211	0	13	36
H2A-after	38	4,640	21,100	611	3,060	4,160	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
H3-before	42	11,300	26,700	1,540	11,000	6,850	7.2	9.1	5.1	7.0	.7	18.4	31.0	5.0	19.2	7.6	7.7	13.6	1.4	7.3	3.4	16	89	2	9	19
H3-after	38	11,900	23,000	1,550	12,500	6,250	7.3	9.0	6.1	7.1	.7	17.9	31.5	8.5	18.0	6.5	8.4	14.8	3.2	7.7	3.2	16	70	3	12	15
H3-all[3]	80	11,600	26,700	1,540	11,800	6,540	7.2	9.1	5.1	7.1	.7	18.2	31.5	5.0	18.5	7.1	8.0	14.8	1.4	7.7	3.3	16	89	2	9	17
H3A-after	36	4,290	11,000	1,510	3,850	2,270	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
B1[4]	28	233	405	126	220	66	7.0	8.7	6.0	6.9	.6	15.6	26.0	4.0	15.2	6.1	7.2	12.9	1.4	6.5	2.6	41	387	4	15	83
B1A[4]	26	219	455	115	199	75	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
B2-before	49	1,170	15,300	159	318	2,780	7.2	9.1	6.1	7.0	.6	16.7	27.0	4.0	17.0	6.6	8.3	15.8	1.7	7.1	4.0	26	161	0	12	38
B2-after	22	678	6,770	148	320	1,410	7.7	8.6	6.6	7.6	.6	17.8	28.0	7.0	19.5	6.7	8.8	17.1	1.7	8.0	4.1	30	150	8	15	37
B2-all[3]	71	1,017	15,300	148	318	2,440	7.3	9.1	6.1	7.2	.7	17.1	28.0	4.0	17.0	6.6	8.4	17.1	1.7	7.4	4.0	27	161	0	12	38
B2A-after	22	274	663	144	237	121	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
B3-before	55	2,815	17,200	180	498	4,589	7.1	8.4	5.6	7.1	.6	17.3	29.0	4.0	17.0	7.0	7.1	16.8	1.2	6.8	4.1	29	240	1	16	42
B3-after	22	1,580	12,200	272	555	2,860	7.3	8.0	5.7	7.4	.5	16.7	26.5	5.5	17.5	6.8	6.5	13.2	1.5	6.5	3.5	22	157	2	13	39
B3-all[3]	77	2,461	17,200	180	502	4,190	7.2	8.4	5.6	7.2	.5	17.1	29.0	4.0	17.0	6.9	6.9	16.8	1.2	6.8	3.9	27	240	1	13	42
B3A-after	22	970	9,600	180	277	2,180	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---
C1[5]	48	10,800	25,000	2,600	9,610	5,430	6.9	9.1	5.4	6.8	.7	19.3	30.0	7.0	19.0	6.5	4.7	13.5	1.3	4.4	2.4	17	165	0	9	25
C1[6]	22	16,800	25,600	5,930	16,600	4,200	7.4	8.9	6.0	7.4	.7	19.0	34.0	9.0	20.2	7.2	5.6	10.9	1.4	5.9	2.3	7	17	2	8	5
C1-all[3]	70	12,600	25,600	2,600	12,100	5,760	7.1	9.1	5.4	6.9	.7	19.2	34.0	7.0	20.0	6.6	5.0	13.5	1.3	4.8	2.4	15	165	0	9	22

[1]Corresponds to the period of record before tide-gate installation at sites H2 and H3.
[2]Corresponds to the period of record after tide-gate installation at sites H2 and H3.
[3]Represents entire period of record (November 1988 to May 1992).
[4]Entire period of record was prior to flashboard-riser installation at sites B2 and B3.
[5]Corresponds to the period of record before flashboard-riser installation at sites B2 and B3.
[6]Corresponds to the period of record after flashboard-riser installation at sites B2 and B3.

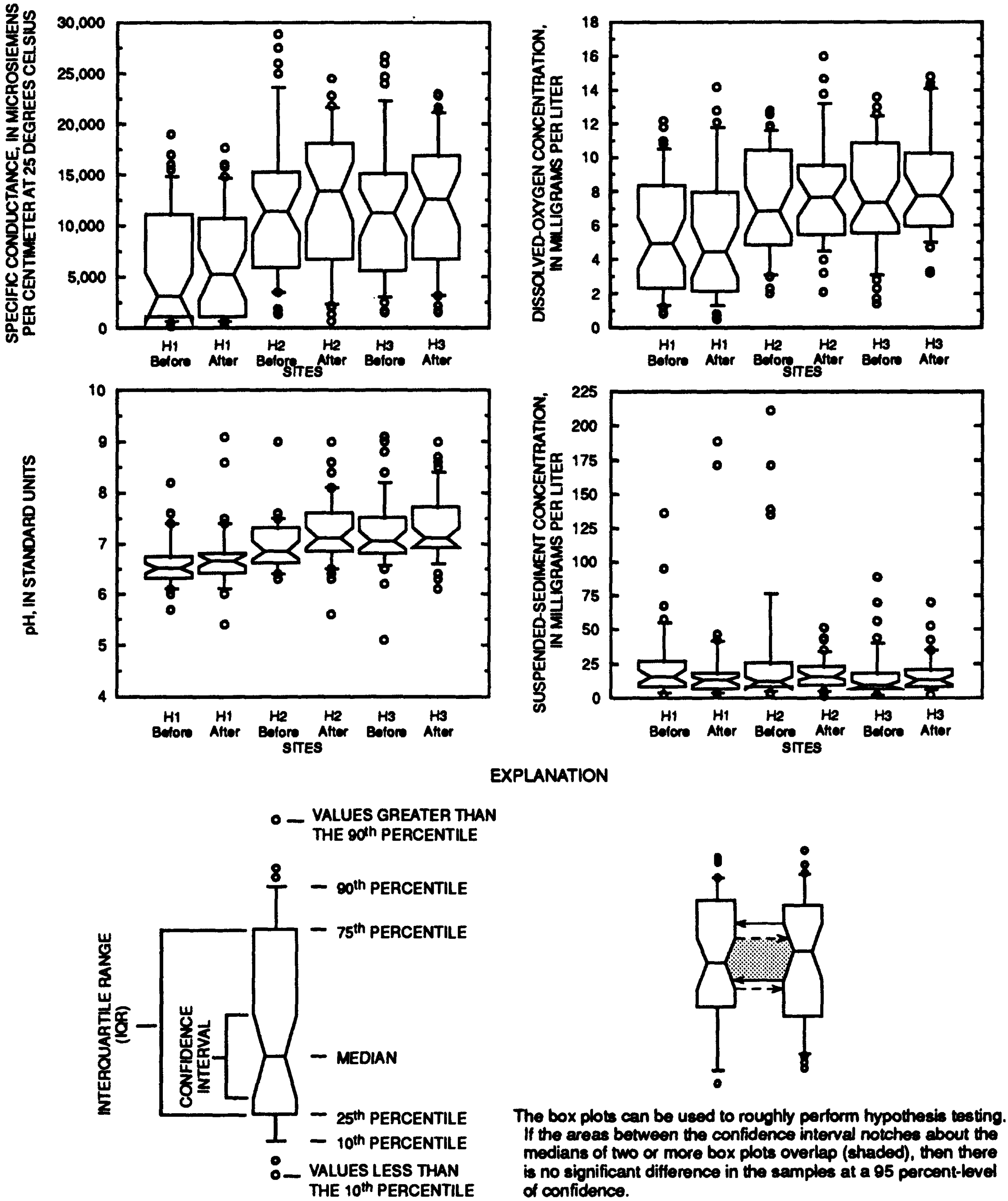

Figure 17. Box plots of specific conductance, dissolved-oxygen concentration, pH, and suspended-sediment concentration for Hyde County sites before and after tide-gate installation at sites H2 and H3. (At site H1, a tide gate was present for the entire study period.)

Table 9. Results of analysis of variance (Wilcoxon rank-sum test) of water-quality conditions before and after water-control structure installation for selected constituents, Hyde and Beaufort Counties, North Carolina

[P-values represent the probability that there is no difference in the before and after sample populations; p-values in bold numbers are statistically significant at a 0.05 level of significance; <, less than; NA, not applicable]

Constituent	Analysis of variance p-values					
	Site H1	Site H2	Site H3	Site B2	Site B3	Site C1
Specific conductance-biweekly measurements	0.82	0.44	0.52	0.35	0.98	**<0.01**
Specific conductance-composite samples	**.01**	**<.01**	**<.01**	.42	**.01**	NA
pH	.18	.09	.46	**<.01**	.06	<.01
Dissolved oxygen	.95	.61	.50	.49	.66	.13
Suspended sediment	.28	.73	.32	.14	.23	.28
Total nitrite plus nitrate	**.03**	.42	**.05**	**.04**	**.03**	**<.01**
Total ammonia	.56	.32	.76	.27	.31	.69
Total ammonia plus organic nitrogen (TKN)	.20	.16	**.04**	.88	.35	.14
Total nitrogen	**.03**	.09	.06	**.03**	**.01**	**.03**
Total phosphorus	.25	.30	.98	.19	.73	**<.01**
Total orthophosphate	**<.01**	**.04**	.10	.97	.25	.44

extremely low water levels upstream. In addition, high specific conductance observed at sites H1A and H2A, and H3A during October 1990 (Treece, 1993) could have been associated with leakage of the tide gates.

Specific conductance followed a seasonal pattern at each Hyde County site (fig. 18). Highest values were recorded May through November and lowest values were recorded December through April. High or increasing specific conductance usually corresponded to an increase in water level due to upstream flow. Water-level rises occurring as a result of rainfall events (particularly November through March) corresponded to low specific-conductance values of 2,000 μS/cm (1.0 ppt salinity) or less.

Water temperature at the Hyde County sites ranged from 2.0 to 32.0 °C during the study period (table 8). For the most part, water temperature followed expected seasonal patterns with lowest temperatures occurring from December through February, and highest temperatures from June through August of each year (fig. 19).

Minor differences in the temperature of water in the drainage canals before and after water-control structures (table 8) were installed can be attributed to prevailing weather during sampling, rather than to effects of the tide gates. The lower maximum temperature at site H1 compared to sites H2 and H3 (table 8) reflects the heavier vegetation and shading at site H1.

A wide range of dissolved-oxygen concentrations was recorded at each sampling site during the study (fig. 17). Seasonal patterns were observed, with highest concentrations occurring in winter and early spring and lowest concentrations occurring during the summer and fall (fig. 19). As expected, these seasonal patterns reflect the inverse relation between water temperature and the solubility of oxygen in water.

The presence of tide gates did not influence dissolved-oxygen concentrations in the drainage canals. Median concentrations at sites H2 and H3 were similar before and after tide gates were installed (table 8; fig. 17). The median concentration for the entire study period at site H1 was 4.7 mg/L, which is significantly lower than the median concentrations of 7.0 and 7.7 mg/L measured at sites H2 and H3, respectively. The minimum dissolved-oxygen concentration of 0.5 mg/L was measured at site H1, and the maximum concentration of 16.0 mg/L was measured at site H2.

The North Carolina Environmental Management Commission (1986) recommends a daily average dissolved-oxygen concentration of at least 5.0 mg/L and a minimum instantaneous concentration of at least 4.0 mg/L to protect organisms living in surface waters. At site H1, 53 percent of the observations were below 5.0 mg/L. At sites H2 and H3, concentrations less than 5.0 mg/L were observed infrequently. Flow velocities at site H1 were low; consequently, there was less saltwater-freshwater exchange at site H1 than at sites H2 and H3, and reaeration was likely lower at site H1. Vegetation cover and organic matter was greater at site H1, which could contribute to lower dissolved-oxygen concentrations. These factors help to account

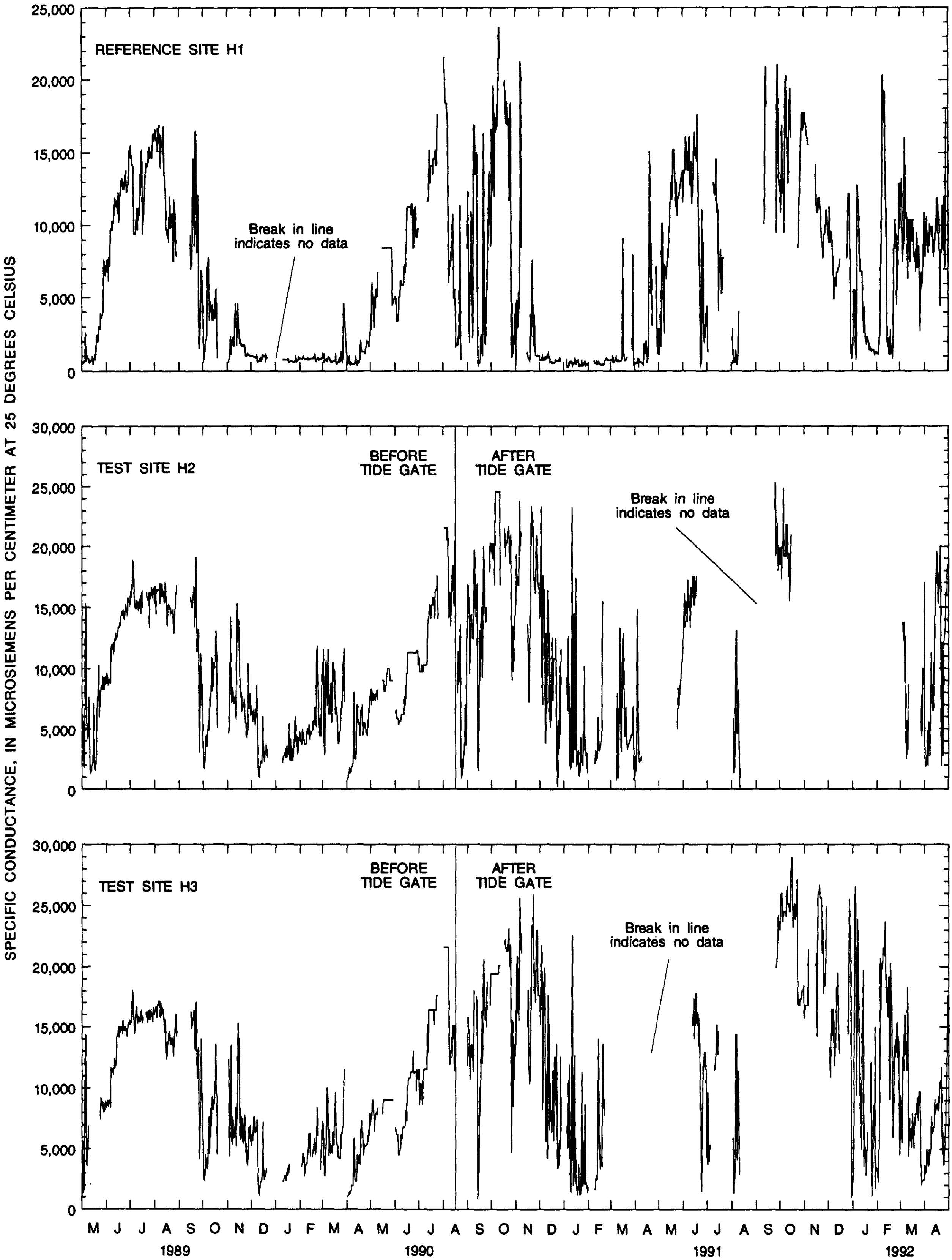

Figure 18. Specific conductance of composite samples at Hyde County sites, May 25, 1989 through April 1992.

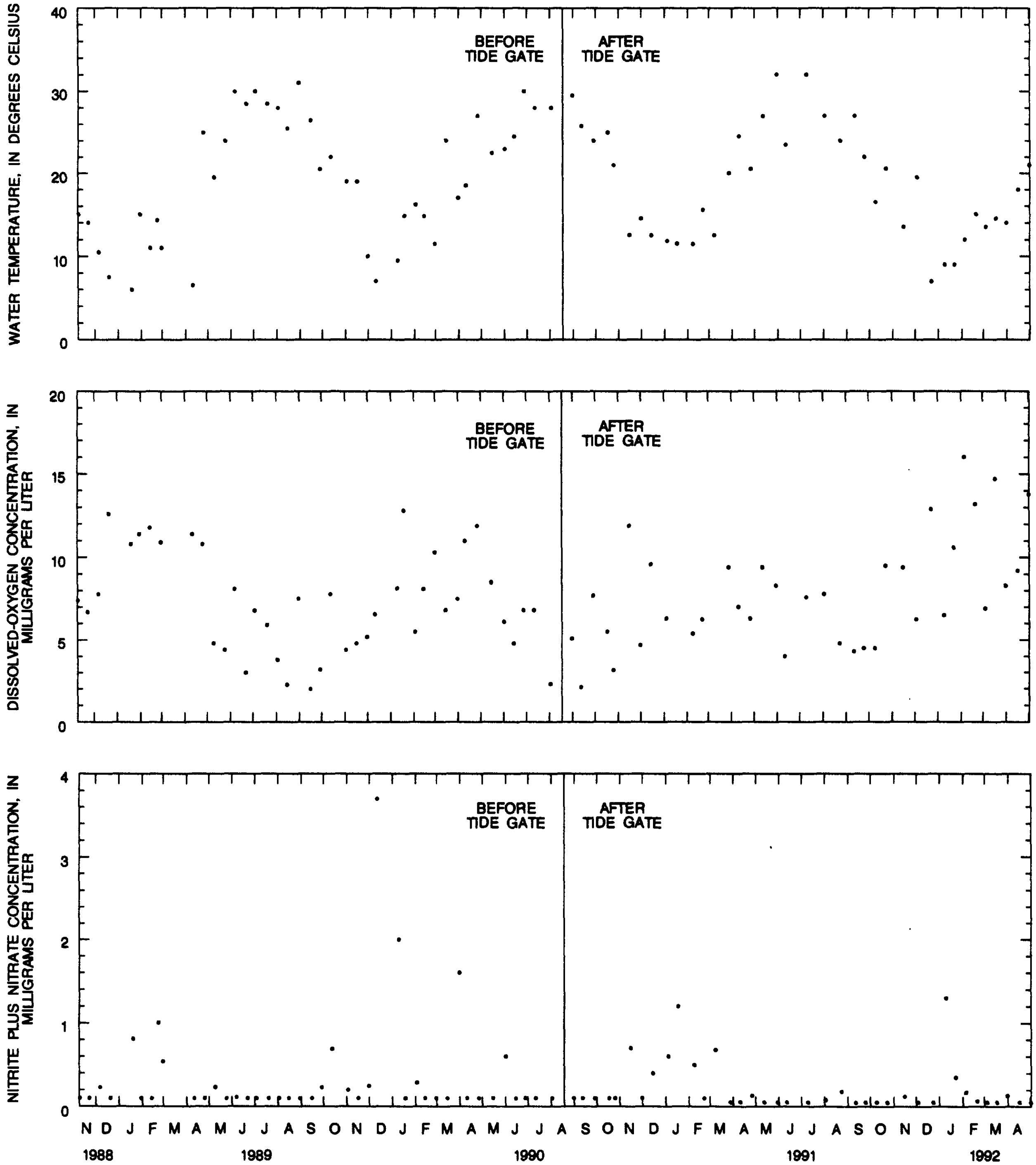

Figure 19. Biweekly measurements of water temperature, dissolved oxygen, and nitrite plus nitrate for site H2, November 1988 through April 1992 Hyde County, North Carolina.

for the differences in dissolved oxygen between sites. Low dissolved oxygen is not unusual for slow-moving waters in the Coastal Plain of North Carolina, but it is ecologically significant, nonetheless.

Water at site H1 tended to be slightly acidic, with a median pH for the entire study period of 6.6. Sites H2 and H3 were circumneutral most of the time (table 8). Except for a few outliers, all observations at these two sites were in the range of 6.5 to 8.5 (fig. 17). Differences between median pH before and after tide gates were installed at sites H2 and H3 were not statistically significant at any of the sites. Thus, there was no apparent effect of the tide gates on the pH of canal waters. Overall, levels of pH recorded at the three canals represented conditions acceptable for aquatic life.

Suspended-sediment concentrations were low at all three sites (table 8). Most observations were less than 50 mg/L, and the maximum was only 211 mg/L at site H2 (fig. 17). Medians were slightly higher at sites H2 and H3 after tide gates were installed (table 8), but these differences were statistically insignificant. There was no appreciable change in the range of suspended-sediment concentrations at sites H1 and H3 during the course of the study. However, after the tide gate was installed at site H2, fewer suspended-sediment concentrations exceeded 50 mg/L at this site. Maximum concentrations at site H2 before and after tide-gate installation were 211 mg/L and 51 mg/L, respectively (table 8).

Nutrients

Nitrogen is usually the macronutrient that regulates phytoplankton growth in estuarine waters of North Carolina (Kuenzler and others, 1979; Paerl and others, 1990; Stanley, 1992). Nitrogen occurs in organic and inorganic fractions, and its cycling involves a complex array of biochemical processes. The inorganic forms of nitrogen, including ammonia, nitrite, and nitrate, are readily assimilated by planktonic organisms. Organic nitrogen occurs in surface waters as dissolved amino acids and polypeptides, as well as live or detrital particulate matter.

Estuarine water quality can be particularly sensitive to nitrate concentrations and loadings. Nitrate is readily available for uptake by estuarine phytoplankton, which are often nitrogen limited. Paerl and others (1990) reported that phytoplankton pulses in the lower Neuse River estuary responded to influxes of nitrate-nitrogen. In addition, high concentrations of nitrate have been associated with declines in submerged aquatic vegetation in estuaries (Burkholder and others, 1992). Therefore, reductions in nitrate could lessen the occurrence of nuisance algal blooms and the decline of desirable aquatic plants.

Most of the nitrogen in the Hyde County canals was present as TKN. Highest concentrations occurred at site H1 (table 10; fig. 20), including the maximum value of 7.8 mg/L. Median concentration for the entire study period at site H1 was 1.3 mg/L, and medians at sites H2 and H3 were less than or equal to 1.0 mg/L. Concentrations of ammonia plus organic nitrogen in the open waters of the Pamlico River near the study area are typically between 0.4 and 0.5 mg/L (Harned and Davenport, 1990; North Carolina Department of Environment, Health, and Natural Resources, 1990b and 1992), which is lower than concentrations measured at all three canal sites. Average concentrations in agricultural field ditches and drainage canals of the A-P peninsula have been reported to be between 0.5 and 3.0 mg/L (Chescheir and others, 1987; Evans and others, 1989), or similar to concentrations observed in the Hyde County canals.

Analysis of variance results (table 9) indicated that the distribution of TKN concentrations changed significantly following tide-gate installation at site H3; however, there were no significant changes in TKN concentrations at sites H1 and H2 after tide gates were installed (fig. 20; table 9). Concentrations were negatively correlated with dissolved oxygen and specific conductance. This indicates that when estuarine waters move into the canals, the TKN in the land-drainage water is diluted by the lower TKN concentrations in the estuarine waters.

The median ammonia-nitrogen concentration for the entire study period was 0.12 mg/L at site H1, compared to medians of less than 0.07 mg/L at sites H2 and H3. In the Pamlico River, ammonia-nitrogen concentrations greater than 0.10 mg/L are uncommon (Kuenzler and others, 1979; North Carolina Department of Environment, Health, and Natural Resources, 1990a, 1990b, 1992). The tide gates apparently had no significant effect on ammonia concentrations in canal receiving waters, but it should be noted that only six samples for ammonia nitrogen were collected prior to the installation of tide gates.

A wide range of ammonia-nitrogen concentrations was observed at site H1. High concentrations, such as the maximum of 1.9 mg/L,

Table 10. Summary of chemical constituents before and after water-control structures were installed at Hyde County (H) and Beaufort County (B) agricultural sites and Campbell Creek (C), November 1988 through May 1992

[mg/L, milligrams per liter; Max, maximum; Min, minimum; Med, median; Std dev, standard deviation; <, less than]

Site	Number of samples	Total nitrite plus nitrate as N (mg/L)					Total ammonia as N[1] (mg/L)					Total ammonia plus organic nitrogen (TKN) (mg/L)					Total phosphorus (mg/L)					Total orthophosphate as P (mg/L)				
		Mean	Max	Min	Med	Std dev	Mean	Max	Min	Med	Std dev	Mean	Max	Min	Med	Std dev	Mean	Max	Min	Med	Std dev	Mean	Max	Min	Med	Std dev
H1-before[2]	44	0.32	1.9	<0.10	<0.10	0.47	0.38	1.8	0.04	0.09	0.70	1.8	5.5	0.40	1.40	1.1	0.09	0.40	0.01	0.06	0.08	0.04	0.17	<0.01	0.03	0.04
H1-after[3]	39	.09	.45	<.05	<.05	.12	.28	1.9	.02	.14	.37	1.5	7.8	.40	1.20	1.3	.06	.18	<.01	.05	.04	.02	.06	<.01	.01	.01
H1-all[4]	83	.21	1.9	<.05	<.10	.37	.29	1.9	.02	.12	.41	1.6	7.8	.40	1.30	1.2	.07	.40	<.01	.05	.06	.03	.17	<.01	.02	.03
H2-before	42	.32	3.7	<.10	<.10	.67	.08	.19	.03	.05	.06	.95	2.5	.40	1.00	.34	.04	.11	.02	.03	.02	.02	.06	<.01	.02	.01
H2-after	38	.19	1.3	<.05	<.10	.31	.12	.39	.02	.08	.10	.85	1.8	.30	.80	.30	.04	.17	<.01	.03	.03	.01	.04	<.01	.01	.01
H2-all[4]	80	.26	3.7	<.05	<.10	.53	.12	.39	.02	.07	.10	.90	2.5	.30	.90	.32	.04	.17	<.01	.03	.02	.01	.06	<.01	.01	.01
H3-before	42	.50	5.0	<.10	<.10	1.0	.08	.24	.02	.03	.09	.98	3.9	.50	.90	.52	.03	.06	.01	.03	.01	.01	.04	<.01	<.01	.01
H3-after	38	.20	1.5	<.05	.07	.35	.07	.18	<.01	.05	.05	.82	1.5	.40	.70	.27	.03	.07	<.01	.03	.02	.01	.06	<.01	<.01	.01
H3-all[4]	80	.36	5.0	<.05	<.10	.78	.07	.24	<.01	.05	.05	.90	3.9	.40	.80	.42	.03	.07	<.01	.03	.02	.01	.06	<.01	<.01	.01
B1[5]	28	1.5	4.5	<.10	1.10	1.4	.15	.21	.10	.15	.08	.95	2.1	<.20	.80	.45	.07	.25	.02	.05	.05	.05	.16	.01	.04	.03
B2-before	49	1.8	8.1	<.05	.30	2.2	.13	.92	.02	.06	.22	1.2	4.9	<.20	.90	.90	.13	.63	.02	.08	.14	.09	.46	<.01	.05	.09
B2-after	22	.45	2.7	<.05	<.05	.75	.08	.47	<.01	.05	.10	1.3	7.8	.40	1.00	1.5	.20	1.1	.02	.13	.24	.09	.41	.01	.05	.10
B2-all[4]	71	1.4	8.1	<.05	.17	2.0	.10	.92	<.01	.06	.16	1.2	7.8	<.20	.90	1.1	.15	1.1	.02	.09	.18	.09	.46	<.01	.05	.09
B3-before	55	1.5	7.0	.07	.36	1.9	.27	.77	.02	.12	.27	1.2	3.7	<.20	1.10	.68	.13	.42	.01	.09	.10	.07	.28	.01	.05	.06
B3-after	22	.57	3.3	<.05	.08	.85	.15	.65	.02	.07	.15	1.1	2.6	.40	.95	.62	.12	.41	<.01	.08	.10	.05	.18	<.01	.03	.05
B3-all[4]	77	1.22	7.0	<.05	.30	1.7	.21	.77	.02	.09	.22	1.2	3.7	<.20	1.0	.66	.12	.42	<.01	.09	.10	.06	.28	<.01	.05	.06
C1[6]	48	.21	1.2	<.05	<.10	.26	.06	.11	<.01	.06	.03	.89	1.8	<.20	.90	.34	.05	.12	.01	.04	.02	.03	.09	<.01	.02	.02
C1[7]	22	.10	1.1	<.05	<.05	.23	.07	.20	<.01	.06	.05	.78	1.5	<.20	.75	.35	.09	.28	<.01	.07	.07	.04	.21	<.01	.02	.05
C1-all[4]	70	.18	1.2	<.05	<0.10	.26	.06	.20	<.01	.06	.04	.86	1.8	<.20	.90	.35	.06	.28	<.01	.04	.05	.03	.21	<.01	.02	.03

[1]The number of samples before water-control structures were installed for which ammonia was analyzed are different from those for the other constituents: 6 for Hyde County sites and 22 for Beaufort County sites.
[2]Corresponds to the period of record before tide-gate installation at sites H2 and H3.
[3]Corresponds to the period of record after tide-gate installation at sites H2 and H3.
[4]Represents entire period of record (November 1988 to May 1992).
[5]Entire period of record was prior to flashboard-riser installation at sites B2 and B3.
[6]Corresponds to the period of record before flashboard-riser installation at sites B2 and B3.
[7]Corresponds to the period of record after flashboard-riser installation at sites B2 and B3.

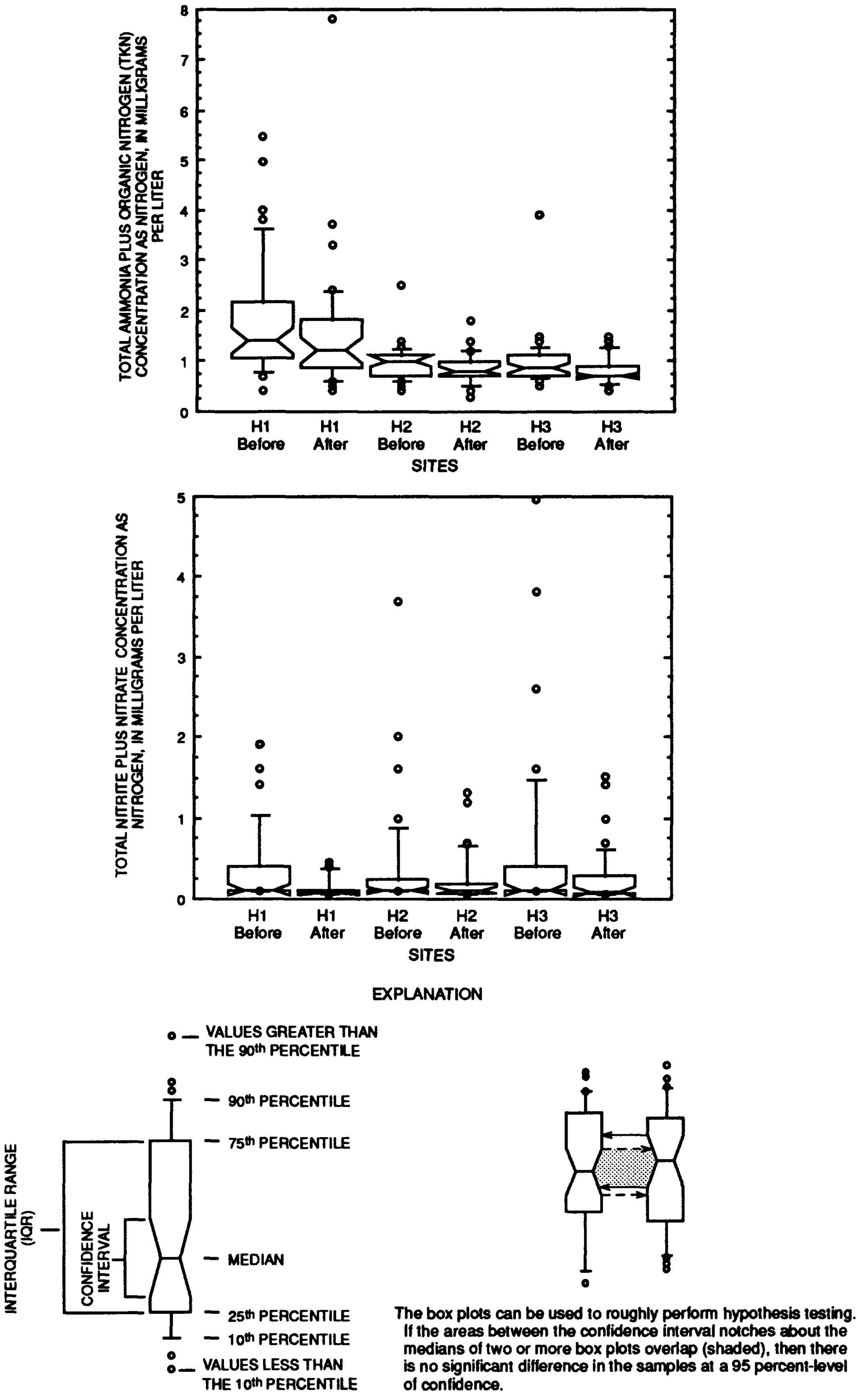

Figure 20. Box plots of total ammonia plus organic nitrogen and total nitrite plus nitrate for Hyde County sites before and after tide-gates installation at sites H2 and H3. (At site H1, a tide gate was present for the entire study period.

indicated that this site was sporadically enriched with ammonia nitrogen, especially when dissolved-oxygen concentrations and water levels in the canal were low. This site also had the lowest dissolved-oxygen concentrations of the tide-gate sites. High ammonia levels do not commonly occur in well oxygenated waters.

Median total nitrite plus nitrate-nitrogen ($NO_2 + NO_3$) concentrations at all sites were generally an order of magnitude less than TKN concentrations (table 10). Median concentrations at all three sites were less than or equal to 0.1 mg/L, and 90 percent of the concentrations were less than 1.0 mg/L. The North Carolina Department of Environment, Health, and Natural Resources (1992) reported typical $NO_2 + NO_3$ concentrations of less than or equal to 0.1 mg/L from 1988 through 1991 at a station in the Pamlico River about 5 miles upriver from the mouth of Rose Bay.

Nitrite plus nitrate concentrations in the Hyde County canals were substantially lower than those reported for other agricultural drainage canals in North Carolina. Chescheir and others (1987) reported average nitrate concentrations of 0.27 to 3.4 mg/L in ditches and canals receiving pumped agricultural drainage water at sites in Dare and Tyrrell Counties, North Carolina. Evans and others (1989) reported average nitrate concentrations ranging from 3.1 to 11.1 mg/L in drainage outflows from several agricultural sites in coastal North Carolina.

There are several explanations for the low $NO_2 + NO_3$ concentrations observed at the Hyde County sites. Water levels, discharge measurements, and specific conductance data indicate that water in these canals often has a large estuarine component; therefore many of the samples were more indicative of constituent levels in the estuary than they were representative of drainage from upland agricultural areas. $NO_2 + NO_3$ concentrations were negatively correlated with specific conductance, indicating concentrations increased with greater amounts of freshwater drainage. Concentrations of $NO_2 + NO_3$ exceeding 1.0 mg/L were frequently observed at all three sites during storm-event sampling (Treece and Bales, 1992; Treece, 1993) and when precipitation and freshwater drainage coincided with routine biweekly sampling. $NO_2 + NO_3$ reached a maximum concentration of 5.4 mg/L at site H1 during a storm event on June 22, 1991 (Treece, 1993).

Even the maximum concentration of 5.4 mg/L was not as high as observed in other studies of agricultural drainage, suggesting that additional factors such as the highly mineral soils or agricultural practices in the study area could have influenced $NO_2 + NO_3$ concentrations in the canals. Land in the Hyde County study area is predominately used to grow soybeans and winter wheat. Less nitrogenous fertilizer can be applied in this crop rotation than in rotations involving other crops with high demand for nitrogen, such as corn. Because nitrogen-fixing bacteria associated with soybeans adds nitrogen to soil, fertilizer is usually not applied. In the Coastal Plain of North Carolina, moderate amounts of nitrogenous fertilizer are applied to winter wheat--20 pounds per acre (lb/acre) in late November and 80-100 lbs/acre in mid-February to mid-March (Ron Jarrett, North Carolina State University, Department of Crop Science, oral commun., 1993).

There appears to be a seasonal pattern in the $NO_2 + NO_3$ concentrations (fig. 19). Concentrations increased during winter, corresponding to typical patterns of fertilizer application in the study area. Moreover, water is usually well oxygenated and biotic assimilation rates tend to be slower in the winter. Both of these factors favor the presence of nitrate over reduced nitrogenous compounds, such as ammonia. Peak concentrations were associated with winter and spring rains, a phenomenon noted in other estuarine studies (Kuenzler and others, 1979; Christian and others, 1989; Paerl and others, 1990).

Mean and maximum concentrations of $NO_2 + NO_3$ following tide-gate installation at sites H2 and H3 were lower than before installation at sites H1, H2, and H3; however the change was statistically significant only at sites H1 and H2 (tables 9 and 10; fig. 19). Because this occurred at the reference site as well as at site H3, the decline in mean and maximum nitrate concentrations at site H3 cannot be ascribed solely to the presence of the tide gates. Median concentrations were below the minimum level of detection (<0.10 mg/L) throughout the study at all three sites. Effects of tide gates on $NO_2 + NO_3$ concentrations should be investigated in canals with higher $NO_2 + NO_3$ concentrations where changes would be more apparent. Because tide gates prolonged or delayed the release of agricultural runoff to receiving waters, this could result in some loss and(or) transformation of $NO_2 + NO_3$ before drainage waters are released downstream.

Total nitrogen ranged from 0.43 to 8.2 mg/L at the Hyde County sites. Site H1 typically had the highest concentrations of total nitrogen, with a median of 1.6 mg/L for the entire study period. Sites H2 and H3 had median concentrations of 1.0 mg/L for this period. These concentrations also were lower than average concentrations in other agricultural drainage ditches in the Coastal Plain, which ranged from 2.6 to 6.3 mg/L (Chescheir and others, 1987). Summertime total nitrogen concentrations greater than 0.6 mg/L appear to be associated with undesirably high algal biomass in the Pamlico River (North Carolina Department of Environment, Health, and Natural Resources, 1990a). Thus, concentrations of total nitrogen at the study sites seem to indicate the potential for over-enrichment of receiving waters with nitrogen. However, some reduction of total nitrogen concentration in water through dilution, sedimentation, and denitrification likely occurs before drainage waters reach the estuary.

Organic nitrogen compounds made up a large proportion of the total nitrogen pool at the Hyde County sites (fig. 21). On average, organic nitrogen accounted for 76 percent of the total nitrogen at site H1, 71 percent at site H2, and 66 percent at site H3. Inorganic fractions--$NO_2 + NO_3$ and ammonia--constituted 24 percent of the total nitrogen at site H1, 29 percent at site H2, and 34 percent at site H3.

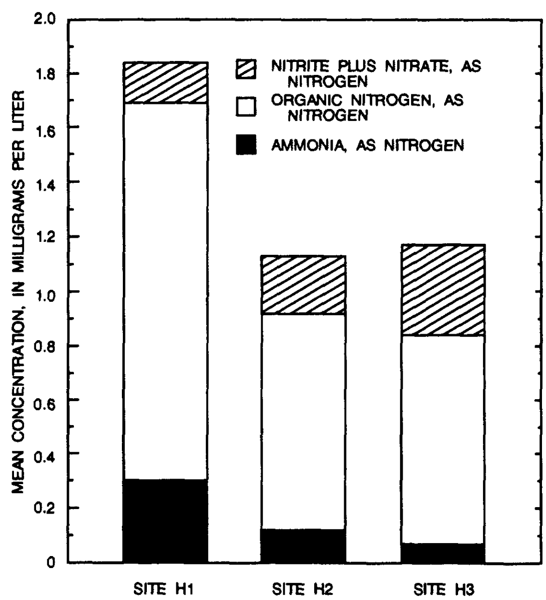

Figure 21. Mean composition of nitrogen species in water at Hyde County sites, November 1988 through April 1992.

Total phosphorus concentrations ranged from less than 0.01 to 0.40 mg/L at the Hyde County study sites (table 10; fig. 22). Highest concentrations were at site H1, where the median of 0.05 mg/L was significantly greater than the median concentration of 0.03 mg/L at sites H2 and H3. However, few observations exceeded 0.10 mg/L at any of the sites, and concentrations were low compared to concentrations reported for other agricultural drainage canals. Chescheir and others (1987) reported average concentrations of total phosphorus ranging from 0.09 to 0.43 mg/L in 33 agricultural canals and field ditches located on the Albemarle-Pamlico peninsula. Evans and others (1989) reported a range of 0.02 to 0.16 mg/L average total phosphorus for five study sites in coastal North Carolina.

Total phosphorus concentrations at the Hyde County sites also were lower than those typically reported for a nearby stretch of the Pamlico River, but were adequate to support nuisance algal growth. Harned and Davenport (1990) observed that the long-term (1967-85), median total phosphorus concentration for the Pamlico River near the Pungo River was 0.11 mg/L, compared to median concentrations that ranged from 0.03 to 0.06 mg/L at Hyde County sites (table 10). The North Carolina Department of Environment, Health, and Natural Resources (1992) reported a median total phosphorus concentration of 0.12 mg/L for the same area of the Pamlico River during 1988-91. Concentrations of total phosphorus in some tributaries, such as the Pungo River, generally are lower than in the mainstem of the Pamlico River. For example, during a synoptic survey of the Albemarle-Pamlico estuary, the North Carolina Department of Environment, Health, and Natural Resources (1990b) reported that total phosphorus concentrations at three sites in the Pungo River ranged from 0.08 to 0.10 mg/L, but ranged from 0.15 to 0.29 mg/L along a nearby transect of the Pamlico River.

Orthophosphate concentrations in the three Hyde County canals also were low, although high concentrations were recorded occasionally. Concentrations ranged from less than 0.01 to 0.17 mg/L and were highest at site H1 (table 10; fig. 22). Median orthophosphate at site H1 was 0.02 mg/L, compared to medians of 0.01 mg/L at sites H2 and H3. Few observations at site H1 were greater than 0.05 mg/L, and concentrations greater than 0.02 mg/L were uncommon at sites H2 and H3.

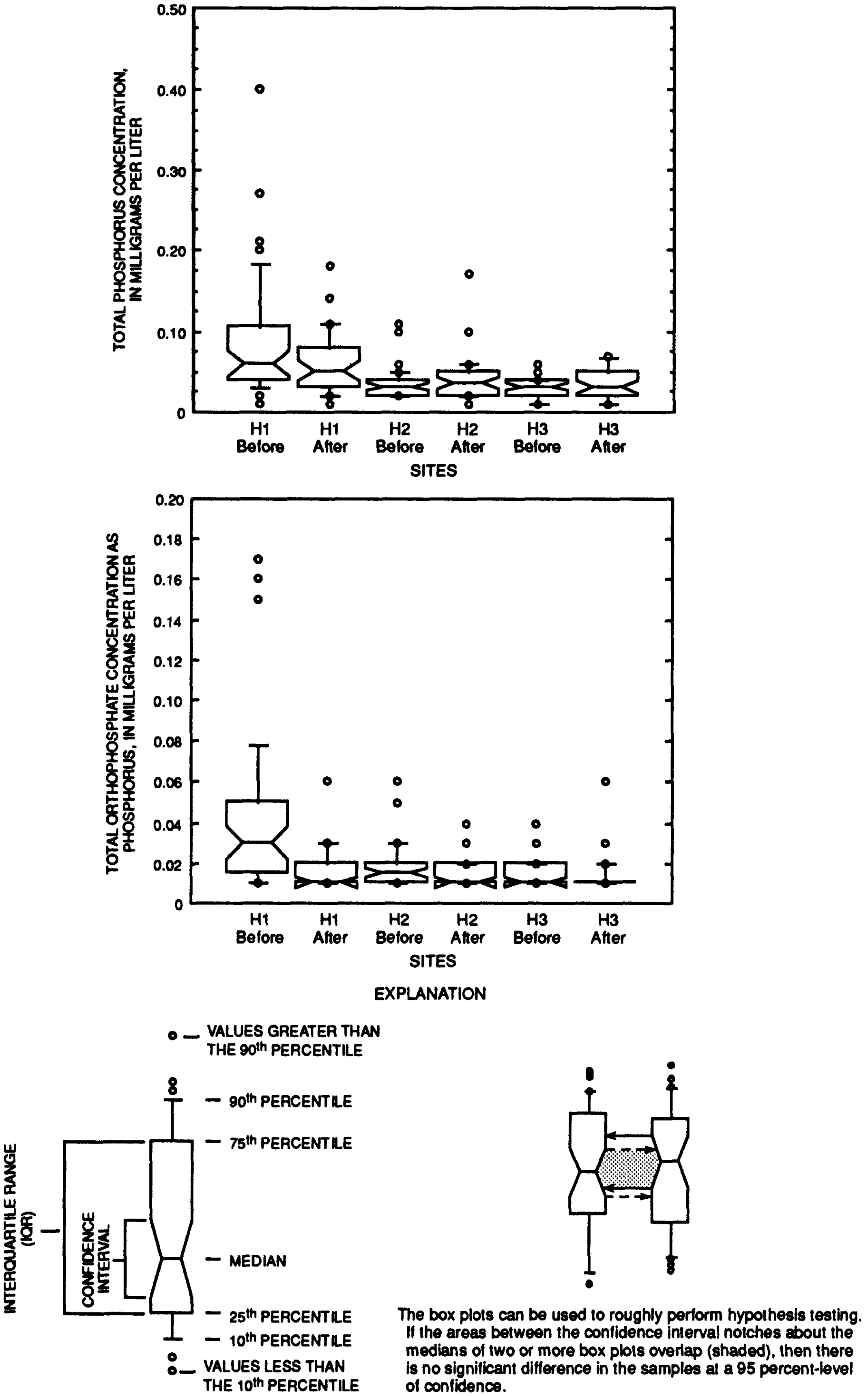

Figure 22. Box plots of total phosphorus and total orthophosphate for Hyde County sites before and after tide-gate installation at sites H2 and H3. (At site H1, a tide gate was present for the entire study period.)

The higher concentrations of total phosphorus and orthophosphate at site H1 can be related to characteristics of this canal described earlier. The greater amount of organic debris at site H1 than at sites H2 and H3 could have been an additional source of phosphorus. At the same time, dilution or flushing of phosphorus-laden waters would be limited by the low volume of tidal exchange at site H1. This site also had the lowest dissolved-oxygen concentrations of any of the three canals, and anoxia would favor release of sediment-bound phosphorus to overlying waters.

Total phosphorus concentrations in the drainage canals were similar before and after tide gates were installed; therefore, tide gates had no observable effect on total phosphorus concentration. Median orthophosphate concentrations dropped from 0.03 to 0.01 mg/L at site H1, and from 0.02 to 0.01 mg/L at site H2, and no change in orthophosphate was seen at site H3 following tide-gate installation. Analysis of variance indicated that the distributions of the orthophosphate concentrations before and after tide-gate installation were statistically different at test site H2, and also at reference site H1 (table 9).

Estimated Loadings of Sediment and Nutrients

When measurable downstream flows were observed at sites H2 and H3, they tended to be of greater magnitude than flows at site H1. As a result, loadings of all nutrient species and sediment were higher at sites H2 and H3 than at site H1, even though nutrient concentrations at site H1 were generally greater (table 11). Sites H2 and H3 exported similar quantities of suspended sediment and most nutrient fractions. The only exception was ammonia, for which loadings were statistically higher at site H2 than at site H3. Median loadings of ammonia nitrogen for the entire study period were 0.57 pound per day (lb/d) at site H2, and 0.17 lb/d at site H3.

After the tide gate was installed at site H3, there was a significant decrease in the median loading of $NO_2 + NO_3$ from 0.63 lb/d to 0.30 lb/d. No statistically significant change in loading of $NO_2 + NO_3$ was observed at site H2. Instantaneous streamflow measured at the time the sample was collected and used to estimate loadings were statistically similar before and after tide gates were installed at sites H2 and H3. Therefore, decreased loading of $NO_2 + NO_3$ at site H3 was a result of lower concentrations and not lower discharge.

Extremely low flows were recorded at site H1 during the first 2 years of the study; therefore, loadings of nutrients and sediment were also low. During the second part of the study, after tide gates were installed at sites H2 and H3, higher flows at site H1 accounted for increased loadings of $NO_2 + NO_3$, TKN, total phosphorus, orthophosphate, and suspended sediment at this site (table 11).

Flashboard Risers

The canals in Beaufort County were markedly different from the canals in the Hyde County study area. The most significant difference was that tidal backflows had little influence on water quality in the Beaufort County canals. Therefore, the data collected here were more representative of actual drainage from upstream sources than in Hyde County, where the canal sites were influenced by large influxes of estuarine waters. Furthermore, the Beaufort County canals had winding channels that contained fallen trees and other debris. The canals were part of extensive networks of drainage ditches, unlike the canals in Hyde County.

Physical Water-Quality Characteristics

Biweekly specific-conductance values recorded from November 1988 through September 1990 at site B1 indicated that water quality at this site was not affected by tidal backflows. Specific conductance ranged from 126 to 405 µS/cm, with a median value of 220 µS/cm (table 8; fig. 23). Results from composite sampling are not presented because the B1 canal was often completely dry and data were limited (Treece and Bales, 1992).

Sites B2 and B3 (fig. 4) typically had higher and more variable specific conductance than site B1 (fig. 23). Results from biweekly sampling indicate that water in these two canals was usually fresh, with median specific conductance for the entire study period of 318 µS/cm (0.14 ppt salinity) at site B2, and 502 µS/cm (0.23 ppt salinity) at site B3 (table 8). Maximum specific conductance recorded during biweekly sampling at site B2 was 15,300 µS/cm (8.9 ppt salinity) and 17,200 µS/cm (10 ppt salinity) at site B3, which represent mildly brackish to mesohaline conditions.

As previously discussed, site B3 was subject to more upstream flow than the B2 canal. Greater influxes of saline water from Campbell Creek account for the higher specific conductance typically characteristic of water at site B3. Instances of elevated specific conductance at sites B2 and B3 corresponded to times when water levels at C1 were higher than at sites B2 and B3 (fig. 4).

Changes in specific conductance were noted at sites B2 and B3 after flashboard risers were installed. Mean specific conductance values for these sites

Table 11. Distribution of estimated instantaneous export of nitrogen, phosphorus, and suspended sediment at Hyde County (H) and Beaufort County (B) drainage-canal sites before and after installation of water-control structures

[lb/d, pounds per day; Max, maximum; Min, minimum; Med, median; WCS, water-control structure]

Site (figures 3 and 4)	Number of samples[2]	Total nitrite and nitrate nitrogen (lb/d)			Total ammonia[1] (lb/d)			Total ammonia plus organic nitrogen (lb/d)			Total nitrogen (lb/d)		
		Max	Min	Med	Max	Min	Med	Max	Min	Med	Max	Min	Med
H1-before[3]	20	6.6	0.00	0.02	0.04	0.04	0.04	9.4	0.01	0.17	15.9	0.01	0.20
H1-after[4]	10	1.1	.01	.06	.36	.02	.04	7.1	.29	1.0	7.5	.30	1.0
H2-before	13	3.5	.06	.49	1.1	.02	.53	41.8	.65	3.0	43.4	.71	3.3
H2-after	15	4.0	.17	.48	2.4	.05	.60	11.3	1.2	4.3	12.4	1.3	5.4
H3-before	18	7.0	.14	.63	.19	.04	.16	7.0	1.1	4.0	8.1	1.3	4.8
H3-after	14	1.6	.03	.30	.73	.02	.20	15.4	.53	4.4	16.1	.56	4.7
B1[5]	24	36.6	.00	.31	.26	.01	.14	12.1	.01	.23	46.7	.02	.81
B2-before	43	52.1	.00	.39	.24	.01	.03	26.5	.02	.41	74.4	.02	1.6
B2-after	18	18.1	.00	.05	.38	.00	.01	6.0	.07	.19	24.1	.07	.20
B3-before	36	5.5	.00	.19	1.5	.01	.05	4.0	.03	.44	6.9	.03	.78
B3-after	8	9.2	.02	.31	.49	.03	.14	3.6	.34	.77	12.9	.47	1.1

Site (figures 3 and 4)	Number of samples[2]	Total phosphorus (lb/d)			Total orthophosphate (lb/d)			Suspended sediment (lb/d)		
		Max	Min	Med	Max	Min	Med	Max	Min	Med
H1-before[3]	20	1.3	0.00	0.01	0.33	0.00	0.00	445	0.18	3.1
H1-after[4]	10	.15	.01	.04	.08	.00	.01	32.2	3.9	5.2
H2-before	13	1.8	.01	.09	.50	.01	.05	2,260	13.8	59.3
H2-after	15	.54	.05	.13	.18	.02	.07	258	0.0	89.8
H3-before	18	.29	.01	.09	.19	.01	.05	203	5.0	36.6
H3-after	14	.32	.03	.15	.14	.01	.07	2,180	8.9	70.0
B1[5]	24	1.29	.00	.01	.57	.00	.01	3,130	.10	15.8
B2-before	43	4.07	.00	.04	3.0	.00	.03	944	.00	5.2
B2-after	18	.523	.00	.03	.30	.00	.01	121	.43	5.0
B3-before	36	.79	.00	.04	.17	.00	.03	452	.24	8.6
B3-after	8	.23	.01	.11	.13	.00	.04	135	1.1	5.6

[1]Analysis of ammonia was added May 31, 1990, to allow calculation of the organic nitrogen part of total ammonia plus nitrogen.
[2]The number of samples for which ammonia was analyzed before-WCS are different from those for the other constituents, and are listed below:

H1 - 1   B1 - 2
H2 - 5   B2 - 13
H3 - 4   B3 - 16

[3]Corresponds to period of record before tide-gate installation at sites H2 and H3.
[4]Corresponds to period of record after tide-gate installation at sites H2 and H3.
[5]Entire period of record was prior to flashboard-riser installation at sites B2 and B3.

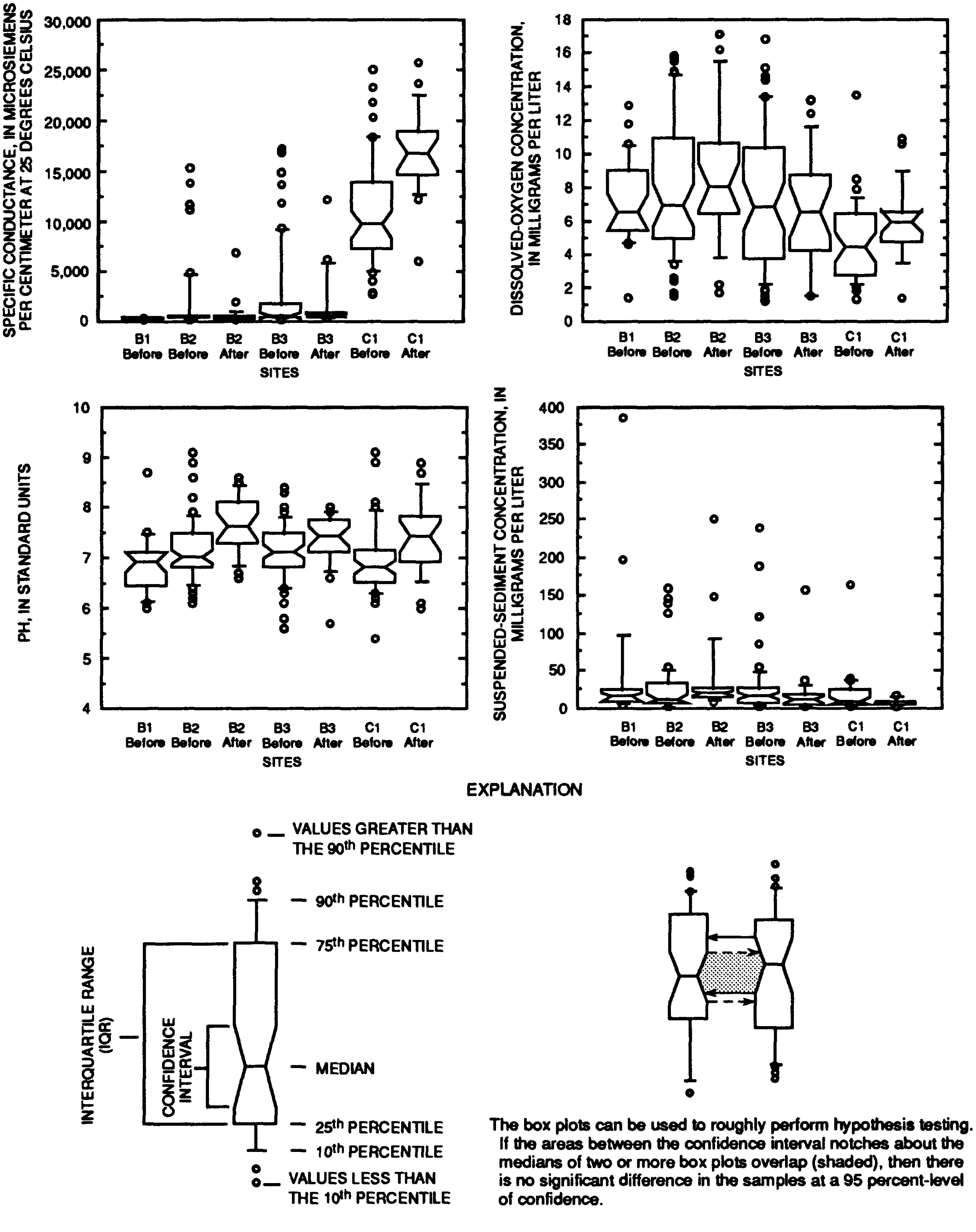

Figure 23. Box plots of specific conductance, dissolved-oxygen concentration, pH, and suspended-sediment concentration for Beaufort County sites before and after flashboard-riser installation at sites B2 and B3.

indicate a drop in specific conductance (table 8); however, these arithmetic averages are heavily skewed by outliers. Composite samples, which consisted of more observations than the biweekly sampling, indicated that median specific conductance at site B3 increased slightly from 510 μS/cm to 596 μS/cm after the flashboard riser was installed (fig. 23). Analysis of variance indicated that there were statistically significant increases in specific conductance after flashboard-riser installation for biweekly measurements at site C1, and for composite samples at site B3 (table 9). However, no significant change in mean or median specific conductance was noted at site B2.

Maximum specific conductance in composite samples from site B3 was lower after riser installation (12,500 μS/cm or 7.2 ppt salinity) than before (17,000 μS/cm or 10 ppt salinity). However, the maximum specific conductance in composite samples from site B2 did not change significantly after riser installation. The riser at site B3 caused an extended release of freshwater runoff. The slow, steady discharge of freshwater likely reduced the maximum concentrations of specific conductance in the canal by diluting the more saline water that occasionally moved upstream to site B3 from Campbell Creek. Also, risers block inland movement of saline water resulting in lower specific conductance conditions upstream than without risers.

Specific conductance at sites B2 and B3 followed the same seasonal pattern that was observed at the Hyde County sites (fig. 24). Specific conductance was greatest in summer and fall, typically from May through October, and lowest during the winter and early spring. However, estuarine influxes had much less influence on specific conductance at the Beaufort County canals than at the Hyde County sites (compare figs. 18 and 24).

Site C1 was more saline than any of the canal sites (table 8). Median specific conductance was 9,600 μS/cm (5.4 ppt salinity) before and 16,600 μS/cm (9.4 ppt salinity) after risers were installed in the upstream canals. This increase in salinity at site C1 most likely accounts for the increase in conductance measured at site B3. This increase at site C1 did not appear to be caused by the water-control structures. The increased specific conductance at site C1 probably reflected salinity fluctuations occurring in the estuary. A similar increase in specific conductance was noted during the same period at the Hyde County study area (Treece, 1993).

Flashboard risers reduced peak specific conductance in the Beaufort County canals. Risers had no effect on specific conductance in Campbell Creek, which was largely controlled by conditions in Goose Creek and the Pamlico River. Although specific conductance in Campbell Creek was substantially higher after risers were installed at sites B2 and B3, specific conductance declines occurred at the two canal sites (table 8). These results indicate that risers dampen the effect of estuarine fluctuations on specific conductance in the canals.

Specific conductance at site C1 was occasionally lowered by freshwater drainage from the canals following a storm event. This occurred when water level in Campbell Creek was relatively low, and there was minimal upstream movement of estuarine water. If rainfall occurred when the water level in Campbell Creek was high as a result of estuarine backflows, specific conductance did not decline at site C1. Apparently upstream flows of saline water mixed with the freshwater drainage, preventing a noticeable change in specific conductance at site C1.

Measurements of specific conductance also were made upstream from the flashboard risers. Data from site B2A indicated that water detained by the flashboard riser was always fresh. Maximum conductance at site B2A was 663 μS/cm, and median conductance was 237 μS/cm (table 8). Specific conductance upstream from the riser at site B2 exceeded values downstream only when downstream values dropped below 250 μS/cm. Saline water occasionally moved upstream from Campbell Creek into the drainage canal at site B2. This was observed twice after riser installation, with no concomitant rise in conductance at site B2A. Therefore, the flashboard riser effectively prevented upstream movement of saline water at this location.

In a similar manner, specific conductance at site B3 was always higher downstream from the flashboard riser than upstream. However, when water levels on either side of the flashboard riser were almost equal and no downstream flow was recorded, some saline water apparently moved upstream through the riser boards. Three such occurrences of elevated conductance were noted at site B3A after the riser was installed.

Water temperature ranged from 4.0 to 29.0 °C at the Beaufort County canal sites and from 7.0 to 34.0 °C at site C1 (table 8). For the most part, water temperature followed expected seasonal patterns at the

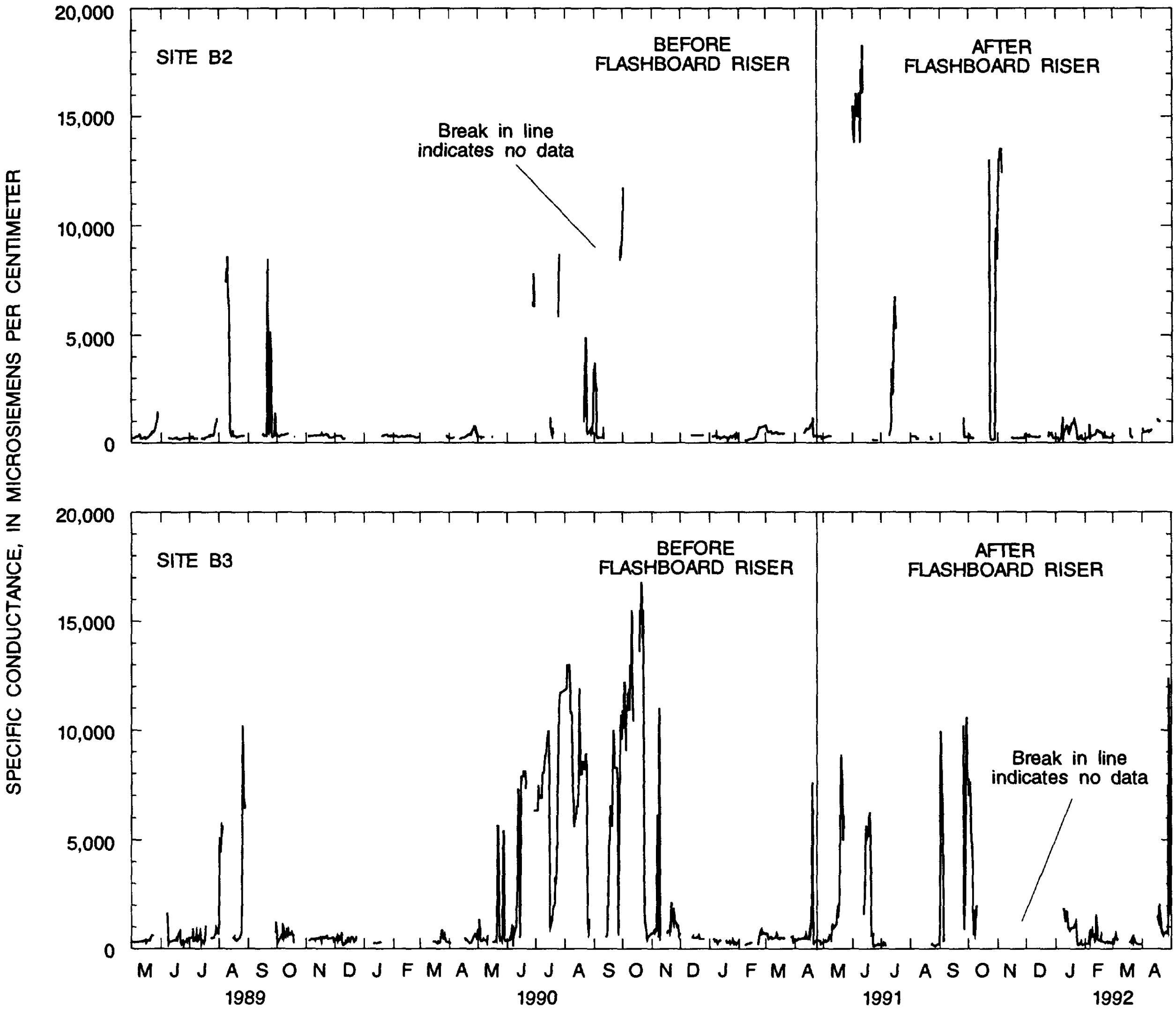

Figure 24. Specific conductance of composite samples at Beaufort County sites, May 1989 through April 1992.

Beaufort County sites (fig. 25). Minor differences in water temperature before and after flashboard risers were installed were attributed to prevailing weather rather than to effects of the flashboard risers.

Site C1 had slightly warmer temperatures than all three canal sites (table 8). Occasional influxes of water from Campbell Creek to sites B2 and B3 could account for the warmer temperatures at these two sites compared to those at site B1, which was located some distance away from the other two canal sites and did not experience tidal backflows.

Dissolved-oxygen concentrations at the Beaufort County sites varied widely (table 8; fig. 23). Highest dissolved-oxygen concentrations occurred in winter, and lowest concentrations typically were found during the summer and early fall (fig. 25). As expected, these seasonal patterns reflected the inverse relation between water temperature and the solubility of oxygen in water.

Dissolved-oxygen concentrations at site B1 were almost always greater than 5.0 mg/L, the minimum daily average recommended by the North Carolina Environmental Management Commission (1986) to protect aquatic organisms from stresses related to insufficient oxygen. During the study, only one measurement at site B1 was recorded below 4.0 mg/L, which is the recommended minimum instantaneous concentration (North Carolina Environmental Management Commission, 1986).

Dissolved-oxygen concentrations at sites B2 and B3 were similar to concentrations at Hyde County sites H2 and H3 (fig. 17). Differences between median concentrations before and after flashboard-riser installation were not statistically significant at either site.

At site B3, dissolved-oxygen concentrations were less than 5.0 mg/L more frequently than at sites B1 or B2 (fig. 23). Several factors could have contributed to occurrences of low dissolved oxygen at site B3. First, water in the B3 canal averaged about 2 ft deep, whereas the other two canals were only about 6 in. to 1 ft deep. Second, discharge measurements indicated that flow velocities at site B3 typically were very low. These two features would result in lower reaeration of the water at site B3 compared to the shallower canals. In addition, the substrate at site B3 was noticeably mucky with a strong sulfide odor, which indicates that anoxic sediments could exert a strong demand for oxygen from canal waters. Finally, of the three canal sites, B3 experienced the greatest amount of tidal exchange. Site C1 typically had lower dissolved-oxygen concentrations than the canal sites (fig. 23), and influxes of creek water into the canal at site B3 could have resulted in lower dissolved oxygen. This is supported by the negative correlation between dissolved-oxygen concentrations at site B3 and specific conductance. Low dissolved-oxygen concentrations are not unusual for slow-moving waters in the North Carolina Coastal Plain; however, results indicate that organisms at site C1 can experience frequent and prolonged periods of low dissolved oxygen.

At site C1, dissolved-oxygen concentrations near the water surface were less than 5.0 mg/L 60 percent of the time before flashboard risers were installed upstream, and 38 percent of the time after risers were installed. Also, median dissolved-oxygen concentrations were significantly higher during the period following flashboard-riser installation at sites B2 and B3 (5.9 mg/L) compared to earlier sampling (4.4 mg/L). The increase in dissolved-oxygen concentration could be indirectly related to the increase in specific conductance at site C1. The higher specific conductance values were caused by increased movement of water (tidal and wind driven) from the estuary up into the creek. This increased movement may have produced higher dissolved-oxygen concentrations, despite increased salinity, by creating an aerating effect.

Interquartile ranges of dissolved-oxygen concentrations at sites B2, B3, and C1 were smaller after flashboard risers were installed, indicating that the bulk of the data was less variable during this period (fig. 23). Fewer samples were collected after risers were installed than before, and a small number of observations can account for lower variability. The lack of a significant change in dissolved-oxygen concentrations at site B2 and B3 meant that the flashboard risers could not account for differences observed at site C1.

All median pH concentrations for Beaufort County sites were close to 7.0, indicating neutral conditions (table 8; fig. 23). After flashboard risers were installed at the canal sites, pH was slightly higher at sites B2, B3, and C1 (fig. 23). Although differences in median pH were statistically significant at sites B2 and C1, they represented a relatively minor shift of only 0.6 standard unit. Analysis of variance indicated that the distribution of pH values at sites B2 and C1 were statistically different before and after flashboard-riser installation (table 9).

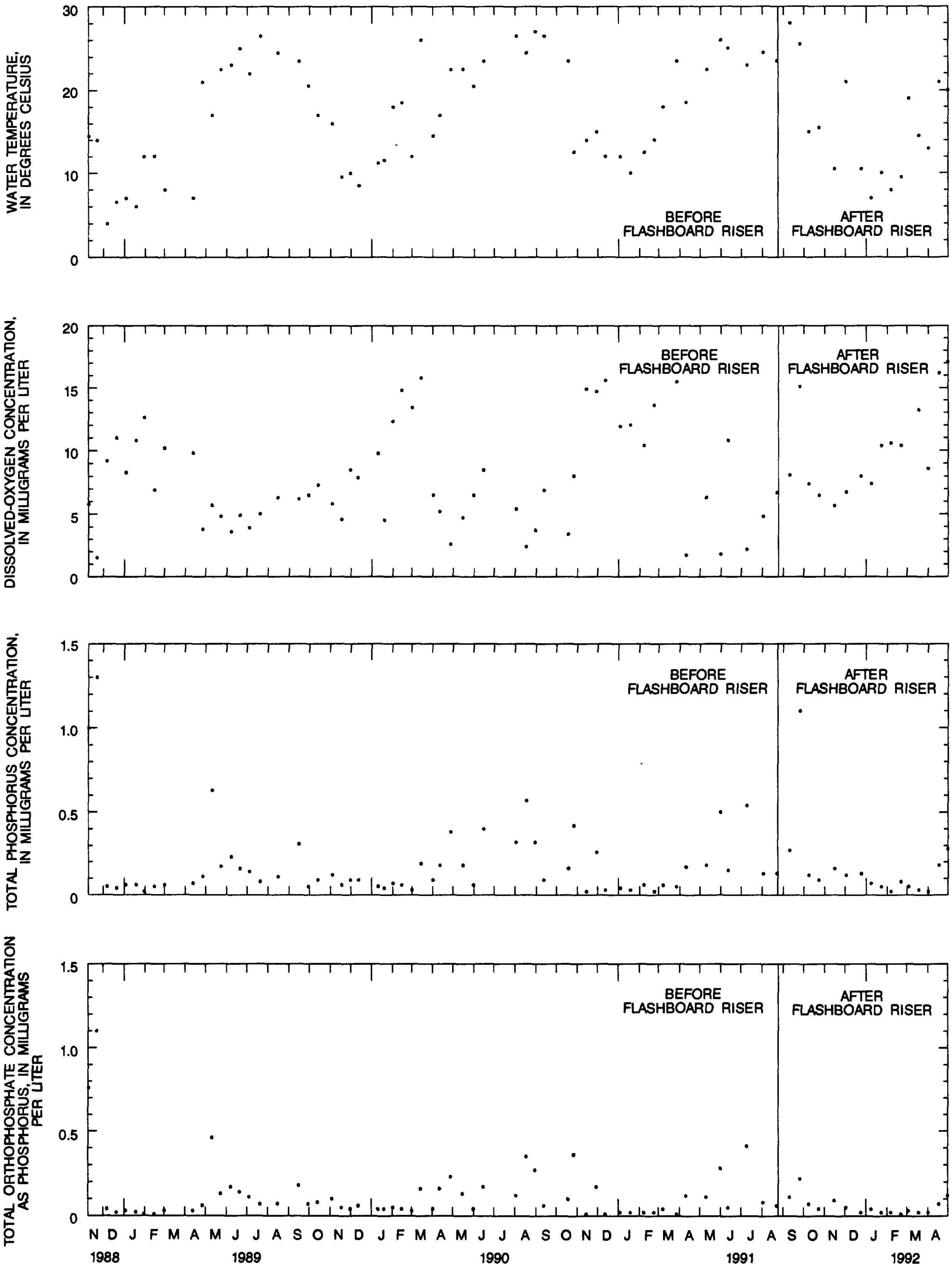

Figure 25. Biweekly measurements of water temperature, dissolved oxygen, total phosphorus, and total orthophosphate for site B2, November 1988 through April 1992, Beaufort County, North Carolina.

Suspended-sediment concentrations were usually low (less than 50 mg/L) at all sites in the Beaufort County study area (fig. 23). A maximum concentration of 387 mg/L was recorded at site B1 (table 8). Median concentrations of suspended sediment increased slightly at site B2 and decreased slightly at site B3 after flashboard risers were installed; however, these differences did not represent a meaningful change in water quality (table 8). Interquartile ranges were smaller at sites B2, B3, and C1 after risers were installed (fig. 23). Precipitation was below average during this study, and higher suspended-sediment concentrations would likely occur during wetter periods.

Nutrients

From November 1988 through September 1990, concentrations of ammonia and organic nitrogen at site B1 were within ranges of concentrations at sites B2 and B3 before flashboard risers were installed (table 10). The median ammonia plus organic nitrogen concentration of 0.8 mg/L at site B1 was similar to median concentrations of approximately 1 mg/L at the other two canal sites (table 10; fig. 26). The maximum concentration reported for the Beaufort County study area was 7.8 mg/L at site B2. No significant differences in median or mean concentration before and after flashboard-riser installation were noted at any site. Average ammonia plus organic nitrogen concentrations in agricultural field ditches and drainage canals of the A-P peninsula have been reported to be between 0.5 and 3.0 mg/L (Chescheir and others, 1987; Evans and others, 1989).

Ammonia plus organic nitrogen concentrations at site C1 indicate that concentrations fluctuate less as waters move from the canals into the estuary. No concentrations greater than 2 mg/L were recorded at site C1 compared to sites B2 or B3 (fig. 26), where at least 10 percent of the samples had TKN concentrations greater than 2.0 mg/L; the maximum concentration of 1.8 mg/L at site C1 was much lower than the maximum concentrations of 7.8 mg/L and 3.7 mg/L recorded at the canal sites (table 10). Concentrations of TKN in the Pamlico River near the study area typically are between 0.4 and 0.5 mg/L (Harned and Davenport, 1990; North Carolina Department of Environment, Health, and Natural Resources, 1990b, 1992), or lower than levels measured at sites B2, B3, and C1.

In general, concentrations of ammonia nitrogen at site B3 were greater than at sites B2 and C1, even though the maximum concentration for the Beaufort County study area (0.92 mg/L) was at site B2 (fig. 26). All ammonia-nitrogen concentrations were less than 1.0 mg/L, and medians for the entire study period at sites B2, B3, and C1 were less than 0.10 mg/L (0.06, 0.09, and 0.06 mg/L, respectively).

Although median concentrations of ammonia nitrogen at sites B2 and B3 were lower after flashboard risers were installed (table 10), these differences were not statistically significant. However, fewer high concentrations (exceeding 0.30 mg/L) were observed at sites B2 and B3 after water-control structures were installed (fig. 26) than before. Results indicate that the flashboard risers can have a dampening effect on peak levels of ammonia nitrogen released to downstream waters.

The median $NO_2 + NO_3$ concentration of 1.10 mg/L at site B1 was significantly higher than median concentrations at sites B2 and B3 (table 10), but comparable to average concentrations ranging from 0.27 to 3.4 mg/L reported for other agricultural-drainage waters by Chescheir and others (1987). The range of concentrations at site B1 (<0.10 to 4.5 mg/L) was comparable to ranges at sites B2 and B3 (table 10).

Concentrations of $NO_2 + NO_3$ often indicated nutrient enrichment at the canal sites, particularly before risers were installed. Pre-installation maximum concentrations at sites B2 and B3 were 8.1 and 7.0 mg/L, respectively (table 10). After risers were installed, concentrations exceeding 1.0 mg/L occurred at sites B2 and B3 less than 25 percent of the time, compared to frequent occurrences before the risers were installed (fig. 26).

Median concentrations of $NO_2 + NO_3$ decreased significantly at sites B2 (from 0.30 to <0.05 mg/L) and B3 (from 0.36 to 0.08 mg/L) after flashboard risers were installed (table 10; fig. 26). Mean concentrations of $NO_2 + NO_3$ decreased significantly following the installation of flashboard risers at all Beaufort County sites. The sample populations were statistically different for the two periods (table 9), which could be a result of either the lower mean or median concentrations, or both. Because no data were collected concurrently from a reference site, it was impossible to prove that the decreases resulted from the risers alone or whether other factors also influenced the results. However, other studies of agricultural drainage systems have shown that flashboard risers can reduce nitrate concentrations in field ditches by up to 20 percent (Evans and others, 1991).

Concentrations of ammonia and $NO_2 + NO_3$ at sites B2 and B3 indicated the potential for over-

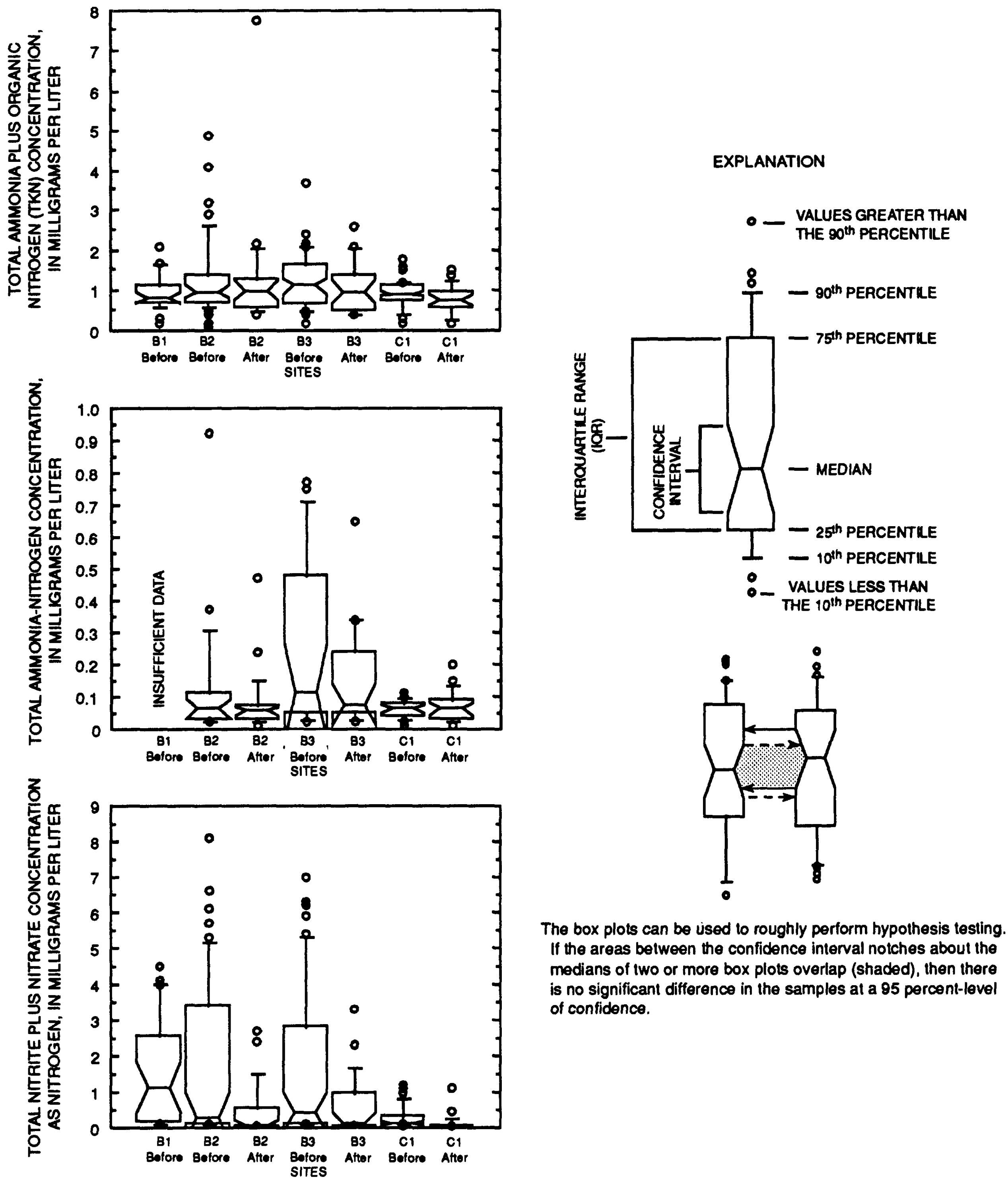

Figure 26. Box plots of total ammonia plus organic nitrogen, total ammonia-nitrogen, and total nitrite plus nitrate nitrogen for Beaufort County sites before and after flashboard-riser installation at sites B2 and B3.

enrichment of receiving waters by these readily available forms of nitrogen. However, relatively low concentrations of both of these constituents characterized the site downstream (C1), indicating that much of the inorganic nitrogen input from the canals was apparently assimilated, diluted, or removed from solution as water moved into the estuary (fig. 26). The maximum concentration of $NO_2 + NO_3$ recorded at site C1 was 1.2 mg/L. During the entire study, 90 percent of the $NO_2 + NO_3$ concentrations at site C1 were less than 0.62 mg/L, and 75 percent were less than 0.22 mg/L. At site C1, the analysis of variance indicated a statistically significant difference in the before and after sample populations (table 9) resulting from lower $NO_2 + NO_3$ concentrations after the installation of flashboard risers at sites B2 and B3.

Total nitrogen concentrations ranged from 0.25 to 9.2 mg/L at the Beaufort County sites. Mean concentrations of $NO_2 + NO_3$, ammonia, and organic nitrogen relative to mean total nitrogen concentrations differed among sites and changed after flashboard risers were installed (fig. 27). Nitrite plus nitrate nitrogen made up 62 percent of the total nitrogen pool at site B2 and 55 percent at site B3 before risers were installed. These percentages decreased to 25 percent at site B2 and 35 percent at site B3 after risers were installed. In contrast, $NO_2 + NO_3$ accounted for only 23 and 14 percent of the total nitrogen at site C1 before and after riser installation, respectively. More than 70 percent of the total nitrogen at site C1 was present in organic form. The contribution of ammonia to total nitrogen concentrations was relatively minor at all of the Beaufort County sites, ranging between 4 and 9 percent.

Median total nitrogen concentrations declined at sites B2 and B3 following installation of the flashboard risers. These changes were a result of reductions in $NO_2 + NO_3$ concentrations rather than ammonia or organic nitrogen. Before risers were installed, median concentrations of total nitrogen were 2.6 mg/L at site B2 and 2.2 mg/L at site B3. After risers were installed, the median concentrations were 1.4 mg/L at site B2 and 1.5 mg/L at site B3.

Canal sites (B2 and B3) had significantly higher concentrations of total nitrogen than the receiving stream at site C1. The median concentration of total nitrogen at site C1 was 1.1 mg/L before, and 0.87 mg/L after risers were installed at the upstream canals. As with the canal sites, this statistically significant decrease in median total nitrogen resulted from lower concentrations of $NO_2 + NO_3$, rather than changes in ammonia or organic nitrogen. The Wilcoxon rank-sum test also indicated a statistically significant difference in the before and after sample populations at sites B2, B3, and C1, which also can be attributed to the change in $NO_2 + NO_3$ concentrations.

Summertime total nitrogen concentrations greater than 0.6 mg/L have been associated with

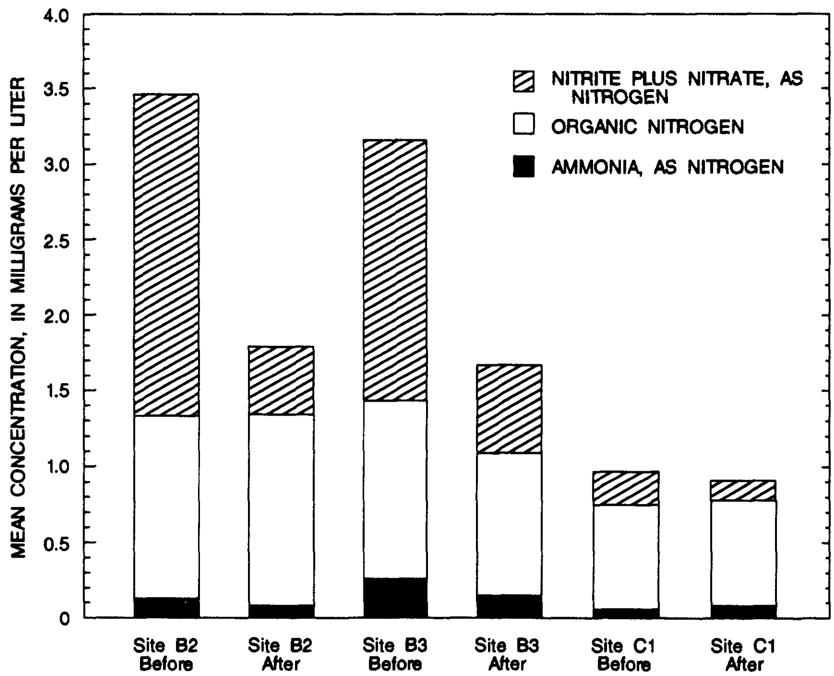

Figure 27. Mean composition of nitrogen species in water at Beaufort County sites before and after flashboard-riser installation, November 1988 through April 1992.

undesirably high algal biomass in the Pamlico River (North Carolina Department of Environment, Health, and Natural Resources, 1990a). Although nitrogen concentrations in the canals were typically higher than 0.6 mg/L, total nitrogen concentrations were reduced by the time water reached the Campbell Creek site.

Total phosphorus concentrations in the Beaufort County canals ranged from less than 0.01 to 1.1 mg/L (table 10; fig. 28). Maximum concentrations were at site B2, before and after (1.1 mg/L) flashboard risers were installed. The median concentration during the entire study was 0.09 mg/L at sites B2 and B3. Total phosphorus concentrations were lower at sites B1 and C1, where medians for the entire study period were 0.05 and 0.04 mg/L, respectively.

Total phosphorus concentrations at sites B2 and B3 tended to be higher than concentrations in the Hyde County canals (table 10; figs. 22 and 28). However, median concentrations at sites B2 and B3 were consistent with concentrations in other agricultural drainage canals in the A-P peninsula of North Carolina (Chescheir and others, 1987). At site C1, total phosphorus concentrations were usually between 0.04 and 0.07 mg/L (fig. 28), or lower than typical concentrations in the Pamlico River, but similar to concentrations reported for Pamlico Sound (0.05 to 0.09 mg/L) during a synoptic survey of the A-P estuary (North Carolina Department of Environment, Health, and Natural Resources, 1992).

Orthophosphate concentrations were higher at sites B2 and B3 than in the Hyde County canals. Although numerous concentrations exceeded 0.10 mg/L at sites B2 and B3 (fig. 28), concentrations in the Hyde County canals were rarely that high (fig. 22). Moreover, orthophosphate concentrations ranged from less than 0.01 to 0.46 mg/L (table 10; fig. 28). The maximum value was at site B2, which also had the highest mean concentration in the study area (0.09 mg/L). Medians for sites B1, B3, and C1 were within the interquartile ranges of 0.02 to 0.06 mg/L, which characterized Pamlico Sound from 1988 through 1991 (North Carolina Department of Environment, Health, and Natural Resources, 1992). At all of the Beaufort County sites, much of the temporal variation in total phosphorus concentrations could be attributed to variations in orthophosphate concentrations because most of the phosphorus occurred in this form.

Flashboard risers had no significant influence on total phosphorus concentrations at sites B2 and B3. Median total phosphorus at site C1 increased from 0.04 to 0.07 mg/L after risers were installed at sites B2 and B3 (table 10). Because no corresponding changes in total phosphorus concentration were noted at the canals upstream, the increase at site C1 could not be attributed to the flashboard risers. The slight decreases in median orthophosphate concentrations at sites B2 and B3 after risers were installed (table 10) were not statistically significant.

Seasonal patterns in total phosphorus and orthophosphate concentrations were detected at site B2 and, to a lesser extent, at site B3. Although there was much variability from one sampling event to the next, phosphorus concentrations tended to be higher during the growing season. Seasonal patterns were less apparent at site C1, but trends generally followed those observed at the two upstream canal sites. No consistent relation between phosphorus concentrations and streamflow was seen at any of the sites.

Increases in summertime phosphorus concentrations at the Beaufort County canal sites can be related to increased agricultural activities, such as tilling and fertilizing during the growing season. Mobilization of phosphorus from sediment to overlying waters during anoxic conditions also could have contributed to elevated phosphorus in these canals. Stanley (1992) discussed the importance of this mechanism to summertime phosphorus dynamics in Pamlico Sound. Measurements of dissolved oxygen at the Beaufort County sites indicated that dissolved oxygen was low during the summer, which corresponded to high total phosphorus concentrations (fig. 25).

Estimated Loadings of Sediment and Nutrients

Instantaneous export values for nutrients and suspended sediment were estimated using discharge measurements and constituent concentrations obtained during biweekly sampling. The range, mean, and median instantaneous load for each constituent were calculated for each canal site (table 11). Median loadings of several constituents changed after flashboard risers were installed at sites B2 and B3. However, most of the differences were statistically insignificant.

At site B2, loadings of $NO_2 + NO_3$ and total nitrogen decreased significantly after the flashboard riser was installed. Median loadings of $NO_2 + NO_3$ decreased from 0.39 to 0.05 lb/d, and median export of total nitrogen fell from 1.6 to 0.20 lb/d (table 11). Decreased loadings of these two constituents were caused by lower instream concentrations and slightly lower flows measured at site B2 after the riser was installed. Other studies of agricultural drainage systems have shown that flashboard risers can lower

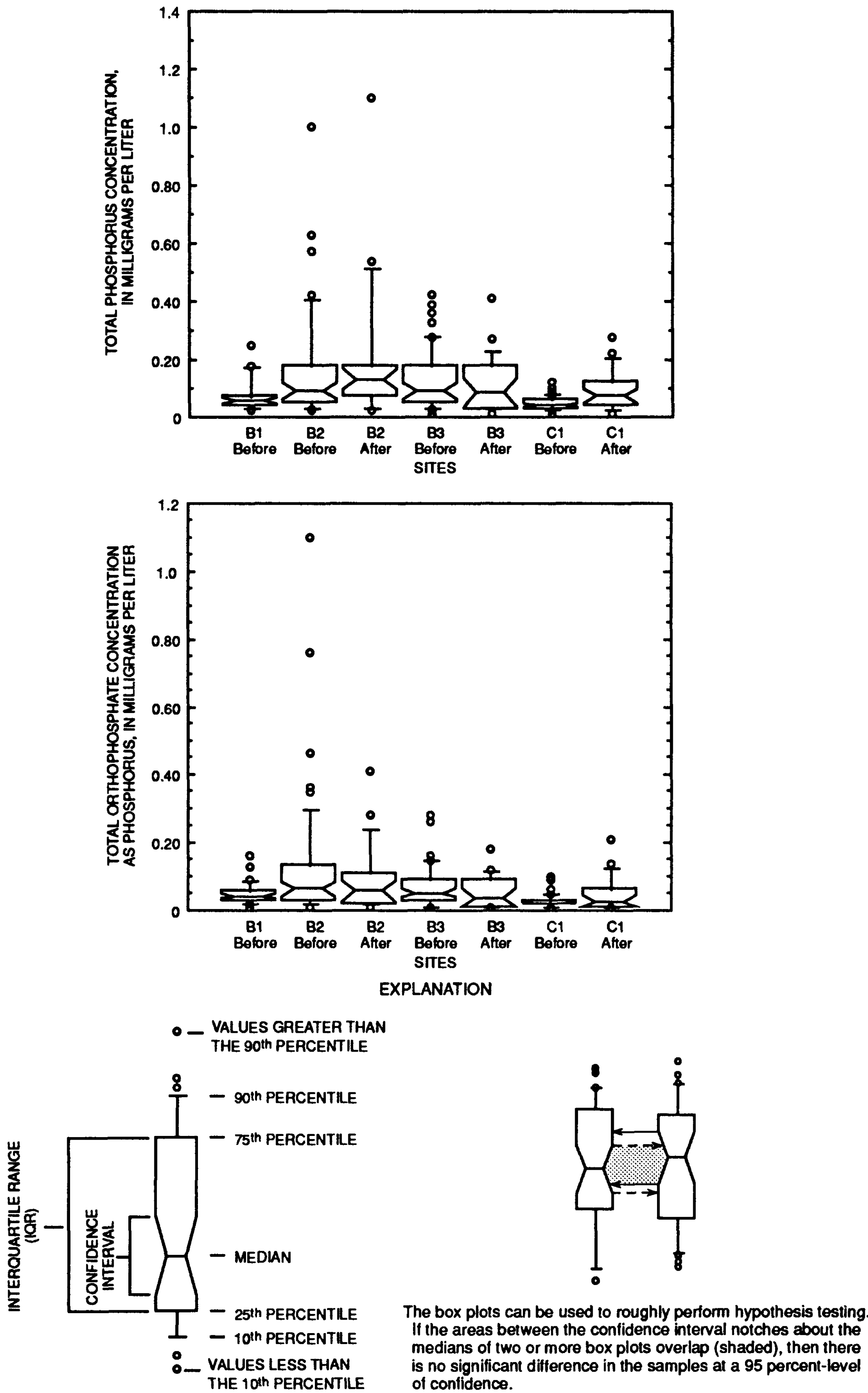

Figure 28. Box plots of total phosphorus and total orthophosphate for Beaufort County sites before and after flashboard-riser installation at sites B2 and B3.

nitrate concentrations in outflows by up to 20 percent; however, less transport of total nitrogen and phosphorus primarily results from reduced outflow volume rather than lower nutrient concentrations (Gilliam and others, 1978; Evans and others, 1989).

No change in median instantaneous export of nitrogen was observed at site B3 following riser installation. Median loadings of each nitrogen species increased slightly, but these differences were not statistically significant (table 11). The power of statistical comparisons was low at site B3, because only eight measurements were made after the riser was installed. Streamflows and loadings of most constituents at site B3 were very low before the riser was installed. Although slightly higher flows were measured at site B3 after the flashboard riser was installed, there were no accompanying changes in nutrient or sediment load.

Loadings of suspended sediment and phosphorus species did not change significantly at site B2 or B3 after risers were installed. Export statistics for suspended sediment, total phosphorus, and orthophosphate were similar at sites B1, B2, and B3 (table 11). Concentrations of phosphorus in the canals did not increase as amounts of drainage outflow increased, indicating no apparent relation between streamflow and total phosphorus or between streamflow and orthophosphate at any of the three sites.

Comparison of Effects of Tide Gates and Flashboard Risers on Water Quality

The presence of water-control structures had no apparent effect on water temperature, dissolved-oxygen concentration, and concentrations of suspended sediment, total ammonia, TKN, or total phosphorus in either Hyde County or Beaufort County drainage canals. Likewise, median suspended-sediment loads did not change at any canal site after water-control structures were installed.

Measurements of water level and discharge indicated that tidal influence and reverse flow were much more prevalent in the Hyde County study area than at the Beaufort County sites. This accounted for the higher specific conductance at the Hyde County sites (table 8). Tide gates appeared to influence specific conductance in the Hyde County canals based on analyses of composite samples. Flashboard risers were associated with a significant decrease in mean and maximum conductance at Beaufort County sites B2 and B3. A slight increase in median specific conductance at sites B2 and B3 resulted from significantly higher conductance at site C1 for the period after risers were installed at sites B2 and B3 (table 8). The use of flashboard risers resulted in the detention and slow release of freshwater runoff diluting saline water that moved upstream in to the canals from Campbell Creek.

No significant difference in concentrations of ammonia plus organic nitrogen were noted at any site after tide gates or flashboard risers were installed. Concentrations of ammonia plus organic nitrogen were usually less than 2.0 mg/L at all sites, although maximums of 7.8 mg/L were recorded once in each study area (table 10; fig. 26). Ammonia-nitrogen concentrations varied among sites, but tended to be highest throughout the study at site H1 and at site B3 before the riser was installed (table 10; fig. 26). Fewer high concentrations of ammonia nitrogen were observed at sites B2 and B3 after risers were installed, indicating that the risers can have a dampening effect on peak levels of ammonia-nitrogen released to downstream waters by increasing the residence time of canal waters.

Tide gates and flashboard risers were associated with decreased mean and maximum concentrations of $NO_2 + NO_3$. Effects of these water-control structures on receiving water quality should be interpreted cautiously, because decreased concentrations also occurred at the reference site (H1).

No change in median concentrations of NO_2+NO_3 was observed at any of the Hyde County sites after tide gates were installed. However, concentrations were low (near the detection limit) compared to concentrations reported for other agricultural drainage canals, and to the Beaufort County canals.

At the Beaufort County canal sites, median concentrations of $NO_2 + NO_3$ decreased by 0.25 mg/L at site B2 and by 0.28 mg/L at site B3 after flashboard risers were installed (table 10). Maximum concentrations also were lower at these two sites after riser installation; the 75th percentile concentration decreased by about 3 mg/L at site B2 and 2 mg/L at site B3 (table 10; fig. 26). Other investigations have shown that nitrate concentrations in agricultural drainage waters decline following the installation of flashboard risers (Evans and others, 1991).

Organic nitrogen compounds made up the largest part (about 70 percent) of the total nitrogen pool at the Hyde County sites (fig. 21). In Beaufort County, $NO_2 + NO_3$ accounted for the largest percentage of the total nitrogen pool at the canal sites B2 (62 percent) and B3 (55 percent). About 70 percent of the total nitrogen at site C1 was present in organic form (fig. 27).

Median instantaneous loadings of $NO_2 + NO_3$ decreased significantly at one site in each study area after water-control structures were installed. At site H3, median nitrate loadings decreased by 0.33 lb/d following tide-gate installation; however, no change in loading was noted at site H2. A small increase in nitrate loading of 0.04 lb/d occurred at site H1. Median nitrate loading decreased by 0.34 lb/d at site B2 after the flashboard riser was installed, but no change in loading was observed at site B3.

Total phosphorus and orthophosphate concentrations were generally higher in the Beaufort County canals than in the Hyde County canals (figs. 22 and 28). Median total phosphorus concentrations of 0.09 mg/L at sites B2 and B3 were consistent with average concentrations reported for other agricultural drainage canals. At sites H2 and H3 in Hyde County, median concentrations of total phosphorus (0.03 mg/L) were relatively low compared to other agricultural outflows. Concentrations and loadings of total phosphorus and orthophosphate were unaffected by the installation of tide gates or flashboard risers.

SUMMARY AND CONCLUSIONS

In 1988, an investigation was conducted in the Coastal Plain Province of North Carolina to evaluate the effect of water-control structures in tidally-affected drainage canals on the hydrology and water quality of the canals and downstream receiving waters. The hydrology and water quality of agricultural drainage canals were characterized before and after the installation of tide gates or flashboard risers. The effects of freshwater drainage on the salinity of a tidal creek also was analyzed. Hydrologic and water-quality data were collected for about 4 years.

Tide gates were installed at three canals in Hyde County. A tide gate was installed at the beginning of the study in one canal to serve as a reference site to relate or explain changes observed at the other two test sites. These canal test sites were monitored before and after the installation of tide gates. Likewise, flashboard risers were installed at three canals in Beaufort County, with one canal set up as a reference site. However, the reference site did not function as such because of severe streambed scouring and hydrologic conditions that differed greatly from the test sites. The two test sites were monitored before and after the installation of flashboard risers. Campbell Creek, a tidal creek that receives drainage from two of the Beaufort County canals, also was monitored to evaluate the effects of freshwater drainage on a tidal receiving stream. Water level and specific conductance were measured upstream and downstream from the water-control structures. Flow, physical properties, and nutrients were monitored at downstream sites.

Water level and flow at the canal sites were influenced by hydrologic conditions in estuarine receiving waters. Water was observed to move in two directions in most of the canals: upstream as a result of estuarine backflows, and downstream as a result of tidal oscillations or freshwater drainage. Tidal influence was especially pronounced in the Hyde County canals, where reverse flows were frequently recorded. Therefore, water quality in the Hyde County canals was often representative of conditions in the estuary rather than runoff from upland agricultural areas. In the Beaufort County canals, estuarine backflows were much less common; therefore, water quality was more representative of agricultural drainage waters. This difference was apparent in the lower specific conductance and higher nutrient concentrations that characterized the Beaufort County canals.

Tide gates and flashboard risers altered upstream water levels in canals. Tide gates resulted in lower upstream water levels because they prevented the upstream canals from being replenished with backflows of estuarine water. In contrast, flashboard risers caused an increase in upstream water levels because the boards acted as a dam to retain water, increasing the upstream storage potential in the canals. Because the height of flashboard risers can be adjusted but tide gates operate passively, flashboard risers have greater potential to change upstream water levels than tide gates.

Water-level data from October 1990 through April 1992 indicate that tide gates at the three canal sites were open 3.7, 0.2, and 2.1 percent of the time. Tide gates had no significant effect on average downstream water levels or flow in the canals, which were largely regulated by water-level interactions among the canals and their receiving waters. However, after tide gates were installed at the two test sites, peak discharge rates following heavy rainfall declined, and the release of runoff to downstream waters was extended over a longer time.

Flashboard risers also had little effect on average downstream water levels and flow in the Beaufort County canals. However, unlike tide gates that released runoff in brief pulses, flashboard risers promoted a steady, prolonged release of agricultural drainage waters. Water-level data indicated downstream flow occurred 94 and 81 percent of the time at two flashboard-riser test sites, and periods of no flow in the canals were less frequent after riser installation. Peak discharge rates following heavy rainfall were comparable before and after riser installation. However, the release of freshwater runoff to downstream waters was extended over a longer time after risers were installed and was delayed or prevented when precipitation coincided with low water levels upstream from the risers.

Water-quality data collected during the investigation were analyzed using a nonparametric analysis of variance procedure. Daily loads of nutrients and sediment were extrapolated from instantaneous discharge measurements and constituent concentrations obtained during biweekly sampling. Neither tide gates nor flashboard risers affected temperature, dissolved-oxygen, or suspended-sediment concentrations in the Hyde County and Beaufort County canals during this investigation.

The presence of tide gates did not appear to influence specific conductance at downstream sites in the Hyde County canals based on biweekly measurements; however, measurements made from nearly continuously collected composite samples indicated that conductance increased significantly after tide-gate installation. Water detained upstream from the tide gates was fresher than at downstream canal sites. Flashboard risers were associated with a decrease in maximum conductance at downstream sites B2 and B3. This most likely resulted from the riser's damming effect and subsequent slow release of freshwater runoff. Specific conductance upstream from the flashboard risers was generally lower (less saline) than at downstream sites.

Water-level data indicate that the hydrology of Campbell Creek was predominantly influenced by conditions in Goose Creek and the Pamlico River; however, upstream canals occasionally influenced water quality. Water at the Campbell Creek site was consistently more saline than any of the Beaufort County canal sites. Specific conductance at the Campbell Creek site decreased briefly following some storm events as a result of freshwater drainage from the canals. This occurred when water level in Campbell Creek was low and there was minimal upstream movement of estuarine water. If rainfall occurred when the water level in Campbell Creek was high, specific conductance did not decline at the Campbell Creek site.

In the Hyde County canals, peak concentrations of $NO_2 + NO_3$ coincided with winter and spring rains. Throughout the study, median concentrations of $NO_2 + NO_3$ were at or near the level of detection at all three sites. These concentrations were lower than those reported for other agricultural drainage canals in North Carolina. Analysis of variance using the Wilcoxon rank-sum statistical test indicated that there was a significant difference between the before and after sample populations in two of the three Hyde County drainage canals. This difference was a result of declines in the mean and maximum concentrations, and the difference in the distribution of concentrations between the two periods. This result might not be solely attributable to the presence of tide gates, because a decline in $NO_2 + NO_3$ concentrations also occurred at the reference site. However, because tide gates prolonged or delayed the release of agricultural runoff to receiving waters, they could result in some loss and(or) transformation of $NO_2 + NO_3$ before drainage waters are released downstream.

Concentrations of $NO_2 + NO_3$ were higher and more variable in the Beaufort County canals than in the Hyde County canals. Median concentrations of $NO_2 + NO_3$ decreased significantly at sites B2 (from 0.30 to <0.05 mg/L) and B3 (from 0.36 to 0.08 mg/L) after flashboard risers were installed. Concentrations rarely exceeded 1.0 mg/L at test sites after risers were installed compared to frequent occurrences at these sites before the risers were installed. Peak ammonia-nitrogen concentrations at the two test sites also declined after riser installation. The distributions of $NO_2 + NO_3$ concentrations were also statistically different for the periods before and after flashboard-riser installation, which was attributed to lower mean and median concentrations after installation.

Nitrite plus nitrate nitrogen concentrations in all three Beaufort County canals were positively correlated with streamflow, indicating that nitrate entered receiving waters in direct relation to the outflow of agricultural drainage. No other nutrient or suspended-sediment concentrations were consistently related to streamflow during this study.

Water-control structures had no significant effect on concentrations of total ammonia plus organic nitrogen, total ammonia, or total phosphorus at any of the canal sites during the study. Although total phosphorus and orthophosphate concentrations were generally higher in the Beaufort County canals than in the Hyde County canals, they were consistent with average concentrations reported for other agricultural drainage canals. The distributions of orthophosphate concentrations after tide-gate installation were significantly different than before installation at one Hyde County test site; however the same result was observed for the reference site, but not at the other test site.

Loadings of $NO_2 + NO_3$ and total nitrogen decreased significantly at one Beaufort County test site after riser installation, but did not change at the other Beaufort County test site or at the Hyde County canals. Loadings of suspended sediment and phosphorus species did not change at any of the canal sites following the installation of water-control structures.

The effects of water-control structures on the hydrology of the drainage canals is perhaps more meaningful than the changes in water quality. Tide gates and flashboard risers altered the hydrologic characteristics of the drainage canals and created an environment favorable for nutrient loss or transformation. Both types of structure retained agricultural drainage upstream, which increased potential storage for infiltration and reduced the potential for surface runoff, sediment and nutrient transport, and higher peak outflow rates.

SELECTED REFERENCES

Bales, J.D., 1990, Data-collection program for Pamlico River estuary model calibration and validation, *in* Spaulding, M.L., ed., Estuarine and coastal modeling: New York, American Society of Civil Engineers, p. 492-501.

Burkholder, J.M., Mason, K.M., and Glasgow, H.B., Jr., 1992, Water-column nitrate enrichment promotes decline of eelgrass Zostera marina: Evidence from seasonal mesocosm experiments: Marine Ecology Progress Series, v. 81, p. 163-178.

Chescheir, G.M., Gilliam, J.W., Skaggs, R.W., and Broadhead, R.G., 1987, The hydrology and pollutant removal effectiveness of wetland buffer areas receiving pumped agricultural drainage water: Raleigh, North Carolina State University, Water Resources Research Institute Report UNC-WRRI 87-231, 170 p.

Christian, R.R., Boyer, J.N., and Stanley, D.W., 1989, Influence of nutrient loading on the Neuse River estuary, North Carolina: National Oceanic and Atmospheric Administration-NURP Report 89-2.

Daniel, C.C., III, 1981, Hydrology, geology, and soils of pocosins--A comparison of natural and altered systems, *in* Richardson, C.J., ed., Pocosin wetlands--An integrated analysis of Coastal Plain freshwater bogs in North Carolina: Stroudsburg, Pa., Hutchinson-Ross Publishing Company, p. 69-108.

Deal, S.C., Gilliam, J.W., Skaggs, R.W., and Konyha, K.D., 1986, Prediction of nitrogen and phosphorus losses as related to agricultural drainage system design: Agricultural Ecosystems and Environment, v. 18, p. 37-51.

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

Evans, R.O., Gilliam, J.W., and Skaggs, R.W., 1989, Effects of agricultural water table management on drainage water quality: Raleigh, North Carolina State University, Water Resources Research Institute Report UNC-WRRI 89-237, 87 p.

-----1991, Controlled drainage management guidelines for improving drainage water quality: Raleigh, The North Carolina State University Cooperative Extension Service, Publication Number AG-443, 15 p.

Evans, R.O., Gilliam, J.W., Skaggs, R.W., and Lemke, W.L., 1987, Effects of agricultural water management on drainage water quality, *in* Proceedings of the fifth national drainage symposium, December 14-15: Chicago, American Society of Agricultural Engineers, Publication 07-87, p. 210-219.

Fishman, M.F., and Friedman, L.C., 1985, Methods for determination of inorganic substances in water and fluvial sediments: U.S. Geological Survey Open-File Report 85-495, 709 p.

Garrett, R.G., and Bales, J.D., 1991, Water-quality data from continuously monitored sites in the Pamlico and Neuse River estuaries, North Carolina, 1989-90: U.S. Geological Survey Open-File Report 91-465, 151 p.

Gilliam, J.W., 1987, Drainage water quality and the environment, *in* Proceedings of the fifth national drainage symposium, December 14-15: Chicago, American Society of Agricultural Engineers, Publication 07-87, p. 19-28.

Gilliam, J.W., and Skaggs, R.W., 1986, Controlled agricultural drainage to maintain water quality: Journal of Irrigation and Drainage Engineering, v. 112, no. 3, p. 254-263.

Gilliam, J.W., Skaggs, R.W., and Weed, S.B., 1978, An evaluation of the potential for using drainage control to reduce nitrate loss from agricultural fields to surface waters: Raleigh, North Carolina State University, Water Resources Research Institute Report UNC-WRRI 78-128, 108 p.

Gregory, J.D., Skaggs, R.W., Broadhead, R.G., Culbreath, R.H., Bailey, J.R., and Foutz, T.L., 1983, Hydrologic and water quality impacts of peat mining in North Carolina: Raleigh, North Carolina State University, Water Resources Research Institute Report UNC-WRRI 83-214 (CEIP Report No. 41), 215 p.

Guy, H.P., 1969, Laboratory theory and methods for sediment analysis: U.S. Geological Survey Techniques of Water-Resources Investigations, book 5, chap. C1, 58 p.

Hardy, A.V., and Hardy, J.D., 1971, Weather and climate in North Carolina: Raleigh, North Carolina State University, Agricultural Experiment Station, Bulletin 396.

Harned, D.A., and Davenport, M.S., 1990, Water-quality trends and basin activities and characteristics for the Albemarle-Pamlico estuarine system, North Carolina and Virginia: U.S. Geological Survey Open-File Report 90-398, 164 p.

Heath, R.C., 1975, Hydrology of the Albemarle-Pamlico region, North Carolina--A preliminary report on the impact of agricultural developments: U.S. Geological Survey Water-Resources Investigations 9-75, 98 p.

Hobbie, J.E., 1971, Phytoplankton species and populations in the Pamlico River estuary of North Carolina: Raleigh, North Carolina State University, Water Resources Research Institute Report UNC-WRRI 71-56, 147 p.

Jones, R.A., and Sholar, T.M., 1981, The effects of freshwater discharge on estuarine nursery areas: Raleigh, North Carolina Department of Natural Resources and Community Development, Division of Marine Fisheries, Report No. 109 (CEIP Report No. 79-11), 60 p.

Kirby-Smith, and Barber, R.T., 1979, Water-quality ramifications in estuaries of converting forest to intensive agriculture: Raleigh, North Carolina State University, Water Resources Research Institute Report UNC-WRRI 79-139, 163 p.

Kuenzler, E.J., Stanley, D.W., and Koenings, J.P., 1979, Nutrient kinetics of phytoplankton in the Pamlico River, North Carolina: Raleigh, North Carolina State University, Water Resources Research Institute Report UNC-WRRI 79-139, 163 p.

Miller, R.L., Bradford, W.L., and Peters, J.E., 1988, Specific conductance--Theoretical considerations and applications to analytical quality control: U.S. Geological Survey Water-Supply Paper 2311, 16 p.

North Carolina Department of Environment, Health, and Natural Resources, 1990a, Interim review (June-November 1988) of baseline water-quality data from the Pamlico and Neuse River estuaries: Raleigh, Division of Environmental Management Report 90-02, 47 p.

-----1990b, Albemarle-Pamlico estuarine study: Synoptic survey data review, July 25, 1989: Raleigh, Division of Environmental Management Report 90-03, 66 p.

-----1990c, Water-quality progress in North Carolina, 1988-89 305(b) report: Raleigh, Division of Environmental Management Report 90-07, 303 p.

-----1992, Albemarle-Pamlico baseline water-quality monitoring data summary, 1988-91: Raleigh, Division of Environmental Management Report 92-01, 80 p.

North Carolina Department of Natural Resources and Community Development, 1982, Chowan/Albemarle action plan: Raleigh, Division of Environmental Management Report 82-02, 103 p.

-----1989, Tar-Pamlico River basin nutrient sensitive waters designation and nutrient management strategy: Raleigh, Division of Environmental Management Report 89-07, 40 p.

North Carolina Environmental Management Commission, 1986, Classifications and water quality standards applicable to surface water of North Carolina: North Carolina Administrative Code, Title 15, chap. 2, p. 2B-1 - 2B-37.

Paerl, H.W., Mallin, M.A., Rudek, J., and Bates, P.W., 1990, The potential for eutrophication and nuisance algal blooms in the lower Neuse River estuary: Albemarle-Pamlico Estuarine Study Report 90-15, North Carolina Department of Environment, Health and Natural Resources, 54 p.

Skaggs, R.W., Gilliam, J.W., Sheets, T.J., and Barnes, J.S.. 1980, Effects of agricultural land development on drainage waters in the North Carolina Tidewater region: Raleigh, North Carolina State University, Water Resources Research Institute Report UNC-WRRI 80-159, 164 p.

Stanley, D.W., 1988, Water quality in the Pamlico River estuary, 1967-86: Greenville, East Carolina University, Institute for Coastal and Marine Resources Technical Report 88-01, 199 p.

-----1992, Historical trends: Water quality and fisheries, Albemarle-Pamlico Sounds, with emphasis on the Pamlico River estuary: University of North Carolina Sea Grant Program Publication UNC-SG 92-04, 215 p.

Treece, M.W., 1993, Hydrologic and water-quality data in selected agricultural drainages in Beaufort and Hyde Counties, North Carolina, 1990-92: U.S. Geological Survey Open-File Report 93-78, 96 p.

Treece, M.W., and Bales, J.D., 1992, Hydrologic and water-quality data in selected agricultural drainages in Beaufort and Hyde Counties, North Carolina, 1988-90: U.S. Geological Survey Open-File Report 92-498, 89 p.

U.S. Environmental Protection Agency, 1986, Quality criteria for water: Washington, D.C., U.S. Government Printing Office, EPA 440/5-86-001, 256 p.

Wilder, H.B., Robison, T.M., and Lindskov, K.L., 1978, Water resources of northeast North Carolina: U.S. Geological Survey Water-Resources Investigations Report 77-81, 113 p.

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