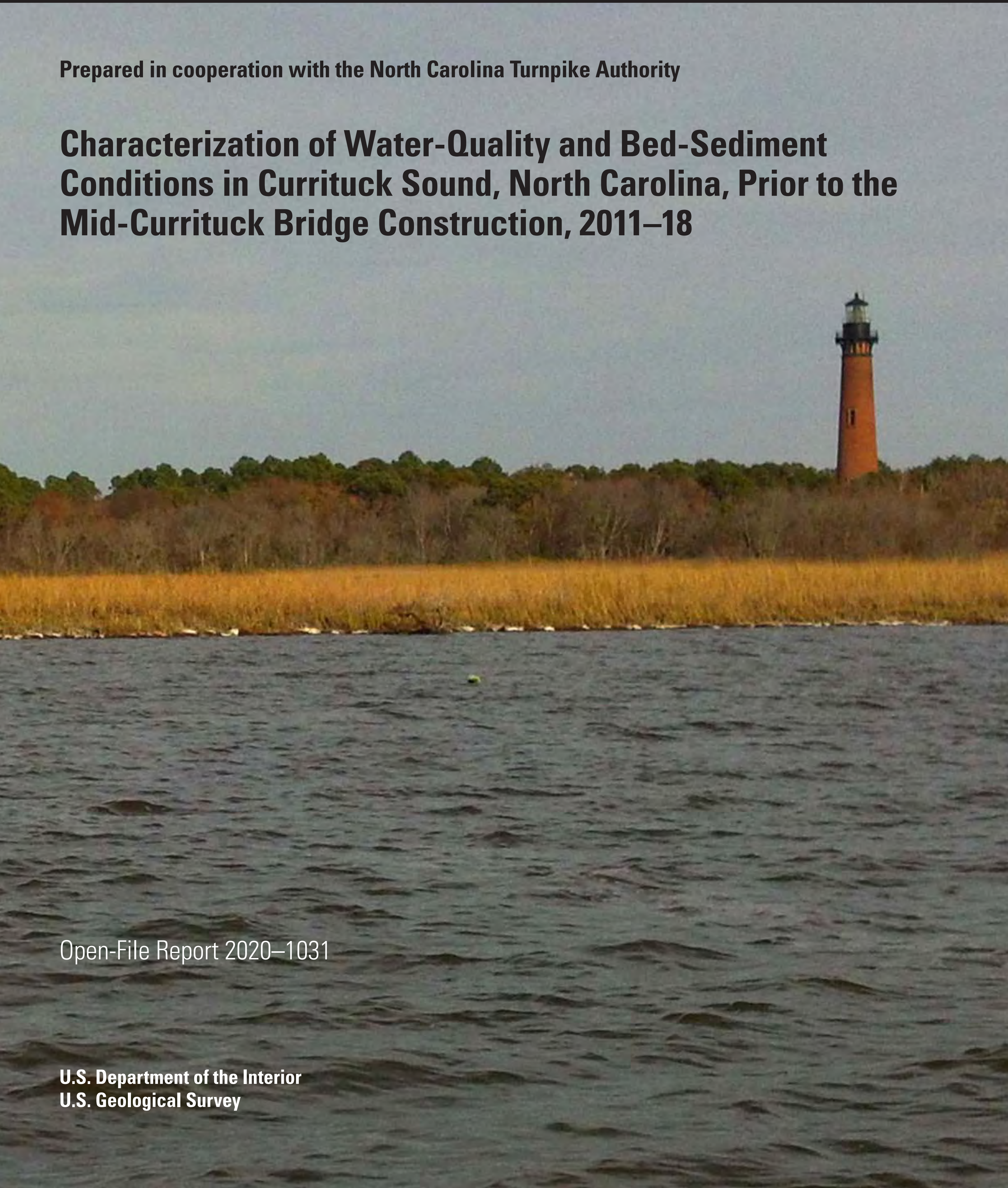
Attachment 15:

Characterization of Water-Quality and Bed Sediment Conditions in Currituck Sound, North Carolina, Prior to the Mid-Currituck Bridge Construction, 2011-18, (USGS Water Quality Report), April 17, 2020

USGS
science for a changing world



Prepared in cooperation with the North Carolina Turnpike Authority

Characterization of Water-Quality and Bed-Sediment Conditions in Currituck Sound, North Carolina, Prior to the Mid-Currituck Bridge Construction, 2011–18

Open-File Report 2020–1031

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

Front and back cover: View from Currituck Sound, North Carolina, showing the Currituck Lighthouse and U.S. Geological Survey water-level and wind gages at the end of a boat dock. Photograph by Chad Wagner, U.S. Geological Survey.

Characterization of Water-Quality and Bed-Sediment Conditions in Currituck Sound, North Carolina, Prior to the Mid-Currituck Bridge Construction, 2011–18

By Stephen L. Harden, Sharon A. Fitzgerald, Chad R. Wagner, Emilia L. Bristow, Keith A. Loftin, and Barry H. Rosen

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Supersedes USGS Open-File Report 2015–1208

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

U.S. Department of the Interior
DAVID BERNHARDT, Secretary

U.S. Geological Survey
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Contents

Figures

Tables

Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)

International System of Units to U.S. customary units

Multiply	By	To obtain
	Length	
meter (m)	3.281	foot (ft)
	Volume	
liter (L)	0.2642	gallon (gal)

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

$$°F = (1.8 \times °C) + 32.$$

Datum

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

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

Gage height, as used in this report, refers to distance above or below the vertical datum.

Supplemental Information

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

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

Concentrations of chemical constituents in bed sediment are given in either milligrams per kilogram (mg/kg), micrograms per kilogram (µg/kg), or percent (%) dry weight.

Abbreviations

ADCP	acoustic Doppler current profiler
ANOVA	analysis of variance
ASCII	American Standard Code for Information Interchange
°C	degrees Celsius
DGPS	differential Global Positioning System
ELISA	enzyme-linked immunosorbent assay
FEIS	final environmental impact statement
ft	foot
ft/s	foot per second
GPS	Global Positioning System
in.	inch
KW	Kruskal-Wallis
L	liter
LRL	laboratory reporting level
m	meter
mg/L	milligrams per liter
mi	mile
mi^2	square mile
mL	milliliter
N	nitrogen
NCDOT	North Carolina Department of Transportation
NWIS	National Water Information System
NWQL	National Water Quality Laboratory
P	phosphorus
PAH	polycyclic aromatic hydrocarbon
PEL	probable effect level
POC	parameter of concern
QA	quality assurance
QC	quality control
RC	remark code
ROD	record of decision
RPD	relative percent difference
SAV	submerged aquatic vegetation
SAWSC	South Atlantic Water Science Center

SPRL	Sediment-Partitioning Research Lab
SQG	sediment quality guideline
SRM	standard reference material
SVOC	semi-volatile organic compound
T_{50}	50 percent probability of toxicity
TEL	threshold effect level
TKN	total Kjeldahl nitrogen
µg/kg	micrograms per kilogram
µm	micrometer
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey
VMT	Velocity Mapping Toolbox
WOE	weight of evidence

Characterization of Water-Quality and Bed-Sediment Conditions in Currituck Sound, North Carolina, Prior to the Mid-Currituck Bridge Construction, 2011–2018

By Stephen L. Harden, Sharon A. Fitzgerald, Chad R. Wagner, Emilia L. Bristow, Keith A. Loftin, and Barry H. Rosen

Abstract

The North Carolina Turnpike Authority plans to improve transportation in the Currituck Sound area by constructing a two-lane bridge—the Mid-Currituck Bridge—across Currituck Sound from the mainland to the Outer Banks, North Carolina. The results of the final environmental impact statement for the project indicate potential water-quality and habitat effects for Currituck Sound associated with the bridge and roadway improvements.

The primary objective of this study is to characterize water-quality conditions and bed-sediment chemistry in the vicinity of the planned Mid-Currituck Bridge, providing a baseline for evaluating the potential effects of bridge construction and bridge deck runoff on environmental conditions in Currituck Sound. From August 2011 through January 2018, water-quality and bed-sediment samples were collected from five sampling stations along the planned bridge alignment. Samples were analyzed for numerous characteristics, including physical properties and constituents that are associated with bridge deck stormwater runoff and are important to estuarine waters. The analyzed characteristics included dissolved oxygen, pH, specific conductance, turbidity, suspended solids, metals, nutrients, semi-volatile organic compounds, bacteria, chlorophyll *a*, cyanotoxins, and phytoplankton abundance. The most common constituents with concentrations above applicable State and Federal water-quality thresholds included chlorophyll *a*, pH, turbidity, Enterococci, and pentachlorophenol. Few bed-sediment samples had constituent concentrations that exceeded applicable sediment-quality guidelines.

Results indicated that water sampled along the planned bridge alignment was well mixed vertically and horizontally but varied temporally. Seasonal changes in water quality best explained the variations in water-quality conditions in Currituck Sound during the study. Wind conditions also influenced water levels and water-quality conditions. Turbidity and concentrations of particle-associated constituents tended to be higher when water levels were lower, possibly reflecting the increased resuspension of bottom materials from wind-driven wave action.

Introduction

Changes in ecological conditions in and around Currituck Sound, in northeastern North Carolina and southeastern Virginia, have been observed since at least the 1980s. Fish-population surveys revealed an increase in estuarine species and a decrease in freshwater species as a response to salinity increases in the Sound (Kornegay, 1989; Southwick and Norman, 1991). The change in salinity conditions is thought to be also associated with a substantial decline in submerged aquatic vegetation (SAV) in Currituck Sound, although other factors may be responsible for the declines (U.S. Army Corps of Engineers, 2001). A decline in SAV beds decreases the food available for migratory waterfowl and reduces potential spawning and nursery habitats for fish species. Furthermore, decreases in SAV root systems and underwater biomass contribute to water-quality degradation through the enhanced resuspension of fine sediments and associated nutrients during wind events (U.S. Army Corps of Engineers, 2001).

A reconnaissance study of Currituck Sound was performed in 2001 by the U.S. Army Corps of Engineers (USACE) under Section 905(b) of the Water Resources Development Act of 1986 (Public Law 99–662, 100 Stat. 4082). The purpose of the study was “to determine whether planning for the improvement of water quality, environmental restoration and protection, and related purposes for Currituck Sound should proceed further” (U.S. Army Corps of Engineers, 2001). The USACE concluded, among other findings, that Currituck Sound is a “threatened resource” (U.S. Army Corps of Engineers, 2001).

In 2005, a team of scientists began an investigation of Currituck Sound to document water-quality trends and collect data needed by the USACE for developing a coupled hydrodynamic and water-quality model of the Sound.

The U.S. Geological Survey (USGS), Elizabeth City State University, the North Carolina National Estuarine Research Reserve, and the U.S. Fish and Wildlife Service partnered in hydrologic and water-quality data collection efforts in and around Currituck Sound during 2006 and 2007. Data were collected at nine locations and included continuous measurements of water elevation, velocity, discharge, and temperature, along with specific conductance, dissolved oxygen, pH, turbidity, and chlorophyll *a* (at a subset of the nine sites). Water-quality samples were also collected at selected sites. The data collected for the study by the USGS and other project partners are summarized by Fine (2008) and are available through the USGS National Water Information System (NWIS) database (U.S. Geological Survey, 2018a) or USGS annual water-resources data reports (U.S. Geological Survey, 2007, 2008). The USGS also collected data from 1998 to 1999 to define the hydrologic and salinity characteristics of the upper Currituck Sound and selected tributaries (Caldwell, 2001).

The North Carolina Turnpike Authority, a division of the North Carolina Department of Transportation (NCDOT), plans to improve transportation in the Currituck Sound area by constructing a 4.7-mile-(mi) long, two-lane toll bridge—the Mid-Currituck Bridge—across Currituck Sound from U.S. Highway 158, south of Coinjock, North Carolina, to North Carolina Highway 12 on the Outer Banks, south of Corolla, North Carolina (fig. 1). Per the National Environmental Policy Act (Public Law 91–190, 83 Stat. 852), the Draft Environmental Impact Statement, Mid-Currituck Bridge Study, Currituck and Dare Counties, North Carolina (Federal Highway Administration and North Carolina Turnpike Authority, 2010) and the Final Environmental Impact Statement [FEIS], Mid-Currituck Bridge Study, Currituck and Dare Counties, North Carolina (Federal Highway Administration and North Carolina Turnpike Authority, 2012) were completed in March 2010 and January 2012, respectively.

A reevaluation of the FEIS (Federal Highway Administration and North Carolina Turnpike Authority, 2019a), which considered changes to the project, its surroundings and effects, applicable laws and regulations, and new issues or circumstances that occurred after approval of the FEIS in 2012, was completed in March 2019. This reevaluation concluded that the FEIS and its preferred alternative decision, including construction of the Mid-Currituck Bridge, was still valid because there were no substantial changes in the proposed action nor significant new circumstances or information relevant to environmental concerns. The Mid-Currituck Bridge Study Administrative Action Record of Decision [ROD] (Federal Highway Administration and North Carolina Turnpike Authority, 2019b) was released in March 2019 and signified the completion of the environmental study. The ROD discusses and details the selected design option for the project, which is the preferred alternative identified in the FEIS that includes design revisions based on the FEIS reevaluation.

The results of the FEIS for the Mid-Currituck Bridge project indicate the potential for temporary and permanent effects on water quality and biotic communities in Currituck Sound related to bridge and roadway stormwater runoff, localized turbidity and sedimentation during construction, altered light levels, and the introduction of piles as a hard substrate (Federal Highway Administration and North Carolina Turnpike Authority, 2012). Common pollutants found in bridge and roadway stormwater runoff include nutrients, particulates, pesticides, metals, and polycyclic aromatic hydrocarbons (PAHs) (Dupuis, 2002; Wagner and others, 2011; Federal Highway Administration and North Carolina Turnpike Authority, 2012; URS Corporation, 2010). Runoff from roadways and bridge decks can carry constituents derived from automotive sources, roadway materials and maintenance activities, and atmospheric deposition (Federal Highway Administration and North Carolina Turnpike Authority, 2012; URS Corporation, 2010).

Constituents in bridge deck runoff or from a hazardous spill that discharged directly into Currituck Sound could dissipate slowly because of limited water circulation and possibly cause bioaccumulation and higher sediment contamination levels than in receiving waters with better circulation and higher flow rates (Federal Highway Administration and North Carolina Turnpike Authority, 2012). Although pollutants that discharge into Currituck Sound could affect water quality and biotic communities adversely, the actual effects of stormwater runoff from bridges on receiving waters are highly site-specific (URS Corporation, 2010; Wagner and others, 2011). The URS Corporation stated that "[w]hile some studies have indicated that bridge deck runoff might result in elevated constituent concentrations in sediment and biota in the immediate vicinity of bridges (Yousef and others, 1984; Mudre and Ney, 1986), there has been no evidence of toxicity of runoff or adverse effects on aquatic biota or water quality degradation over larger spatial scales (Dupuis, 2002; Mudre and Ney, 1986)" (URS Corporation, 2010, p. 3-1).

In collaboration with the NCDOT, the USGS (Wagner and others, 2011) and the URS Corporation (2010) recently completed studies to characterize stormwater runoff from 15 bridges across North Carolina and assess the water quality and effects of runoff on the receiving streams at the bridge sites. A primary focus of these studies was to evaluate the potential effects of parameters of concern (POCs; defined as any monitored constituent whose maximum concentration exceeds the most stringent, applicable water-quality criteria threshold) from bridge deck runoff to receiving streams (Wagner and others, 2011; URS, 2010). Twenty-eight POCs were identified for water samples, including metals, nutrients, pH, suspended solids, PAHs, and other organic compounds. With some exceptions, the bridge deck runoff concentrations of POCs at all bridge sites were similar to the instream concentrations measured at the four stream-monitoring sites. In examining constituent loads, the bridge deck runoff loads were lower than the stream loads for all POCs; however, when normalized for contributing drainage areas, the bridge deck runoff yields were usually higher than the yields from the four stream sites for most POCs (Wagner and others, 2011).

A weight-of-evidence (WOE) approach was used to collectively evaluate multiple types of evidence—namely bridge deck runoff and instream water quality and quantity, streambed sediment quality, and biological assessments—to determine if, and under what conditions, bridge deck runoff may affect receiving stream quality (URS Corporation, 2010). Potentially adverse effects of the bridge deck runoff pollutant loads on receiving streams were evaluated in combination with biological assessment results, including bioassays and biosurveys. The evaluations showed potential ecological effects for only one bridge deck runoff sample, which was from winter deicing activities and revealed no significant effects in the benthic communities and habitats downstream from the bridge sites (Wagner and others, 2011; URS, 2010). While bridge deck runoff was not consistently found to be a primary source of pollutants to receiving streams, there were indications that periodic toxicity—such as runoff after deicing treatments during stream-baseflow conditions—and hydromodification may be stressors related to bridge deck runoff (Wagner and others, 2011; URS, 2010). Based on the WOE evaluation, the URS Corporation report concluded that “bridge deck runoff does not have a widespread effect on receiving waters and that NCDOT’s current use of stormwater control measures for the mitigation of bridge deck runoff is protective of surface waters” (URS Corporation, 2010, p. 8-1).

In support of the Mid-Currituck Bridge project, the USGS South Atlantic Water Science Center (SAWSC) conducted a cooperative study with the North Carolina Turnpike Authority to characterize water-quality and bed-sediment conditions in Currituck Sound in the vicinity of the planned alignment of the Mid-Currituck Bridge. The primary objective of this study was to establish baseline water-quality conditions and bed-sediment chemistry in the study area before bridge construction. Data collected during this baseline study can be used to evaluate the potential effects associated with the bridge construction and bridge deck runoff from the completed bridge. These data can be beneficial in evaluating the effectiveness of storm control measures, including routine bridge deck cleaning activities, for removing potential pollutants from bridge deck runoff to Currituck Sound.

Purpose and Scope

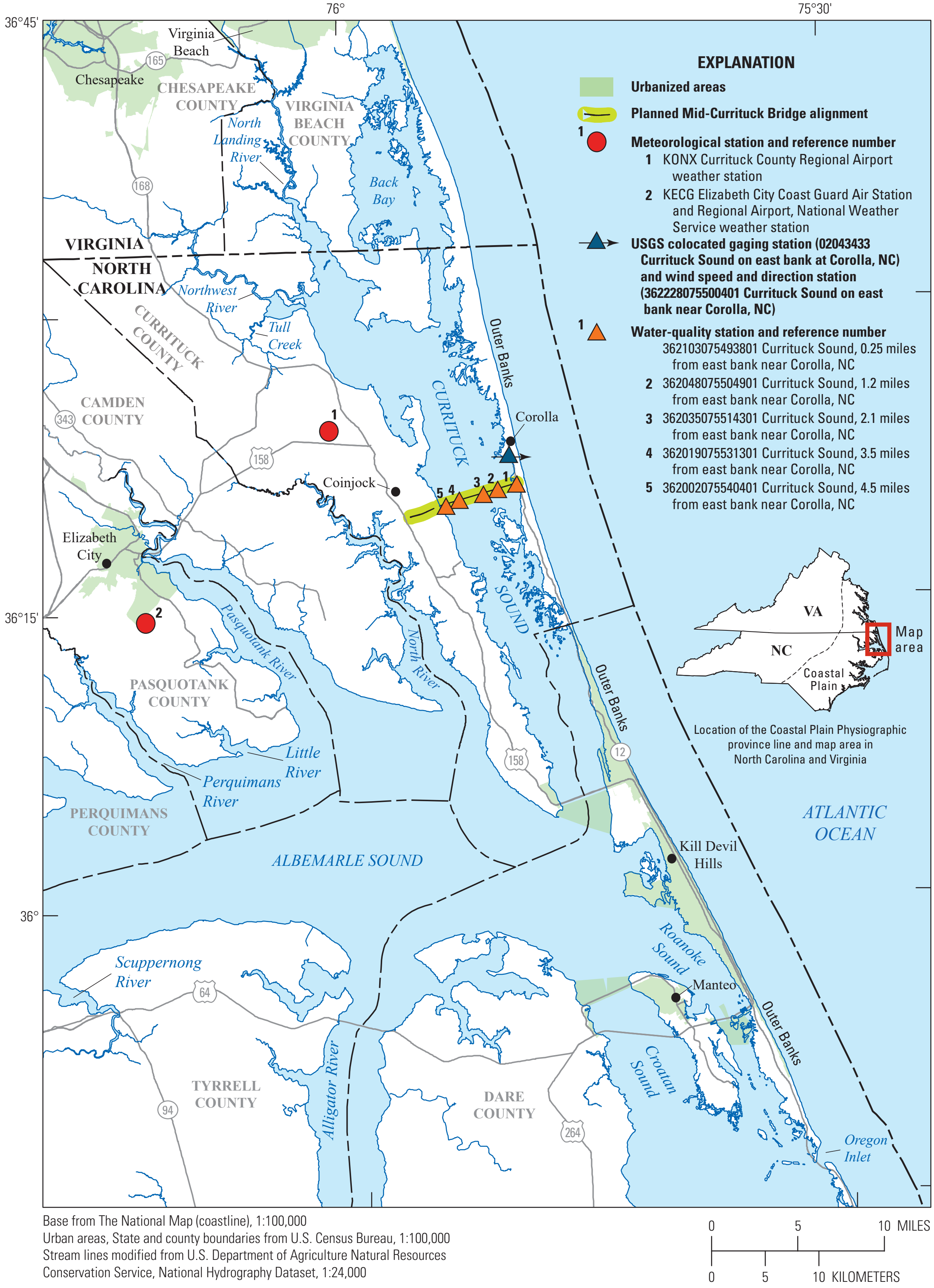
The purpose of this report is to document the data collection efforts of the USGS SAWSC to characterize the baseline water-quality and bed-sediment conditions in Currituck Sound in the vicinity of the planned Mid-Currituck Bridge. In addition to describing the methods used for data collection and quality assurance, this report provides a summary of the analytical results for water and bed-sediment samples collected along the planned alignment of the Mid-Currituck Bridge.

The scope of work included the field measurement of water-quality properties and the collection of surface-water samples for laboratory analysis. From August 2011 to January 2018, there were 48 sets of water-quality samples collected at 5 sampling locations along the planned bridge alignment. Bed-sediment chemistry was analyzed four times at the sampling sites. The full suite of analyses performed on samples included the physical properties and chemical constituents that are associated with bridge deck stormwater runoff (Wagner and others, 2011) and are used to identify impaired waters designated as “Class SC” (saltwater protected for aquatic life propagation and secondary recreation) under North Carolina’s water-quality classifications by the North Carolina Department of Environmental Quality (North Carolina Department of Environmental Quality, 2018). Precipitation data were also compiled, and wind speed and direction, water-level, and water-velocity data were collected in Currituck Sound by the USGS to document climatic and hydrologic conditions during the water-quality sampling events.

Study Area

Currituck Sound is part of the Albemarle Sound estuarine system located in the northeastern part of the Coastal Plain Physiographic province of North Carolina (fig. 1). Currituck Sound is an oligohaline estuary, defined as having salinities from 0.5 to 5.0 parts per thousand (ppt). The surface area of Currituck Sound within North Carolina is 153 square miles (mi^2) (Caldwell, 2001). The overall drainage area of Currituck Sound is estimated to be 733 mi^2; however, the exact drainage area is unclear because the basin has low topographic relief and several canals that connect Currituck Sound to Chesapeake Bay have a bidirectional flow that can move northward or southward (Rideout, 1990; Caldwell, 2001). Most of the contributing drainage area to Currituck Sound is located in the cities of Chesapeake and Virginia Beach, Virginia, and northwestern Currituck County, North Carolina. The freshwater input to Currituck Sound is mostly provided by three major tributaries, including North Landing River, Northwest River, and Tull Creek (fig. 1). The Virginia portion of North Landing River has a drainage area of about 117 mi^2 (Caldwell, 2001). Northwest River and Tull Creek mostly drain agricultural lands and have drainage areas of 196 mi^2 and 52 mi^2, respectively.

The climate of the study area is humid subtropical. In the Northern Coastal Plains area of North Carolina, including Currituck Sound, the average annual precipitation was about 49 inches (in.) during the period of 1988–2017, and monthly totals were typically greatest from July through September (North Carolina Climate Office, 2019). Hurricanes or tropical storms and convective thunderstorms with flood-producing rainfalls and high winds typically occur during summer or fall. Nor’easters that occur along the east coast during fall and winter months can generate strong winds and heavy rainfall that can result in high-water elevations or flooding in Currituck Sound.



Base from The National Map (coastline), 1:100,000
Urban areas, State and county boundaries from U.S. Census Bureau, 1:100,000
Stream lines modified from U.S. Department of Agriculture Natural Resources Conservation Service, National Hydrography Dataset, 1:24,000

Figure 1. Map showing the location of the study area, including data collection sites, in Currituck Sound, North Carolina.

The circulation and movement of water in Currituck Sound is primarily wind-driven rather than tidally driven because of the long distance between the Sound and its connection with the Atlantic Ocean at Oregon Inlet, North Carolina (Giese and others, 1985; Caldwell, 2001) (fig. 1). Freshwater inflows into the upper Currituck Sound are small, and the tidal effect is minimal, typically resulting in a less than 0.5-foot (ft) difference between the daily maximum and minimum water levels (Caldwell, 2001) in the vicinity of the planned bridge alignment. Caldwell (2001) estimates that water in Currituck Sound has a hydraulic residence time of about three-fourths of a year. The mixing effects of winds and tides inhibits significant salinity stratification from occurring within Albemarle Sound, including Currituck Sound (Giese and others, 1985; Caldwell, 2001).

Historical hydrologic and water-quality data collected by the USGS (Caldwell, 2001; Fine, 2008) suggest that wind events dominate the circulation and movement of water in Currituck Sound and that water tends to be well mixed spatially and vertically in the vicinity of the planned bridge alignment within the central part of the Sound. During 1998 and 1999, Caldwell (2001) examined the hydrologic and salinity characteristics of Currituck Sound and indicated that salinity values were less than about 3.5 ppt and had the lowest variability in the central part of the Sound throughout the study period. Little lateral or vertical variation was observed in measured water-quality properties—including specific conductance, pH, salinity, temperature, and dissolved oxygen—along a transect across the Sound at the CU3 site[1] from Caldwell (2001), which is near the planned Mid-Currituck Bridge. The most appreciable changes in water-quality are likely to occur during wind events (Caldwell, 2001). Southwestern winds are dominant in the spring and summer and push more saline water up from the south into the Sound, thereby increasing water levels and conductivity-salinity. North winds are dominant in the fall and winter and tend to push water out of the Sound, decreasing the water levels and the conductivity-salinity. Average surface-water depths at the five sampling stations in Currituck Sound (fig. 1) for this 2011–2018 study were as follows:

- station 1 at 0.25 mi from the east bank of Currituck Sound: 1.9 ft;
- station 2 at 1.2 mi from the east bank of Currituck Sound: 5.9 ft;
- station 3 at 2.1 mi from the east bank of Currituck Sound: 6.3 ft;
- station 4 at 3.5 mi from the east bank of Currituck Sound: 8.1 ft;
- station 5 at 4.5 mi from the east bank of Currituck Sound: 4.4 ft.

Methods

The collection of climatic, hydrologic, water-quality, and bed-sediment data within Currituck Sound occurred during two field sampling periods. Initially, field data were collected for period 1 from August 2011 to January 2015. At the onset of this study, initial construction of the Mid-Currituck Bridge was planned for November 2012. Because of delays in the start date, the study period was expanded to allow the collection of additional field data during period 2, which took place between October 2016 and January 2018. Collectively, the data from both sampling periods are considered representative of baseline conditions for the entire study period (2011–2018) before bridge construction, which is projected to begin in the spring of 2022. This section of the report provides a discussion of the methods used to compile precipitation data, to measure water levels, wind speed and direction, and water velocities, and to collect and analyze field samples. The supporting data for this report are available in Cain and others (2020).

Precipitation Data

Precipitation data were compiled near Currituck Sound to examine rainfall amounts before each water-quality sampling event. Hourly precipitation data were obtained from the State Climate Office of North Carolina (2018) for the following meteorological stations (fig. 1):

- Federal Aviation Administration meteorological station at Currituck County, [N.C.], Regional Airport (KONX) (http://climate.ncsu.edu/cronos/?station=KONX),
- National Weather Service meteorological station at Elizabeth City, [N.C.], Coast Guard Air Station and Regional Airport (KECG) (http://climate.ncsu.edu/cronos/?station=KECG).

Water Levels, Wind Speed, and Wind Direction Data

The USGS gaging stations for measuring continuous water levels (USGS station number 02043433) and wind speed and direction (USGS station number 362228075500401) are colocated on the east bank of Currituck Sound near Corolla, North Carolina (fig. 1). The gaging stations are equipped with a pressure transducer to measure water levels, a sensor to measure wind speed and direction, and a data collection platform to record and transmit data at 15-minute intervals to the NWIS database administered by the USGS. Water-level data were collected according to standard USGS methods (Rantz and others, 1982; Sauer and Turnipseed, 2010). The water-level—or gage-height—data are available through NWIS (U.S. Geological Survey, 2018b).

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[1] CU3—Currituck Sound at Poplar Branch, North Carolina (Caldwell, 2001, p. 6).

Wind speed and direction data were measured using a Gill WindSonic anemometer with a specified wind-speed resolution of 0.02-mile per hour and an accuracy of ±2 percent, and a wind direction resolution of 1 degree and an accuracy of ±2 degrees. For this study, wind speed and direction data were collected every second and averaged over a 2-minute period before being transmitted to the NWIS database at 15-minute intervals. The wind speed and direction data are also available through NWIS (U.S. Geological Survey, 2018c).

Water-Velocity Data

The circulation dynamics in the vicinity of the planned bridge were measured, for most sampling events, using an acoustic Doppler current profiler (ADCP) integrated with a differential Global Positioning System (DGPS), which allows three-dimensional velocities to be measured from approximately 1.0 ft beneath the water surface to within 6 percent of the depth to the bottom. The ADCP velocity data were collected using standard USGS techniques (Mueller and others, 2013).

During field sampling periods 1 and 2, velocity magnitudes and directions were continuously collected along a transect connecting the five water-quality stations located near the planned bridge alignment (fig. 1). Transect velocity data could not be collected during some sampling events due to DGPS malfunction issues with the ADCP. A more frequently encountered issue was that the velocity measurements could not be acquired in some areas due to the presence of SAV that interfered with the readings or minimal water depths, resulting in data gaps along the transect. This issue was most prevalent at the shallowest sampling site (the 0.25-mile station) near the eastern side of the Sound (water-quality station 1 in fig. 1). Additional velocity information, acquired during field period 2 of the study, included measurements of stationary velocity profiles at each site that were made while water-quality samples were collected, with measurements typically lasting up to an hour at each site. The stationary measurements provide a much larger sample size with which to characterize water circulation at each site over time.

Data files obtained with the ADCP were exported through the RiverSurveyor Live software in MATLAB format for the transect velocity datasets and American Standard Code for Information Interchange (ASCII) format for the profile velocity datasets. The transect-data output files were subsequently processed using the Velocity Mapping Toolbox (VMT) developed by Parsons and others (2013). The VMT software is publicly available (U.S. Geological Survey, 2018d) and allows users different processing and visualization options; such as projecting, averaging, smoothing, contouring, and displaying; for analyzing three-dimensional velocity data. Using VMT, the transect data were projected to a fixed transect line and interpolated to 1-meter (m) (3.28-ft) intervals along that line. These data were output in tabular form for each projected point with easting, northing, line distance, bed depth, east and north velocity vectors, and velocity magnitude and direction. The spatial mean of the depth-averaged water velocity magnitudes and directions were computed from these data across 400-ft sections, or windows, of the transect that were centered on each of the 5 sampling stations. The averaging windows were selected by finding the point along each transect line with an easting coordinate closest to the easting coordinate of each sampling site, then including any points with eastings within 61 m (200 ft) of that point.

The profile-data output files from the ADCP were processed using Python to compile tabular data files for each sampling date, in which each 1-second measurement is represented by one row that contains time, location, and measurement settings information, as well as the velocity for each of the multiple depth cells sampled in that measurement. The number of individual cells measured in the water column for a profile varied depending on the water depth, site conditions, and measurement settings. These profile data were used to determine depth-averaged water-velocity magnitudes and directions for each date and site. Mean velocities were calculated for each depth cell, and then the individual depth-cell mean values were averaged together to calculate the overall depth-averaged (mean) water column velocity. The supporting transect and stationary water-velocity data used in this report are available in Cain and others (2020).

Surface-Water Samples

Discrete surface-water samples were collected for laboratory analyses at five selected locations from a crewed boat along an approximately 4-mi transect across Currituck Sound in the vicinity of the planned bridge alignment (fig. 1). Latitude and longitude coordinates were established for each sampling location using a Global Positioning System receiver, which allowed both water and bed-sediment samples to be collected from the same locations throughout the study. During field sampling period 1, water-quality samples were collected on a routine (monthly) basis from August 2011 through December 2013; field period 1 concluded with the collection of storm-event samples in January 2015. During field sampling period 2, monthly samples were collected from December 2016 through January 2018. The monthly samples were supplemented with nine storm-event samples collected between August 2011 and August 2017 after significant rainfall in the Currituck Sound study area (table 1). With one exception, samples for this study were deemed to be associated with a storm event when the average total rainfall for the KONX and KECG weather stations (fig. 1) was greater than or equal to 0.5 in. within 48 hours or 0.75 in. within 72 hours before the median sample-collection time on each sampling date. Although the samples collected on October 13, 2016, did not meet these criteria, they are considered storm samples because they were collected shortly after Hurricane Matthew (October 8–9, 2016), which produced more than 8 in. of rainfall in many locations and caused substantial flooding throughout eastern North Carolina.

Table 1. Summary of total antecedent precipitation over the 48-hour and 72-hour period prior to water-quality sampling events in Currituck Sound, North Carolina, 2011–18.

[h, hour; in., inch; KONX, Currituck County Regional Airport weather station; KECG, Elizabeth City Coast Guard Air Station and Regional Airport, National Weather Service weather station]

Sample date	Median sample time	Sampling event type	Season	Total 48-h antecedent precipitation (in.)		Total 72-h antecedent precipitation (in.)	
				KONX	KECG	KONX	KECG
08/30/11	1215	Storm	Summer	0	0.01	1.60	1.40
09/28/11	1145	Routine	Summer	0.01	0.01	0.12	0.16
10/18/11	1120	Routine	Fall	0	0	0	0
11/15/11	1015	Routine	Fall	0	0	0	0
12/20/11	0955	Routine	Fall	0	0	0	0
01/24/12	1200	Routine	Winter	0.21	0.24	0.45	0.42
02/22/12	1245	Routine	Winter	0	0	0.72	0.50
03/06/12	1315	Storm	Winter	0.10	0.05	0.97	0.79
03/21/12	1115	Routine	Winter	0	0.04	0	0.04
04/17/12	1345	Routine	Spring	0	0	0	0
05/31/12	1230	Storm	Spring	1.93	1.71	1.93	1.71
06/20/12	1215	Routine	Spring	0	0	0	0
07/18/12	1345	Routine	Summer	0	0	0	0
08/15/12	1330	Routine	Summer	0.01	0	0.01	0
09/12/12	1215	Routine	Summer	0	0	0	0
10/09/12	1345	Storm	Fall	1.22	1.59	1.25	1.65
10/10/12	0945	Storm	Fall	1.21	1.60	1.25	1.66
11/15/12	1130	Routine	Fall	0	0	0.03	0.02
12/18/12	1200	Routine	Fall	0.02	0.19	0.03	1.06
01/17/13	1115	Routine	Winter	0	0.03	0	0.03
02/27/13	0930	Storm	Winter	1.32	1.00	1.32	1.00
03/20/13	0915	Routine	Winter	0.01	0	0.04	0
04/09/13	1115	Routine	Spring	0	0	0	0
05/30/13	1030	Routine	Spring	0	0	0	0
06/10/13	1045	Routine	Spring	0	0.46	0.01	0.51
06/26/13	1130	Routine	Spring	0	0	0	0
07/24/13	1015	Routine	Summer	0	0.03	0	0.03
08/15/13	1300	Routine	Summer	0.12	0.17	0.18	0.45
09/11/13	1145	Routine	Summer	0	0.01	0	0.01
10/23/13	0900	Routine	Fall	0	0	0	0
11/21/13	1200	Routine	Fall	0	0	0	0
12/19/13	1115	Routine	Fall	0	0	0	0
01/25/15	1115	Storm	Winter	1.00	1.03	1.00	1.03
10/13/16	1215	Storm	Fall	0	0	–	0
12/21/16	1100	Routine	Fall	0.24	0.31	0.63	0.79
01/25/17	1030	Routine	Winter	0.01	0	0.31	0.38
02/22/17	1115	Routine	Winter	0	0	0	0
03/21/17	1145	Routine	Winter	0.03	0.06	0.51	0.56
04/19/17	1230	Routine	Spring	0.19	0.30	0.19	0.30

Table 1. Summary of total antecedent precipitation over the 48-hour and 72-hour period prior to water-quality sampling events in Currituck Sound, North Carolina, 2011–18.—Continued

[h, hour; in., inch; KONX, Currituck County Regional Airport weather station; KECG, Elizabeth City Coast Guard Air Station and Regional Airport, National Weather Service weather station]

Sample date	Median sample time	Sampling event type	Season	Total 48-h antecedent precipitation (in.)		Total 72-h antecedent precipitation (in.)	
				KONX	KECG	KONX	KECG
05/17/17	1100	Routine	Spring	0	0	0	0
06/15/17	1145	Routine	Spring	0	0	0	0
07/20/17	1130	Routine	Summer	0	0	0	0
08/16/17	1045	Storm	Summer	0.04	1.05	0.04	1.05
09/20/17	1000	Routine	Summer	0.28	0.17	0.28	0.17
10/25/17	1130	Routine	Fall	0.01	0.04	0.01	0.04
11/15/17	1115	Routine	Fall	0	0	0.22	0.34
12/19/17	1045	Routine	Fall	0	0.01	0	0.01
01/24/18	1145	Routine	Winter	0.29	0.44	0.29	0.44

Before sample collection, in situ measurements of water temperature, dissolved oxygen, pH, and specific conductance were made at 1.64 ft (0.5-meter) intervals at the sampling location along with water transparency, which was measured by Secchi disk. If the water column was well mixed or the water was shallow (less than 6.5 ft [2 meters] deep), one sample was collected at that site. If the water column was stratified (thermally or regarding salinity) or deeper than 6.5 ft, two discrete samples were collected: one sample about 1.64 ft (0.5 meter) below the top of the column and one sample about 1.64 ft (0.5 meter) above the bottom of the column. For the 2011–2018 study period, a total of 48 top samples were collected at each site except for the 3.5-mi station (fig. 1), which had 47 samples. Bottom samples were only collected at the 1.2-mi (n=3), 2.1-mi (n=8), and 3.5-mi (n=39) stations, primarily in response to water-column depth and not stratification.

Top and bottom water samples were collected using either a Van Dorn or Kemmerer point sampler for analysis of turbidity, total suspended solids, nutrients, metals, and semi-volatile organic compounds (SVOCs). Near-surface grab samples for analysis of bacteria were collected directly into sterilized bottles. Samples for chlorophyll *a*, cyanotoxins, and algal taxonomy were collected throughout the euphotic zone—operationally defined as the depth equal to twice the Secchi transparency depth—using a depth-integrating weighted-bottle sampler. Water collected for the analysis of unfiltered constituents was transferred to sample containers, preserved, and placed on ice at collection. Additional water collected for the analysis of filtered constituents was transferred directly to a 4-liter (L) polyethylene bottle and immediately placed on ice for subsequent processing at the University of North Carolina Coastal Studies Institute in Wanchese, North Carolina. USGS staff delayed the filtering of water samples—up to 5 hours after the samples were collected—until they had departed Currituck Sound so that all water-quality sampling and water-velocity data collection could be completed during daylight hours. The samples were collected and processed using the techniques described in the USGS National Field Manual for the Collection of Water-Quality Samples (U.S. Geological Survey, variously dated).

Water-Quality Analyses

Surface-water samples were submitted for laboratory analyses of one or more different groups of physical properties, chemical constituents, biological constituents, and cyanotoxins. Analyses varied among sampling events, stations, and depths. The overall suite of analyses covered 7 physical properties, 5 nutrients, 13 metals (filtered and unfiltered), 14 SVOCs, the bacteria Enterococci and *Escherichia coli* (*E. coli*), the pigment chlorophyll *a* and its degradation product pheophytin *a*, and 18 cyanotoxin groups or congeners.

Laboratory analyses of surface-water samples collected during field periods 1 and 2 are described here. Analyses for turbidity, total suspended solids, nutrients, minor inorganics (mostly metals), and SVOCs (including polycyclic aromatic hydrocarbons) were done by the USGS National Water Quality Laboratory (NWQL) in Denver, Colorado. The University of North Carolina Coastal Studies Institute in Wanchese, N.C., analyzed the bacteria Enterococci and *E. coli*. A list of the constituents analyzed in surface-water samples during period 1, including the analyzing laboratories, laboratory reporting levels (LRLs), and method references, is available in Cain and others (2020).

The differences in laboratory analyses that occurred between period 1 and 2 are described here. Analysis of chlorophyll *a* for samples during period 1 was performed at Meritech, Inc., Environmental Laboratories in Reidsville, North Carolina. An analysis of chlorophyll *a* for samples during period 2 was performed at the USGS NWQL. Beginning with the samples in period 2, select samples were submitted to the USGS Kansas Water Science Center's Organic Geochemistry Research Laboratory in Lawrence, Kans., for the analysis of cyanotoxins. Three classes of cyanotoxins—microcystins plus nodularins, cylindrospermopsin, and saxitoxin—were analyzed by enzyme-linked immunosorbent assays (ELISA), including a modification for samples with a salinity greater than 3.5 practical salinity units, as recommended by Abraxis, Inc., the manufacturer of the assays (Loftin and others, 2008; Graham and others, 2010; Loftin and others, 2016a; Loftin and others, 2016b; https://abraxis.eurofins-technologies.com/home/).

Additionally, 15 specific cyanotoxins, including anatoxin-a, cylindrospermopsin, microcystin congeners, and nodularin-R were analyzed using a liquid chromatography with tandem mass spectrometry (LC/MS/MS) technique on a bioinert Agilent 1260 SL liquid chromatograph and an Agilent 6460 triple-quadrupole mass spectrometer in electrospray positive and negative mode using the Jetstream ion source (Loftin and others, 2016a; Loftin and others, 2016b).

The LC/MS/MS method is a reverse-phase separation using a Waters Corp. Atlantis T3 analytical column. The salt from brackish water samples was removed from the separated sample postcolumn using a switching valve in the mass spectrometer bypassed to waste for the first 2 minutes of the analytical run. Samples were analyzed by ELISA and LC/MS/MS in duplicate every tenth sample, and the relative-percentage standard deviation was less than or equal to 28.3 percent. All laboratory blanks were below the minimum reporting levels for each constituent and control standards were less than or equal to 28.3 percent of the expected value.

Over 250 known microcystin congeners are reported to date (Meriluoto and others, 2017), and the ELISA for microcystin is used as a screening technique for the class of microcystins. Only 10 certified reference materials for microcystins were available at the time of this study. Therefore, it is expected that the LC/MS/MS may underreport the concentration of microcystins when other congeners are present in the samples (Loftin and others, 2008; Loftin and others, 2016b). The additions and changes to surface-water constituents measured during period 2 are available in Cain and others (2020).

The water-quality data for surface-water samples were retrieved from NWIS (U.S. Geological Survey, 2018a). Retrievals of water-quality data included remark codes (RC) associated with analytical results, such as "less than" (<) for values censored at the LRL and "estimated" (E) values that fall between the LRL and method detection level. Estimated concentrations are considered semiquantitative because of the greater uncertainty in the measurement at that level (Childress and others, 1999).

In summarizing the analytical results of the study, constituents with estimated concentrations were used as reported. Nutrient samples included analysis of the following nitrogen (N) fractions: total ammonia plus organic N (also referred to as total Kjeldahl nitrogen [TKN]), filtered ammonia, and filtered nitrate plus (+) nitrite. Concentrations for the N species are reported in milligrams per liter (mg/L) as N. A direct laboratory measurement of total N was not performed on the samples, so values of total N were computed using the measured concentrations for TKN and nitrate + nitrite. It is of note that (by default) calculated total N concentrations retrieved from the NWIS database retain the "<" RC if an underlying constituent is left-censored. The handling of censored data is left to the discretion of data users.

For this report, calculations for total N concentrations, and how left-censored "<" RCs for measured constituents were applied to the computed total N concentrations, were based on the same approach presented in Saad and others (2011). The steps used for calculating total N concentrations, based on the reported TKN and nitrate + nitrite concentrations, along with the number of environmental and quality-assurance (QA) samples, where the computed total N values were assigned "<" RCs, are summarized in table 2. There were no cases where the computed total N concentrations for environmental samples were assigned a "<" RC. Some of the computed total N concentrations for QA samples—all blanks—were assigned a "<" RC, primarily because concentrations of TKN and concentrations of nitrate + nitrite were less than the LRLs (table 2). All analytical results for the surface-water environmental and QA samples presented and discussed in this report are compiled in Cain and others (2020).

Table 2. Summary of approach used for calculating total nitrogen concentrations and applying left-censored remark codes to the computed total nitrogen values for surface-water environmental and quality-assurance samples collected in Currituck Sound, North Carolina, 2011–18 (adapted from Saad and others, 2011).

[TKN, total ammonia plus organic nitrogen; NO_3NO_2, dissolved nitrate plus nitrite; TN, total nitrogen; conc., concentration; LRL, laboratory reporting level; <, less than; ≥, greater than or equal to; /, divided by]

Total ammonia plus organic nitrogen (TKN) concentration	Dissolved nitrate plus nitrite (NO_3NO_2) concentration	Calculation used for total nitrogen (TN) concentration	Remark code applied to computed TN value	Number of samples with applied remark code	
				Surface water environmental samples	Surface water quality assurance samples
Not censored	Not censored	NO_3NO_2 conc. + TKN conc.	None	84	6
<LRL	<LRL	NO_3NO_2 LRL + TKN LRL	<	0	21
<LRL	≥2 × TKN LRL	NO_3NO_2 conc. + (TKN LRL/2)	None	0	0
<LRL	<2 × TKN LRL	NO_3NO_2 conc. + TKN LRL	<	0	1
≥2 × NO_3NO_2 LRL	<LRL	(NO_3NO_2 LRL/2) + TKN conc.	None	200	21
<2 × NO_3NO_2 LRL	<LRL	NO_3NO_2 LRL + TKN conc.	<	0	0

Phytoplankton Taxonomy and Abundance

Water samples used for the analysis of phytoplankton taxonomy and abundance were collected during field sampling period 2 at the 0.25-mi, 2.1-mi, and 4.5-mi stations. Phytoplankton samples were collected in 1-L bottles, preserved with Lugol's solution, and kept cold and in the dark until analyzed. The amount of preservative added was recorded for each sample.

The USGS quantitatively analyzed the samples for cyanobacteria and eukaryotic algae by using microscopy to identify the organisms present and count their abundance (Rosen and St. Amand, 2015). The contents of each sample bottle were poured into a 1-L graduated cylinder for determining sample volume and allowing the organisms to settle for a minimum of 24 hours. The volume of water above the 100-milliliter (mL) line was aspirated and discarded; the remaining 100 mL was transferred to a 100-mL graduated cylinder and allowed to settle for a minimum of 24 hours. The volume of water above 10 mL was aspirated and discarded; the remaining 10 mL was transferred to a plastic centrifuge tube and kept cold (4 degrees Celsius [°C]) until phytoplankton were identified and enumerated.

The 10-mL sample in the centrifuge tube was homogenized by vigorous shaking to disperse the colonies before an aliquot was withdrawn using a micropipette and placed onto a glass microscope slide. The precise weight was determined (x 0.0001 gram [g]) with an Ohaus Explorer EX224 Analytical Electronic Balance. The weight was considered equivalent to the volume (1 mL = 1 g) and evenly distributed under a 22 square millimeter glass coverslip. Counting was done microscopically, at 400× magnification, by enumerating the organisms observed in linear strips across the full length of the coverslip. The diameter of the strip was measured with a stage micrometer. The number of organisms per unit volume was calculated by using the volume distributed under the coverslip per unit area.

Four primary groups of phytoplankton were identified in samples, including cyanobacteria, diatoms, green algae, and cryptophytes. Because euglenoids and dinoflagellates were rarely present, they are not discussed further. Within the cyanobacteria group, several coiled organisms (*Planktolyngbya contorta*, *Pseudanabaena contorta*, and *Dactylococcopsis irregularis*), which are likely three separate taxa, were lumped as *Planktolyngbya* cf. *contorta* for this study. Morphological features that allow the separation of these species are only discernible at higher magnification under the microscope. In general, *Planktolyngbya contorta* was uncommon; *Pseudanabaena contorta* and *Dactylococcopsis irregularis* compose most of this grouping. The phytoplankton taxonomy and abundance results are compiled in Cain and others (2020). Phytoplankton abundance, in natural units of organism per L, is reported without rounding.

Bed-Sediment Samples

Bed-sediment samples were collected at the five surface-water sites (fig. 1) on four dates: three during field period 1 and one during field period 2. The samples were collected and processed using the techniques described in chapter A8 (bottom-material samples) of the USGS National Field Manual for the Collection of Water-Quality Data (U.S. Geological Survey, variously dated). Grab samples of surficial bed sediment were collected using an Ekman dredge. Any overlying water present within the dredge was first siphoned off before a Teflon tube was used to collect approximately 2 centimeters of the uppermost bed sediment. The collected sediment was homogenized in a mixing bowl and subdivided into separate prebaked, wide-mouth glass jars with Teflon-lined lids for processing and laboratory analysis. Quality-control samples, including field replicates, split replicates, and matrix spike samples, were also collected for laboratory analysis. The collected samples were kept chilled until submitted for laboratory analysis of one or more different groups of physical properties and chemical constituents. Bed-sediment samples were not analyzed for all the same constituents during the 4 sampling events but included total nitrogen, phosphorus, up to 38 metals, 38 SVOCs, carbon, and percent fine fraction.

Differences in the laboratory preparation and analysis of bed-sediment samples collected during field periods 1 and 2 are described here. During period 1, analyses were performed on the fine (< 63 micrometers [µm]) fraction of the samples, which contains silt and clay particles but excludes the coarser sand fraction. Analyses during period 2 were performed on the entire bulk sediment, not only the fine material. Trace elements and organic constituents in bed sediment are more commonly associated with the fine fraction than the coarser sand fraction due to the larger surface to volume ratio of the fines. Analyses for period 1 samples were performed on the fine fractions to help achieve lower LRLs by removing the dilution effects of the sand fraction. However, the limited mass of fine material available for analysis caused the laboratory to raise the LRLs for many constituent results. Therefore, analyses for period 2 were performed on bulk sediment with sufficient amounts of sample material, which helped achieve lower LRLs relative to the period 1 samples. A full list of the constituents analyzed in bed-sediment samples during period 1, along with the analyzing laboratories, LRLs, and method references is available in Cain and others (2020). The additions and changes to bed-sediment constituents measured during period 2 are also provided in Cain and others (2020).

During period 1, samples were sent to the USGS Sediment-Partitioning Research Lab (SPRL) for initial sample preparation and subsequent analyses. At the laboratory, each wet sediment sample was homogenized and split into two subsamples. Each subsample was wet-sieved (mesh size < 63 µm) under pressure. One subsample was sieved using a stainless steel mesh, and the resulting wet-sieved sediment was transferred to a prebaked glass jar with a Teflon-lined lid and shipped to the USGS NWQL for analysis of SVOCs. The second subsample was sieved using a nylon-polyethylene mesh. Several grams of the wet-sieved sediment were dried and retained by the SPRL for analysis of nutrients, inorganics (mostly metals), and carbons (total and the organically associated fraction). The SPRL analyses were based on total concentration—defined as 95 percent or more of the analyzed constituent present—because it is less operationally defined when compared to the total recoverable concentration (Horowitz, 1991). The weight percent of fines (< 63 µm) in the overall samples were also determined.

During field period 2, samples of wet bulk sediment collected at the sites were homogenized and subdivided in the field. Samples of wet bulk sediment were sent directly to the USGS NWQL for analysis of SVOCs and to the USGS Sediment Laboratory in Louisville, Ky., for analysis of the weight percent of fines (< 63 µm). Some of the collected wet bulk sediment was further processed at the Raleigh, N.C., office of the USGS SAWSC, where it was oven-dried (at 60 °C) to a constant weight, ground, homogenized, and subdivided. Samples of the dried bulk sediment were provided to AGAT Laboratories in Mississauga, Ontario, Canada, for analysis of major and minor inorganics (mostly metals), and for total P. Dried sediment samples were also provided to the North Carolina State University Environmental and Agricultural Testing Service in Raleigh, N.C., for an analysis of total N and carbons (total and the organically associated fraction). All analytical results for the bed-sediment environmental and QA samples presented and discussed in this report are compiled in Cain and others (2020).

Quality Assurance and Quality Control

All scientific work done by the USGS follows established quality-assurance and quality-control (QA/QC) policies and procedures to ensure continued confidence in its products. Water-resource activities of the USGS SAWSC are supported by a series of quality-assurance policy statements and guidelines that describe responsibilities for specific functional elements, including project planning and implementation, equipment calibration and maintenance, data collection and processing, data management and storage, data analysis and interpretation, synthesis, reports preparation and processing, and training. Project activities are systematically conducted under a hierarchy of supervision and management that is designed to ensure conformance with agency goals for quality assurance. All methods used by the USGS to collect and review scientific data are fully documented, and project data and records are archived using guidelines jointly approved by the USGS and the National Archives and Records Administration.

The QA/QC samples, including field and equipment blanks, replicate samples, and matrix-spike samples, were collected to document potential bias and variability in data that may result during the collection, processing, shipping, and handling of environmental samples (U.S. Geological Survey, variously dated). Equipment blanks help to identify contamination resulting from improperly cleaned equipment and laboratory practices. Field blanks help to identify contamination resulting from field sampling activities and exposure, as well as improperly cleaned equipment and laboratory practices. Replicate samples were collected to help document the variability in data results associated with sample collection, processing, and laboratory analysis. Matrix-spike samples were used to assess the effects of sample matrices on the performance of laboratory analytical methods.

Surface-Water Samples

Potential positive contamination bias of measured analyte concentrations in water samples was assessed using field and equipment blanks analyzed throughout field periods 1 and 2 to determine if potential contamination occurred during sample collection, handling and processing, and laboratory analysis. In further discussions of data for constituents in water, filtered constituents are referred to as "dissolved," and unfiltered constituents are referred to as "total." Twenty-five blanks (22 field blanks and 3 equipment blanks) were analyzed for one or more constituent groups (physical properties, nutrients, metals, SVOCs, bacteria, and cyanotoxins). Overall, the results of the field and equipment blanks did not indicate any systematic or substantial quality-assurance issues with the environmental data.

Analysis of bacteria (Enterococci and *E. coli*) and cyanotoxin (18 constituents) concentrations in 5 and 4 field blanks, respectively, did not indicate any detections above LRLs. For the remaining constituent groups, 49 constituents were analyzed, and 1,018 blank results were generated. Most of these results, about 94 percent (961 of 1,018), were less than the constituent LRLs. Twenty-six of the 49 constituents had quantified detections in 1 or more blanks. Even so, the number of detections overall was low, and most of the detections were at or near the LRLs, indicating negligible systematic positive bias. A constituent detection frequency of less than 10 percent of the combined field and equipment blanks was deemed acceptable for this study.

The potential for constituents detected in blanks to produce a positive contamination bias on the environmental results was assessed by using 2 sequential criteria: (1) the constituent was detected in more than 10 percent of the blanks, and (2) the constituent concentrations in more than 10 percent of the environmental samples were less than 3 times the highest detected blank concentration. In a few cases, some SVOCs had estimated "E" concentrations, but due to their inherent uncertainty, they were excluded from this assessment, which focused on those constituent results with detected concentrations above LRLs. Only 6 of the 26 detected constituents in blanks had detections in more than 10 percent of the analyzed blanks, including dissolved ammonia (56.5 percent), dissolved manganese (26.1 percent), total manganese (13.0 percent), dissolved zinc (13.0 percent), total zinc (13.0 percent), and bis(2-ethylhexyl)phthalate (11.1 percent). For these constituents, blank detections were further evaluated in relation to concentrations observed in environmental samples. Four of the constituents had reported concentrations—in over 10 percent of the environmental samples—that were less than 3 times the highest blank concentration (table 3) and were, therefore, considered potentially biased by contamination during field sampling or laboratory analysis. Concentrations of dissolved and total manganese in most environmental samples (97.6 and 100 percent, respectively) were more than 3 times the highest blank concentration and likely were not biased by contamination; therefore, these constituents were not listed in table 3.

Ammonia was commonly detected at low levels near LRLs in both blanks and samples. Ammonia was detected in about 56 percent of the blanks at concentrations of 0.01 to 0.03 mg/L. About 90 percent of the environmental samples had ammonia concentrations less than 3 times the highest blank concentration (0.09 mg/L), indicating low-level contamination may have occurred. Samples frequently become contaminated when exposed to the atmosphere—both in the field and the laboratory (Fishman, 1993). Contamination is especially apparent when samples are analyzed using low-level techniques, as was done in this study. Both dissolved and total zinc were detected in 3 of 23 blanks (13 percent). Dissolved and total zinc were only detected in 3.5 and 14.5 percent, respectively, of the environmental samples (table 3). All detected concentrations of zinc in the samples were less than three times the highest blank concentrations, indicating some sporadic contamination of this constituent may have occurred during field sampling activities. Similarly, bis(2-ethylhexyl)phthalate was detected in 2 of 18 blanks (11.1 percent) and 30 of 194 samples (15.5 percent). About 63 of the environmental samples with quantified detections of bis(2-ethylhexyl)phthalate were less than 3 times the highest blank concentration. Sporadic contamination of this common plasticizer may have also occurred during field sampling or laboratory analysis; these results should be interpreted with caution.

Both positive and negative bias of water constituents were assessed by recovery determination in four environmental samples spiked (fortified) with known concentrations of select metals, nutrients, and SVOCs (table 4). Matrix-spike recoveries were considered acceptable if the average recovery for each constituent was between 75 and 125 percent. For the single matrix-spike sample analyzed for nutrients, total P (141 percent) fell outside the acceptable range. Of the total and dissolved metals analyzed in 1 and 2 samples, respectively, only total chromium (37 percent) was outside the acceptable range.

The average recoveries for SVOCs in 3 samples ranged from 31 to 88 percent; only *N*-nitrosodi-*n*-propylamine (88 percent) and pentachlorophenol (78 percent) had acceptable recoveries. Bis(2-chloroethyl) ether, with an average recovery of 74 percent, was below the acceptable range. The other 11 SVOCs had low average recoveries of 62 percent or less. For the environmental samples, SVOCs were rarely detected at concentrations above LRLs. Twelve of the 14 SVOCs had concentrations below the LRL in

95 percent or more of the samples. Bis(2-ethylhexyl)phthalate was the most common SVOC detected above LRLs in the environmental samples (30 of 194); however, as discussed previously for the blank results, sporadic contamination of this compound may have occurred during field sampling or laboratory analysis. With few exceptions, most quantified detections of SVOCs in the environmental samples were at concentrations near their individual LRLs. Although *N*-nitrosodi-*n*-propylamine had an acceptable average recovery in the matrix-spike samples, this compound was not detected in any of the 194 environmental samples having a median LRL of 0.4 micrograms per liter (µg/L) (LRLs for SVOCs were periodically raised by the laboratory due to instrument calibration and matrix effects issues). It is likely that most SVOCs in surface-water samples collected during the study were not present at detectable concentrations, but the extent to which matrix interference effects may have influenced the laboratory analyses to detect low concentrations of SVOCs in the samples is unclear.

The variability of sampling and analysis was assessed through 36 sets of field replicates analyzed during the study. Relative percent differences (RPD; absolute difference times 100 divided by the average) were determined for concentration pairs where both values were above the LRLs and for those discordant pairs (one value detected above the LRL and the other value less than the LRL) only when the detected values were higher than the left-censored values. The RPDs based on discordant values represent minimum variabilities. The many pairs where both values were left-censored cannot be used to assess variability and so were not considered. Estimated “E” coded values were used as reported and included as part of the assessment.

Potentially variable constituents were screened as follows. Paired concentrations with RPDs less than 25 percent are considered to demonstrate acceptable reproducibility. The RPDs that were equal to or greater than 25 percent were further evaluated by calculating the absolute concentration difference between the paired sample and replicate. Large RPD values are common and expected when they result from small absolute differences near the constituent LRLs. If the RPDs exceeding 25 percent had absolute concentration differences less than or equal to 3 times their respective censoring level (based on those reported for associated blank samples), they were accepted without further discussion. Constituents were considered to have high variability when the number of RPDs greater than 25 percent had absolute concentration differences higher than 3 times the censoring levels for more than 10 percent of the paired replicate sample sets. A statistical summary of the RPDs and the number and percent of replicate pairs exceeding the screening criteria is provided in table 5.

Overall, results for replicate pairs indicated acceptable reproducibility for most of the water-quality constituents. Several metals exceeded the variability screening criteria (table 5), including dissolved aluminum (20.0 percent), dissolved iron (16.7 percent), dissolved manganese (33.3 percent), and total nickel (16.6 percent). Bis(2-ethylhexyl)phthalate (50.0 percent) was the only SVOC to exceed the criteria, and, as previously indicated, this constituent was likely influenced by contamination during field sampling or laboratory analysis. For the cyanotoxins, total microcystins plus nodularins (16.7 percent) and domoic acid (50.0 percent) exceeded the threshold based on a small number of replicate pairs; cyanotoxins were infrequently detected in samples above LRLs.

Assessments of bacteria were performed between the laboratory duplicates associated with the environmental and replicate samples, as well as between the regular environmental and field replicate sample pairs. All bacterial samples were routinely analyzed as analytical duplicates. For the laboratory duplicate pairs, both *E. coli* and Enterococci barely exceeded the 10 percent threshold. Higher variability was noted for *E. coli* (25.0 percent) and Enterococci (28.6 percent) in the field replicates, although very few pairs were available for examination (table 5). In both environmental and replicate samples, bacteria were infrequently detected above LRLs. In addition, bacteria measurements are often difficult to replicate because bacteria are associated with particles that are not homogenously distributed in the water. Overall, the analytical variability of the bacterial analyses was considered acceptable.

Variability in total phytoplankton, as well as the four main taxonomic groups, was examined with up to six replicate sets. Only statistical summaries of the RPDs are provided for phytoplankton in table 5; screening criteria used for other constituents do not apply to the phytoplankton. For the total phytoplankton density, the median RPD was 12.2 percent. The median RPD was 9.5 percent for total cyanobacteria. The median RPDs were somewhat higher for the total diatoms (45.4 percent), total green algae (44.8 percent), and total cryptophytes (27.1 percent).

Water-quality data were also reviewed to identify any questionable results. For some metals, concentrations for the dissolved phase exceeded concentrations for the total recoverable phase in some samples. Because the total fraction includes the dissolved fraction, the former can never be smaller than the latter. The noted discrepancies where laboratory-derived concentrations for some trace elements in filtered samples exceeded those in associated unfiltered samples likely reflect differences in analytical bias and error resulting from sample-matrix chemistry or instrument variability (Paul and others, 2016). In assessing whether these results were deemed acceptable for the purpose of this study, the RPD was calculated to consider analytical variability for all metal concentration pairs where the reported dissolved concentration was higher than the total concentration. Samples having RPDs less than 20 percent were considered acceptable.

The remaining samples having RPDs greater than 20 percent were further assessed by comparing concentration differences between the dissolved and total fractions in relation to differences in their respective LRLs for the relevant time period in the dataset. Analytical uncertainties in the results were deemed acceptable for most instances in which the dissolved concentration exceeded the total concentration, except for arsenic, cadmium, and zinc (1 sample each); copper (6 samples); nickel (10 samples); and selenium (37 samples). Results for those 56 concentration pairs (dissolved and total) were excluded from the final dataset. All 37 excluded selenium concentration pairs were from field period 1 (August 2011–January 2015). Due to the high level of analytical uncertainty associated with the selenium results, all dissolved and total selenium concentrations for environmental and replicate samples collected during period 1 were excluded from the final datasets. This analytical issue was solved for field period 2, where no selenium data were excluded.

Table 3. Summary of selected constituent data observed in equipment and field blanks and surface-water environmental samples collected in Currituck Sound, North Carolina, 2011–18.

[mg/L as N, milligrams per liter as nitrogen; µg/L, micrograms per liter]

Constituent (units)	Blanks				Environmental samples			
	Blanks with detections			3 times the highest blank concentration	Samples with detections			Percent less than 3 times the highest blank concentration
	Number	Percent	Range of quantified detections		Number	Percent	Range of quantified detections	
Ammonia, filtered (mg/L as N)	13 of 23	56.5	0.01–0.03	0.09	185 of 284	65.1	0.01–0.22	90.3
Zinc, filtered (µg/L)	3 of 23	13.0	1.8–5.4	16.2	10 of 283	3.5	2.1–9.0	100
Zinc, unfiltered (µg/L)	3 of 23	13.0	3.1–9.1	27.3	41 of 283	14.5	2.0–23.4	100
Bis(2-ethylhexyl) phthalate, unfiltered (µg/L)	2 of 18	11.1	0.162–0.239	0.717	30 of 194	15.5	0.031–22	63.3

Table 4. Matrix-spike recoveries for nutrients, metals, and semi-volatile organic compounds in surface-water samples collected in Currituck Sound, North Carolina, 2012–17.

[–, no data]

Constituent	Matrix-spike recovery (percent)				Average (percent)
	October 10, 2012	April 19, 2017	August 16, 2017[a]	October 25, 2017	
Nutrients					
Ammonia, dissolved	–	100	–	–	100
Phosphorus, total	–	141	–	–	141
Orthophosphate, dissolved	–	101	–	–	101
Metals					
Aluminum, dissolved	–	122	96	–	109
Aluminum, total	–	–	110	–	110
Arsenic, dissolved	–	121	109	–	115
Arsenic, total	–	–	106	–	106
Cadmium, dissolved	–	106	94	–	100
Cadmium, total	–	–	104	–	104
Chromium, dissolved	–	119	104	–	111
Chromium, total	–	–	37	–	37
Copper, dissolved	–	108	96	–	102
Copper, total	–	–	97	–	97
Iron, dissolved	–	96	105	–	101
Iron, total	–	–	99	–	99
Lead, dissolved	–	96	114	–	105
Lead, total	–	–	90	–	90
Manganese, dissolved	–	114	94	–	104
Manganese, total	–	–	102	–	102
Nickel, dissolved	–	109	98	–	104
Nickel, total	–	–	94	–	94
Selenium, dissolved	–	120	104	–	112
Selenium, total	–	–	106	–	106
Silver, dissolved	–	82	75	–	78
Silver, total	–	–	88	–	88
Zinc, dissolved	–	115	105	–	110
Zinc, total	–	–	106	–	106

Table 4. Matrix-spike recoveries for nutrients, metals, and semi-volatile organic compounds in surface-water samples collected in Currituck Sound, North Carolina, 2012–17.—Continued

[–, no data]

Constituent	Matrix-spike recovery (percent)				Average (percent)
	October 10, 2012	April 19, 2017	August 16, 2017[1]	October 25, 2017	
Semi-volatile organic compounds					
Dibenzo[a,h]anthracene	30	27	–	35	31
Chrysene	32	33	–	33	33
Benzo[a]anthracene	34	38	–	[2]39	37
Hexachlorobenzene	50	59	–	42	50
Benzo[a]pyrene	33	37	–	41	37
Benzo[b]fluoranthene	31	33	–	43	36
Benzo[k]fluoranthene	30	32	–	39	33
Bis(2-chloroethyl) ether	81	95	–	45	74
N-Nitrosodi-n-propylamine	102	103	–	59	88
N-Nitrosodimethylamine	52	57	–	26	45
Indeno[1,2,3-cd]pyrene	31	31	–	39	34
Phenanthrene	67	80	–	40	62
Pentachlorophenol	81	88	–	[2]65	78
Bis(2-ethylhexyl)phthalate	[2]52	43	–	[2]65	54

[1] The percent recoveries listed for metals represent the average of two duplicate spikes.

[2] This constituent was detected in associated environmental sample but concentration was not subtracted from spike sample so percent recovery is overestimated.

Table 5. Summary of relative percent differences in constituent results for the surface-water environmental and replicate sample sets collected in Currituck Sound, North Carolina, 2011–18.

[RPD, relative percent difference; %, percent; –, not applicable]

Constituent	Number of paired replicate samples	Statistical measure				Number of pairs exceeding screening threshold	Percent of pairs exceeding screening threshold
		Minimum RPD (%)	Maximum RPD (%)	Mean RPD (%)	Median RPD (%)		
Physical properties and nutrients							
Turbidity	22	0	24.3	6.5	4.8	0	0
Total suspended solids	13	5.1	94.4	36.0	33.8	1	7.7
Ammonia, dissolved	17	0	85.7	16.9	0	0	0
Ammonia + organic N, total	26	0	15.4	4.6	3.0	0	0
Nitrate + nitrite, dissolved	4	0	22.2	7.4	3.7	0	0
Phosphorus, total	26	0	19.5	4.4	2.6	0	0
Orthophosphate, dissolved	1	40.0	40.0	40.0	40.0	0	0
Total nitrogen, computed	26	0	15.3	4.4	3.2	0	0
Biological							
Chlorophyll *a*	17	0.8	17.6	4.7	3.4	0	0
E. coli (for lab duplicates)	40	0	135	50.7	66.7	5	12.5
Enterococci (for lab duplicates)	76	0	122	52.2	66.7	8	10.5
E. coli (for field replicates)	4	0	193	89.8	83.3	1	25.0
Enterococci (for field replicates)	7	6.5	102	63.6	66.7	2	28.6
Metals							
Aluminum, dissolved	10	1.0	61.2	23.7	19.1	2	20.0
Aluminum, total	26	0.2	33.0	9.1	7.2	2	7.7
Arsenic, dissolved	26	0	10.8	4.4	5.1	0	0
Arsenic, total	25	0	35.9	12.0	8.7	0	0
Cadmium, total	1	17.1	17.1	17.1	17.1	0	0
Chromium, dissolved	2	3.2	5.5	4.3	4.3	0	0
Chromium, total	6	7.4	40.0	20.4	16.0	0	0
Copper, dissolved	4	0	14.3	6.5	5.9	0	0
Copper, total	7	0	66.7	16.0	9.5	0	0
Iron, dissolved	12	0	64.6	20.8	9.0	2	16.7
Iron, total	26	0	17.5	4.0	2.6	0	0
Lead, dissolved	7	1.2	60.5	14.6	4.4	0	0
Lead, total	26	0	18.2	5.1	2.3	0	0
Manganese, dissolved	24	1.3	131	32.3	23.0	8	33.3
Manganese, total	26	0	20.4	3.9	3.2	0	0
Mercury, total	1	18.2	18.2	18.2	18.2	0	0
Nickel, dissolved	21	0	43.5	11.8	9.0	1	4.8
Nickel, total	12	0	160.8	24.6	8.7	2	16.6
Selenium, dissolved	4	8.7	24.0	16.6	16.8	0	0
Selenium, total	4	0	66.7	16.7	0	0	0
Zinc, dissolved	2	4.9	18.2	11.5	11.5	0	0
Zinc, total	3	0	22.2	7.4	0	0	0

Table 5. Summary of relative percent differences in constituent results for the surface-water environmental and replicate sample sets collected in Currituck Sound, North Carolina, 2011–18.—Continued

[RPD, relative percent difference; %, percent; –, not applicable]

Constituent	Number of paired replicate samples	Statistical measure				Number of pairs exceeding screening threshold	Percent of pairs exceeding screening threshold
		Minimum RPD (%)	Maximum RPD (%)	Mean RPD (%)	Median RPD (%)		
Semi-volatile organic compounds							
Dibenzo[a,h]anthracene	1	22.2	22.2	22.2	22.2	0	0
Indeno[1,2,3-cd]pyrene	1	22.2	22.2	22.2	22.2	0	0
Pentachlorophenol	1	29.8	29.8	29.8	29.8	0	0
Bis(2-ethylhexyl)phthalate	4	12.8	154	101	119	2	50.0
Cyanotoxins							
Total cylindrospermopsins	3	0	2.2	0.7	0	0	0
Total microcystins plus nodularins	6	0	54.0	21.6	15.2	1	16.7
Cylindrospermopsin	2	6.6	100	53.3	53.3	0	0
Domoic acid	2	60.9	161	111	111	1	50.0
Microcystin WR	1	2.8	2.8	2.8	2.8	0	0
Phytoplankton							
Total organisms	6	3.7	62.5	20.4	12.2	–	–
Total cyanobacteria	6	0.1	85.7	22.5	9.5	–	–
Total diatoms	5	3.7	66.2	37.2	45.4	–	–
Total green algae	6	1.2	95.0	41.4	44.8	–	–
Total cryptophytes	3	0.1	56.6	27.9	27.1	–	–

Bed-Sediment Samples

Assessments of potential bias of constituents measured in bed-sediment samples were based on analysis of standard reference materials (SRMs; reference samples with known concentrations) and matrix spikes. For an analysis of bed-sediment samples, the laboratory routinely includes and analyzes SRMs in line with the environmental sample sets. Recovery determinations for nutrients, carbons, and metals were examined using 12 analyses of 11 unique SRMs and an analysis of 1 field-matrix spike sample (table 6). Recoveries of SVOCs were examined with two laboratory matrix spike samples. Median recovery for constituents in the SRMs and individual recoveries for the matrix spikes were considered acceptable if they were between 75 and 125 percent. Median recoveries for nutrients, carbons, and metals in the SRMs were all within acceptable limits, ranging from 86 percent for tin and 109 percent for total organic carbon. Chromium was the only constituent in the 2017 field matrix spike that had a recovery (65 percent) outside the acceptable range.

Recovery of trace organic compounds in the 2012 matrix spike done on the fines fraction was notably lower than for the 2017 matrix spike done on bulk sediment (table 6). For the 2012 spike, 9,10-anthraquinone had a recovery equal to the lower acceptable limit of 75 percent; recoveries for the other 37 SVOCs fell below this lower limit. Collectively, SVOCs analyzed on the fine fraction of samples collected during period 1 may be biased low. Better overall recoveries were noted for SVOCs in the 2017 spike performed on bulk sediment. Only 9 of 38 the compounds for this spiked sample had recoveries less than the acceptable limits, ranging from 74 percent for anthracene to 45 percent for 1,2,4-trichlorobenzene (table 6). Thus, concentrations of some of these 9 SVOCs may potentially be biased low in bed-sediment samples collected during field period 2.

The variability of constituent concentrations measured in bed sediment was assessed from seven sample sets, including three field replicates, two split replicates, and two analytical duplicates. These three types of sample sets are nested, meaning that the field replicates reflect the overall variability of sampling, handling, and analysis. Split replicates reflect variability in the sample handling and analysis, and the analytical duplicates reflect variability in the sample analysis. By analyzing all three types of sample sets, major sources of variability could be isolated. In general, the variability in analytical duplicates should be less than the variability in split replicates, which in turn should be less than the variability in field replicates.

Potentially variable constituents in bed sediment were examined following the same screening criteria as previously described for the surface-water samples. Overall, results for the replicate and duplicate sample sets indicated acceptable reproducibility for most of the bed-sediment constituents, where RPDs were less than 25 percent and the absolute concentration differences were less than or equal to 3 times the censoring levels (table 7).

Five of the seven sample sets (two field replicates, one split replicate, and two analytical duplicates) had acceptable variability for all measured constituents. The variability of most SVOCs could not be assessed due to the prevalence of left-censored values in the sample sets. The field replicate from July 24, 2013, had the highest number of constituents (n=6) with RPDs that did not meet the acceptable criteria. Arsenic and copper were the only constituents for the split replicate from August 17, 2017, that exceeded the screening criteria. Field replicates, because they capture sampling-site heterogeneity, often have the largest variability, followed by split replicates.

Statistical Analyses

Summary statistics for water-quality results, including the top and bottom samples at each study site, were computed using the methods described in Bonn (2008). The total number of observations, number and percentage of censored observations, minimum and maximum values, and the 25th, 50th, and 75th percentile values were computed for each site-constituent pairing. For constituents having left-censored data with one or more LRLs, summary statistics were estimated using the Kaplan-Meier method (Helsel, 2005). Percentiles were not computed if greater than 75 percent of the data values in a dataset were censored.

Additional statistical evaluations of the study data were used to determine if differences among treatment groups existed. Because most of the study data are non-normally distributed, a Kruskal-Wallis (KW) nonparametric test, which is a one-way analysis of variance (ANOVA) test, was performed on rank-transformed data to determine if statistically significant differences were present (Helsel and Hirsch, 2002). The KW test was used to look for significant differences in surface water physical properties and chemical constituents (top-depth samples only) among categories of sampling event type, sampling site, and sampling season. Most of the surface-water property and constituent datasets evaluated with the KW tests contained no left-censored data. For those constituents having estimated concentrations (“E” RCs), the values were used as reported for the analyses.

The KW test results for a given property or constituent may indicate that a statistically significant difference in mean ranks of the concentrations exists among a particular treatment group (such as sampling season), but it does not specify which of the group treatments (such as the winter, spring, summer, or fall seasons) are different. Those properties or constituents with significant differences identified by the KW tests were analyzed further with Tukey pairwise multiple comparison tests (Helsel and Hirsch, 2002), based on the ranked data, to identify which sampling-site comparison pairs and sampling-season comparison pairs had statistically different means in their ranked data. The ANOVA and multiple comparison analyses were conducted within the S-PLUS software suite (by TIBCO Software, Inc.). Statistical differences were tested at the 95 percent (alpha level = 0.05) confidence level.

The use of statistical analyses that rely on data ranks rather than actual data values is also appropriate for examining water-quality data containing left-censored “<” values when those “<” values for a given constituent are censored to the same analytical level (Helsel and Hirsch, 2002; Helsel, 2005). For a constituent dataset with censored results at one LRL, the censored values and any detected observations reported below the LRL are all set equal, or censored, to the single LRL value before the data is ranked for statistical analysis. This approach was used for two cyanotoxin datasets (total cylindrospermopsins and total microcystins plus nodularins) from field period 2 that contained censored results having only one LRL and detected observations that were all higher than the LRL. For a dataset having censored results with more than one LRL, the censored values and any detected observations reported between the LRLs are all set equal, or censored, to the highest LRL value, such that they are all ranked equally before analysis.

Datasets for several total metals (aluminum, arsenic, and lead) evaluated with the KW tests only contained a few left-censored results (1 to 5 samples with 1 to 4 LRLs) out of the total datasets for each constituent (283 to 284 samples). Although less than 2 percent of these datasets contained left-censored results, the associated LRLs were substantially high relative to the overall range observed for the detected observations. The high LRLs for these few samples reflect the higher than usual sample dilutions performed by the laboratories before analyzing these brackish water samples. Setting all the censored results and detected observations between the LRLs equal to the highest LRL would cause most, or all, of the reported observations to be censored to the same level, which was deemed inappropriate for evaluating this group of total metal datasets. Therefore, the few left-censored values reported for total aluminum, total arsenic, and total lead were set equal to one-half of their respective LRLs before the data were ranked for statistical analysis.

For the seasonal analysis of water-quality data, the winter season consisted of January, February, and March; the spring season consisted of April, May, and June; the summer season consisted of July, August, and September; and the fall season consisted of October, November, and December. Hereafter, the spring and summer seasons are referred to as the “warmer” months, and the fall and winter seasons are referred to as the “cooler” months.

Table 6. Recovery of constituents in standard reference materials and semi-volatile organic compounds (SVOC) in spiked samples of bed sediment collected in Currituck Sound, North Carolina, 2011–17.

[SRM, standard reference material; %, percent; –, no data]

Nutrients, carbons, and metals		
Constituent	SRMs (2011, 2013, 2017)	Matrix spike (2017)
	Median recovery (%)	Recovery (%)
Nitrogen, total	106	101
Phosphorus	99	100
Carbon, total organic	109	–
Carbon, total	101	101
Aluminum	100	96
Antimony	94	102
Arsenic	97	124
Barium	97	91
Beryllium	94	–
Cadmium	96	91
Calcium	100	93
Cerium	–	98
Cesium	–	106
Chromium	96	65
Cobalt	97	110
Copper	94	78
Iron	98	87
Lanthanum	–	109
Lead	100	102
Lithium	99	–
Magnesium	100	88
Manganese	100	92
Mercury	98	102
Molybdenum	94	–
Nickel	96	82
Potassium	100	89
Rubidium	–	104
Scandium	–	94
Selenium	104	104
Silver	108	–
Sodium	100	91
Strontium	98	90
Sulfur	101	–
Tantalum	–	88
Terbium	–	99
Thallium	–	88
Thorium	–	90
Tin	86	–
Titanium	99	87

Semi-volatile organic compounds		
Constituent	Matrix spike (2012)[1]	Matrix spike (2017)[2]
	Recovery (%)	Recovery (%)
1,2,4-Trichlorobenzene	46	45
1,2-Dimethylnaphthalene	62	75
1,6-Dimethylnaphthalene	63	75
1-Methyl-9H-fluorene	65	83
1-Methylphenanthrene	62	78
1-Methylpyrene	57	89
2,3,6-Trimethylnaphthalene	61	79
2,6-Dimethylnaphthalene	63	73
2-Ethylnaphthalene	61	73
2-Methylanthracene	53	88
4H-Cyclopenta[def]phenanthrene	65	82
Acenaphthene	61	76
Acenaphthylene	19	56
Anthracene	58	74
9,10-Anthraquinone	75	101
Benzo[a]anthracene	56	89
Benzo[a]pyrene	47	80
Benzo[b]fluoranthene	48	91
Benzo[e]pyrene	51	87
Benzo[ghi]perylene	53	91
Benzo[k]fluoranthene	50	81
Bis(2-ethylhexyl) phthalate	47	123
Carbazole	54	80
Chrysene	54	81
Dibenzo[a,h]anthracene	55	93
Dibenzothiophene	67	81
Diethyl phthalate	59	80
Fluoranthene	65	81
9H-Fluorene	66	85
Hexachlorobenzene	48	72
Indeno[1,2,3-cd]pyrene	54	94
Naphthalene	53	55
Pentachloroanisole	55	71
Pentachloronitrobenzene	51	66
Perylene	58	76
Phenanthrene	64	81
Phenanthridine	63	83
Pyrene	63	80

Table 6. Recovery of constituents in standard reference materials and semi-volatile organic compounds (SVOC) in spiked samples of bed sediment collected in Currituck Sound, North Carolina, 2011–17.—Continued

[SRM, standard reference material; %, percent; –, no data]

Nutrients, carbons, and metals		
Constituent	SRMs (2011, 2013, 2017)	Matrix spike (2017)
	Median recovery (%)	Recovery (%)
Uranium	102	91
Vanadium	96	85
Zinc	100	85

[1] Recovery of SVOCs for this matrix spike was based on the fine fraction less than 63 micrometers.

[2] Recovery of SVOCs for this matrix spike was based on the bulk sediment.

Table 7. Summary of relative percent differences in constituent results for the bed-sediment replicate and duplicate sample sets collected in Currituck Sound, North Carolina, 2011–17.

[Bolded values indicate those RPDs that exceeded the 25 percent screening level and had absolute concentration differences greater than 3 times the censoring levels. RPD, relative percent difference; %, percent; µm, micrometer; –, not applicable]

Constituent	November 15, 2011[1]			July 24, 2013[1]		August 17, 2017[2]	
	Field replicate, RPD (%)	Split replicate, RPD (%)	Analytical duplicate, RPD (%)	Field replicate, RPD (%)	Analytical duplicate, RPD (%)	Field replicate, RPD (%)	Split replicate, RPD (%)
	Nutrients, carbons, and physical properties						
Total nitrogen	2.2	8.2	4.1	22.2	18.2	13.3	0
Phosphorus	4.8	1.4	4.4	22.6	1.4	5.7	4.3
Total organic carbon	0	14.6	13.3	**114**	0	0	0
Total carbon	0	9.8	0	0	10.5	5.8	4.8
Bed sediment, <63 µm	0	40.0	0	**27.5**	0	6.8	0
	Metals						
Aluminum	7.9	1.6	1.9	9.7	6.3	4.6	3.2
Antimony	18.2	18.2	50.0	22.2	0	29.3	14.8
Arsenic	4.1	0	9.5	**25.5**	0	6.7	**27.2**
Barium	6.3	14.8	2.8	2.5	2.5	0	3.1
Beryllium	5.7	0	7.4	6.5	6.9	7.9	0.9
Cadmium	66.7	–	0	66.7	40.0	0	33.3
Calcium	13.3	0	0	20.0	0	1.1	1.4
Cerium	–	–	–	–	–	6.8	3.8
Cesium	–	–	–	–	–	8.9	2.3
Chromium	9.0	0	2.3	23.5	0	0.8	1.0
Cobalt	0	0	0	22.2	0	6.0	5.1
Copper	0	6.9	0	35.3	0	11.4	**62.5**
Iron	5.9	3.1	0	15.9	3.5	8.7	2.4
Lanthanum	–	–	–	–	–	12.8	8.2
Lead	11.8	5.4	9.5	13.3	0	11.9	9.8
Lithium	10.9	1.8	9.5	24.4	2.8	5.7	4.8
Magnesium	10.5	9.5	0	11.8	0	6.9	2.9
Manganese	12.0	0	5.6	7.2	0	2.5	2.0
Mercury	0	66.7	40.0	0	0	0	0
Molybdenum	40.0	0	0	40.0	0	7.6	22.5
Nickel	8.7	4.3	0	24.4	5.7	2.9	2.3
Potassium	0	0	6.1	16.2	0	0.6	3.4
Rubidium	–	–	–	–	–	4.7	2.3
Scandium	–	–	–	–	–	2.6	3.9
Selenium	0	0	0	40.0	0	10.5	10.5
Silver	–	–	–	–	–	10.9	14.3
Sodium	9.1	24.6	0	8.7	8.7	0	4.1
Strontium	0	8.0	6.5	6.5	0	0.7	1.6
Sulfur	20.7	6.5	6.7	**40.0**	0	13.3	9.5

Table 7. Summary of relative percent differences in constituent results for the bed-sediment replicate and duplicate sample sets collected in Currituck Sound, North Carolina, 2011–17.—Continued

[Bolded values indicate those RPDs that exceeded the 25 percent screening level and had absolute concentration differences greater than 3 times the censoring levels. RPD, relative percent difference; %, percent; µm, micrometer; –, not applicable]

Constituent	November 15, 2011[1]			July 24, 2013[1]		August 17, 2017[2]	
	Field replicate, RPD (%)	Split replicate, RPD (%)	Analytical duplicate, RPD (%)	Field replicate, RPD (%)	Analytical duplicate, RPD (%)	Field replicate, RPD (%)	Split replicate, RPD (%)
Metals—Continued							
Tantalum	–	–	–	–	–	8.1	22.6
Terbium	–	–	–	–	–	1.2	7.3
Thallium	–	–	–	–	–	12.3	7.4
Thorium	–	–	–	–	–	1.2	1.5
Tin	0	40.0	66.7	–	–	6.5	22.2
Titanium	0	1.9	9.0	16.9	0	2.8	7.8
Uranium	–	–	–	–	–	3.0	4.5
Vanadium	8.3	2.1	5.0	17.7	1.5	0	2.7
Zinc	11.0	2.6	2.0	**25.8**	3.6	5.4	10.3
Semi-volatile organic compounds							
1-Methylphenanthrene	–	–	–	0	–	–	–
2,6-Dimethlnaphthalene	–	–	–	34.5	–	–	–
Bis(2-ethylhexyl) phthalate	–	–	–	**63.2**	–	–	–
Fluoranthene	–	–	–	–	–	–	8.7
Perylene	–	–	–	16.9	–	27.5	11.8

[1] Relative percent differences for these replicates and duplicates were based on constituents measured in the fine fraction less than 63 micrometers.

[2] Relative percent differences for these replicates were based on constituents measured in the bulk sediment.

Characterization of Water-Quality and Bed-Sediment Conditions in Currituck Sound

The following sections summarize the water-quality, phytoplankton taxonomy, and bed-sediment data collected in Currituck Sound from August 2011 to January 2018. Summaries of the wind- and water-velocity data compiled during the study are also provided.

Summary of Water-Quality Sample Results

Water-quality results were compared with applicable State and Federal water-quality standards and criteria, which were available for 23 physical properties and constituents (North Carolina Department of Environmental Quality, 2017; U.S. Environmental Protection Agency, 2019; table 8). These standards and criteria, hereafter referred to as “thresholds,” relate to actual or potential impairment for designated uses: aquatic life, fish consumption, swimming, and secondary recreation. If more than one threshold existed, the most stringent value was used for comparison to sample results. When present, estimated “E” concentration values were included in the comparisons.

The overall number of observations exceeding the water-quality thresholds was limited. Ten of the 23 properties or constituents had concentrations above the thresholds in one or more samples (table 8; Cain and others, 2020). Of these, 6 had exceedances in 5 percent or more of the samples, including chlorophyll *a* (16.7 percent), bis(2-ethylhexyl)phthalate (14.4 percent), pH (13.5 percent), turbidity (8.5 percent), Enterococci (6.1 percent), and pentachlorophenol (5.7 percent). Exceedances for the remaining four, including dissolved copper, total manganese, total mercury, and total PAHs, were limited to one or two samples. As previously discussed, bis(2-ethylhexyl)phthalate was likely influenced by contamination during field sampling or laboratory analysis. Dissolved copper, dissolved silver, bis(2-ethylhexyl)phthalate, pentachlorophenol, and total PAHs had high numbers of left-censored “<” results with LRLs higher than their corresponding thresholds, and, therefore, it could not be determined whether those samples were above or below those thresholds (table 8). Raised LRLs typically reflected sample dilutions performed by the laboratories before analysis of these brackish water samples.

In a previous study of bridge deck runoff in North Carolina, Wagner and others (2011) identified 28 POCs for receiving streams (including metals, nutrients, pH, suspended solids, PAHs, and other organic compounds). These POCs were analyzed in water samples collected for this study in Currituck Sound. Fourteen of these POCs had water-quality thresholds applicable to Currituck Sound, including pH, eight metals (dissolved cadmium, copper, lead, nickel, and zinc, and total manganese, mercury, and arsenic), and five SVOCs (bis(2-chloroethyl)ether, bis(2-ethylhexyl)phthalate, n-nitrosodimethylamine, n-nitrosodi-n-propylamine, and pentachlorophenol). Water samples from Currituck Sound exceeded applicable water-quality thresholds for only six POCs, including pH, dissolved copper, total manganese, total mercury, bis(2-ethylhexyl)phthalate, and pentachlorophenol (table 8).

Historical water-quality data collected by the USGS (Caldwell, 2001; Fine, 2008) suggest that water in the Currituck Sound study area is mostly well mixed. An initial review of the data for the 50 top and bottom sample pairs collected during this study indicated little vertical variability in the water column during sampling. Minimal differences (less than 4 percent) in water-quality properties were noted between the top and bottom samples based on the average values for dissolved oxygen (top = 9.6 and bottom = 9.3 mg/L), dissolved oxygen percent saturation (top = 101.7 and bottom = 98.2 percent), pH (top = 8.0 and bottom = 8.0 standard units), temperature (top = 18.6 and bottom = 18.4 °C), specific conductance (top = 5,340 and bottom = 5,458 microsiemens per centimeter at 25 °C), and turbidity (top = 12.0 and bottom = 12.4 nephelometric turbidity ratio units).

Statistical summaries based on all water-quality sample results for each surface-water sampling station are provided in table 9. Given that the water sampled along the planned bridge alignment was well mixed vertically, the results for both top and bottom samples were combined to compute summary statistics at each location. Many constituents had high percentages of left-censored results less than LRLs. Those constituents having more than 75 percent censored results for all 5 sample stations were omitted from table 9. These constituents included orthophosphate for nutrients, six dissolved metals (cadmium, chromium, copper, mercury, silver, and zinc), and four total metals (cadmium, mercury, silver, and zinc). Most of the cyanotoxins (14 of 18) measured in samples from the 0.25-, 2.1-, and 4.5-mile sites had more than 75 percent censored results. The majority of the 14 SVOCs (including PAHs) measured in all surface-water samples had 95 percent or more censored results. Because the SVOCs were rarely detected in surface water, they are omitted from further discussion.

The amount of censored data associated with the physical properties and constituents listed for the 5 study sites varied from little to no censoring (such as turbidity and chlorophyll *a*) to more than 50 percent censored (such as nitrate plus nitrite, Enterococci, and *E. coli*). The most frequently detected nutrients at the sites included ammonia plus organic N, total P, and total N; none of these results were censored. In the case of metals, the total fractions typically had a higher percentage of detected observations above LRLs than did the dissolved fractions, especially for aluminum, iron, lead, and manganese (table 9). The minimum amount of censored data for these 4 metals at the 5 sites varied from 6.4 percent for dissolved manganese to 72 percent for dissolved lead, whereas the total fractions had 1.8 percent or less censored data. Total microcystins plus nodularins, followed by total cylindrospermopsins, were the most frequently detected cyanotoxins in samples collected during field period 2. Total microcystins plus nodularins were detected in about 80 to 93 percent of the samples, and total cylindrospermopsins were detected in about 40 to 53 percent of the samples.

Statistical evaluations using nonparametric KW ANOVA tests and Tukey pairwise multiple-comparison tests on ranked data were performed to characterize the differences in physical properties and constituents among the two sampling-event types (monthly routine and storm samples), five sites (0.25-, 1.2-, 2.1-, 3.5-, and 4.5-mile stations), and four seasons. These evaluations for assessing significant differences among the treatment groups were conducted only using the top sample results compiled for all five sampling sites. Most bottom samples were collected at the 3.5-mile site (n=39), while either a few or none were collected at the 0.25-mile (n=0), 1.2-mile (n=3), 2.1-mile (n=8), and 4.5-mile (n=0) sites, which led to the exclusion of the results for bottom samples so that the analysis would be based on more comparable datasets among the sites.

The KW tests were performed on 16 selected physical properties (temperature, dissolved oxygen, pH, specific conductance, and turbidity) and chemical constituents, the latter including nutrients (ammonia plus organic N, total N, and total P), total metals (aluminum, arsenic, iron, lead, and manganese), cyanotoxins (total cylindrospermopsins and total microcystins plus nodularins), and chlorophyll *a* (table 10). These properties and constituents typically had the least amount of censored data for the study sites (table 9). The KW tests were also performed on the four primary phytoplankton taxonomic groups (total cyanobacteria, total diatoms, total green algae, and total cryptophytes [table 10]). The KW and Tukey test results for the physical properties and chemical constituents are discussed below, whereas the results for the phytoplankton groups are discussed in the following section.

The KW tests between sampling-event types (monthly routine and post-storm samples) were limited to 13 properties and constituents measured throughout both field periods 1 and 2; therefore, total cylindrospermopsins, total microcystins plus nodularins, and chlorophyll *a* were excluded from this evaluation. Distributions, by sampling event type, of the original (nonranked transformed) data, top samples only, for each property measurement and constituent concentration are summarized as box plots (figure 2). Results of the Tukey pairwise multiple comparison tests between the routine and storm-event samples are denoted as letters along the top of the plots; events that do not share the same letter are statistically different from each other (probability value [P-value] less than 0.05) (fig. 2). Statistical differences were identified by KW tests between monthly routine and storm samples for 6 of the 13 properties and constituents (table 10). Tukey test results determined that storm samples had lower specific conductance and higher turbidity, total P, total aluminum, total arsenic, and total lead than routine samples (figs. 2*D*, 2*E*, 2*H*, 2*I*, 2*J*, and 2*L*, respectively).

No statistically significant differences among the 5 sampling sites were identified for any of the 16 properties or constituents based on the KW test evaluations (table 10). These results indicated that the water at the surface-water sites sampled along the planned bridge-alignment transect was well mixed horizontally during this baseline study period. Also, as previously mentioned, samples collected at top and bottom depths at certain locations indicated that water in the study area was vertically well mixed. These findings agree with previous studies (Caldwell, 2001; Fine, 2008) that indicated that water is well mixed spatially and vertically in the central part of Currituck Sound.

In contrast, all 16 of the properties and constituents differed significantly among seasons (table 10). Distributions, by sampling season, of the original (nonranked transformed) data, top samples only, for each property measurement and constituent concentration are displayed in figure 3 to highlight the seasonal variability in water-quality conditions. Results of the Tukey pairwise multiple comparison tests among the seasons are denoted as letters along the top of the plots (fig. 2); seasons that do not share the same letter are statistically different from each other (P-value less than 0.05) (fig. 3). Based on these statistical and graphical evaluations, the variability in water-quality conditions observed during the study period was better explained by seasonal changes than by sampling event or location (table 10, fig. 3).

Constituents that tended to have higher values during the warmer months, or at least in the summer, and lower values in the colder months, or at least in the winter, included water temperature, pH, specific conductance, total arsenic, total manganese, total cylindrospermopsins, and total microcystins plus nodularins (figs. 3*A*, *C*, *D*, *J*, *M*, *O*, and *P*, respectively). Ammonia plus organic N, total N, and chlorophyll *a* also had higher values during summer, but the lower values tended to occur during the spring (figs. 3*F*, *G*, and *N*, respectively). Constituents having higher values in the colder months, or at least in the winter, and lower values in the warmer months, or at least in the summer, included dissolved oxygen, turbidity, total P, total aluminum, total iron, and total lead (figs. 3*B*, *E*, *H*, *I*, *K*, and *L*, respectively).

In summary, environmental conditions in Currituck Sound are such that water chemistry is relatively uniform spatially but variable temporally. Seasonal differences in the water-quality constituents likely reflect a combination of environmental factors, including such things as algal and plant production, adsorption and desorption processes, changes in sources and sinks, and variations in climatic and hydrologic conditions.

Table 8. Water-quality standards applicable to constituents or properties measured in surface-water samples collected in Currituck Sound, North Carolina, 2011–18.

[NC, North Carolina; USEPA, U.S. Environmental Protection Agency; diss., dissolved; –, not applicable; >, greater than; NTRU, nephelometric turbidity ratio units; MPN/100 mL, most probable number per 100 milliliters; µg/L, micrograms per liter; PAHs, polyaromatic hydrocarbons]

Constituent or property name (unit)[1]	NC standard–all waters, fish consumption[2]	NC standard–saltwater, aquatic life, and secondary recreation[2]	USEPA standard –all waters, fish consumption[2]	USEPA recommended –recreational and swimming[3]	Number greater than standard	Number of samples where the reporting level exceeded the standard
pH (standard units)	–	6.8–8.5	–	–	38 of 281 (all >8.5)	0
Turbidity (NTRU)	–	25	–	–	24 of 284	0
Enterococci (MPN/100 mL)	–	35	–	–	14 of 228	5
Chlorophyll *a* (µg/L)	–	40	–	–	9 of 54	0
Cadmium, diss. (µg/L)	–	8.8	–	–	0 of 283	0
Copper, diss. (µg/L)	–	3.1	–	–	1 of 278	103
Lead, diss. (µg/L)	–	8.1	–	–	0 of 284	0
Manganese, total (µg/L)	–	–	100	–	1 of 284	0
Mercury, total (µg/L)	–	0.025	–	–	2 of 284	0
Nickel, diss. (µg/L)	–	8.2	4,600	–	0 of 274	4
Arsenic, diss. (µg/L)	–	36	–	–	0 of 283	0
Arsenic, total (µg/L)	10	–	–	–	0 of 283	0
Selenium, total (µg/L)	–	71	4,200	–	0 of 96	0
Silver, diss. (µg/L)	–	0.1	–	–	0 of 284	100
Zinc, diss. (µg/L)	–	81	–	–	0 of 283	4
Bis(2-chloroethyl)ether (µg/L)	–	–	2.2	–	0 of 194	0
Bis(2-ethylhexyl)phthalate (µg/L)	–	–	0.37	–	28 of 194	154
N-nitrosodimethylamine (µg/L)	–	–	3	–	0 of 194	0
N-nitrosodi-n-propylamine (µg/L)	–	–	0.51	–	0 of 194	6
Pentachlorophenol (µg/L)	–	–	0.04	–	11 of 192	170
PAHs, total (µg/L)[4]	0.0311	–	–	–	2 of 194	191
Total cylindrospermopsins (µg/L)	–	–	–	15	0 of 46	0
Total microcystins + nodularins (µg/L)[5]	–	–	–	8	0 of 46	0

[1] Bolded constituents and properties indicate those parameters of concern identified for the bridge deck runoff study by Wagner and others (2011).

[2] Standards obtained from North Carolina Department of Enivronmental Quality (2017).

[3] Standards obtained from U.S. Environmental Protection Agency (2019).

[4] Sum of benzo[a]anthracene, benzo[a]pyrene, benzo[b]fluoranthene, benzo[k]fluoranthene, chrysene, dibenz[a,h]anthracene, and indeno[1,2,3-cd]pyrene.

[5] Cyanotoxin measurements for samples included concentrations of total microcystins plus nodularins. These combined concentrations were all lower than the recommended USEPA standard of 8 µg/L which is only for total microcystins.

Table 9. Statistical summary of water-quality properties and constituents for sampling stations in Currituck Sound, North Carolina, 2011–18.

[mg/L, milligrams per liter; diss., dissolved; µg/L, micrograms per liter; %, percent; µS/cm @ 25 °C, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; m, meter; NTRU, nephelometric turbidity ratio units; diss., dissolved; N, nitrogen; P, phosphorus; MPN/100 mL, most probable number per 100 milliliters; –, not applicable]

Constituent or property name (unit)	Number of observations	Number censored	Percent censored	Number censoring levels	Minimum censor level	Maximum censor level	Minimum value	25th percentile	50th percentile (median)	75th percentile	Maximum value
					0.25-mile station						
Dissolved oxygen (mg/L)	46	0	0	0	–	–	7.0	8.9	10.3	11.5	13.1
Dissolved oxygen, % saturation	46	0	0	0	–	–	74	99	105	111	139
pH (standard units)	46	0	0	0	–	–	7.2	7.7	8.1	8.4	9.2
Specific conductance (µS/cm at 25 °C)	46	0	0	0	–	–	822	3,735	5,560	6,715	10,400
Temperature, water (°C)	46	0	0	0	–	–	6.0	10.4	18.7	25.1	31.6
Secchi depth (m)	42	0	0	0	–	–	0.25	0.40	0.53	0.60	0.80
Turbidity (NTRU)	47	0	0	0	–	–	3.9	6.9	9.4	14	29
Total suspended solids (mg/L)	47	21	44.7	6	15	75	<15	17	30	42	130
Ammonia, diss. (mg/L as N)	47	15	31.9	1	0.01	0.01	<0.01	<0.01	0.02	0.04	0.22
Ammonia + organic N, total (mg/L as N)	47	0	0	0	–	–	0.57	1.0	1.2	1.3	1.9
Nitrate + nitrite (mg/L as N)	47	34	72.3	3	0.01	0.04	<0.01	<0.01	<0.01	0.01	0.22
Phosphorus, total (mg/L as P)	47	0	0	0	–	–	0.028	0.047	0.053	0.061	0.089
Total nitrogen (mg/L as N)	47	0	0	0	–	–	0.57	1.06	1.20	1.32	1.90
Enterococci (MPN/100 mL)	46	25	54.3	2	10	100	<10	<10	<10	20	11,000
E. coli (MPN/100 mL)	46	32	69.6	2	10	100	<10	<10	<10	10	540
Chlorophyll *a* (µg/L)	15	0	0	0	–	–	11.2	14.5	21.2	35.5	53.9
Aluminum, diss. (µg/L)	47	29	61.7	11	6.0	24	<6.0	<6.0	7.7	12.9	299
Aluminum, total (µg/L)	47	0	0	0	–	–	28.8	63.5	158	327	736
Chromium, total (µg/L)	47	31	66.0	8	0.60	2.5	0.35	0.35	0.68	1.1	62.1
Copper, total (µg/L)	45	30	66.7	11	0.6	4.9	<0.6	0.7	0.9	1.6	17.8
Iron, diss. (µg/L)	47	29	61.7	11	4.0	40.0	<4.0	<4.0	11.9	19.8	306
Iron, total (µg/L)	47	0	0	0	–	–	86.1	164	238	444	1,400
Lead, diss. (µg/L)	47	35	74.5	11	0.040	1.50	<0.040	<0.040	<0.040	0.119	1.39
Lead, total (µg/L)	47	1	2.1	1	3.60	3.60	0.35	0.60	1.00	1.41	3.08
Manganese, diss. (µg/L)	47	3	6.4	2	1.20	2.00	<1.20	2.31	3.73	4.52	29.4
Manganese, total (µg/L)	47	0	0	0	–	–	10.5	19.8	30.6	53.3	77.9
Nickel, diss. (µg/L)	45	14	31.1	8	0.45	9.0	0.38	0.47	0.58	0.65	5.2
Nickel, total (µg/L)	45	22	48.9	10	0.38	1.6	<0.38	0.50	0.58	0.90	27.9
Arsenic, diss. (µg/L)	46	0	0	0	–	–	0.72	1.1	1.45	1.9	2.8

Table 9. Statistical summary of water-quality properties and constituents for sampling stations in Currituck Sound, North Carolina, 2011–18.—Continued

[mg/L, milligrams per liter; diss., dissolved; µg/L, micrograms per liter; %, percent; µS/cm @ 25 °C, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; m, meter; NTRU, nephelometric turbidity ratio units; diss., dissolved; N, nitrogen; P, phosphorus; MPN/100 mL, most probable number per 100 milliliters; –, not applicable]

Constituent or property name (unit)	Number of observations	Number censored	Percent censored	Number censoring levels	Minimum censor level	Maximum censor level	Minimum value	25th percentile	50th percentile (median)	75th percentile	Maximum value
Arsenic, total (µg/L)	46	0	0	0	--	–	1.2	1.4	1.8	2.2	4.1
Selenium, diss. (µg/L)	15	7	46.7	4	0.15	0.40	0.07	0.10	0.11	0.13	0.28
Selenium, total (µg/L)	15	7	46.7	3	0.1	0.4	<0.1	<0.1	0.1	0.1	0.25
Total cylindrospermopsins (µg/L)	15	9	60.0	1	0.05	0.05	<0.05	<0.05	<0.05	0.15	0.92
Total microcystins + nodularins (µg/L)	15	1	6.7	1	0.10	0.10	<0.10	0.13	0.31	1.00	1.80
Cylindrospermopsin (µg/L)	15	10	66.7	1	0.10	0.10	<0.10	<0.10	<0.10	0.25	0.63
Microcystin WR (µg/L)	15	14	93.3	1	0.30	0.30	<0.30	–	–	–	0.36
1.2-mile station											
Dissolved oxygen (mg/L)	49	0	0	0	–	–	7.2	8.7	9.3	11.3	12.6
Dissolved oxygen, % saturation	49	0	0	0	–	–	92	99	102	104	118
pH (standard units)	49	0	0	0	–	–	7.1	7.8	8.0	8.2	9.2
Specific conductance (µS/cm at 25 °C)	49	0	0	0	–	–	648	3,810	5,650	7,230	10,700
Temperature, water (°C)	49	0	0	0	–	–	5.8	10.0	18.3	24.2	29.9
Secchi depth (m)	46	0	0	0	–	–	0.24	0.40	0.53	0.60	0.80
Turbidity (NTRU)	50	0	0	0	–	–	5.2	7.7	11	19	37
Total suspended solids (mg/L)	50	14	28.0	5	15	60	<15	29	34	50	110
Ammonia, diss. (mg/L as N)	50	15	30.0	1	0.01	0.01	<0.01	<0.01	0.02	0.05	0.13
Ammonia + organic N, total (mg/L as N)	50	0	0	0	–	–	0.81	1.0	1.1	1.3	1.9
Nitrate + nitrite (mg/L as N)	50	32	64.0	3	0.01	0.04	<0.01	<0.01	<0.01	0.02	0.25
Phosphorus, total (mg/L as P)	50	0	0	0	–	–	0.028	0.040	0.047	0.057	0.090
Total nitrogen (mg/L as N)	50	0	0	0	–	–	0.82	1.04	1.17	1.34	1.90
Enterococci (MPN/100 mL)	46	31	67.4	2	10	100	<10	<10	<10	10	65
E. coli (MPN/100 mL)	46	37	80.4	2	10	100	<10	–	–	–	76
Aluminum, diss. (µg/L)	50	28	56.0	10	6.0	170	<6.0	<6.0	9.1	23.2	392
Aluminum, total (µg/L)	50	0	0	0	–	–	40.4	77.2	184	412	944
Chromium, total (µg/L)	50	29	58.0	9	0.90	5	0.70	0.72	0.85	1.5	42.7
Copper, total (µg/L)	47	33	70.2	10	0.8	7	0.7	0.8	1.1	1.7	4.6
Iron, diss. (µg/L)	50	28	56.0	11	4.0	60.0	<4.0	<4.0	12.2	22.5	407
Iron, total (µg/L)	50	0	0	0	–	–	104	169	284	618	1,200
Lead, diss. (µg/L)	50	36	72.0	12	0.040	1.50	<0.040	<0.040	0.049	0.084	1.42

Table 9. Statistical summary of water-quality properties and constituents for sampling stations in Currituck Sound, North Carolina, 2011–18.—Continued

[mg/L, milligrams per liter; diss., dissolved; µg/L, micrograms per liter; %, percent; µS/cm @ 25 °C, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; m, meter; NTRU, nephelometric turbidity ratio units; diss., dissolved; N, nitrogen; P, phosphorus; MPN/100 mL, most probable number per 100 milliliters; –, not applicable]

Constituent or property name (unit)	Number of observations	Number censored	Percent censored	Number censoring levels	Minimum censor level	Maximum censor level	Minimum value	25th percentile	50th percentile (median)	75th percentile	Maximum value
Lead, total (µg/L)	50	0	0	0	--	--	0.32	0.61	1.04	1.39	2.83
Manganese, diss. (µg/L)	50	8	16.0	5	0.80	13.0	<0.80	2.05	3.19	4.41	45.1
Manganese, total (µg/L)	50	0	0	0	--	--	11.3	17.8	36.8	55.6	90.7
Nickel, diss. (µg/L)	49	14	28.6	8	0.40	9.0	0.37	0.50	0.60	0.73	5.4
Nickel, total (µg/L)	49	23	46.9	10	0.38	2	<0.38	0.40	0.69	1.1	2.8
Arsenic, diss. (µg/L)	50	0	0	0	--	--	0.12	0.97	1.2	1.7	4.7
Arsenic, total (µg/L)	50	1	2.0	1	2.8	2.8	1.1	1.3	1.6	2.0	6.4
Selenium, diss. (µg/L)	17	9	52.9	5	0.10	0.45	0.07	0.10	0.10	0.12	0.29
Selenium, total (µg/L)	17	7	41.2	4	0.1	0.5	<0.1	0.1	0.1	0.1	0.35
2.1-mile station											
Dissolved oxygen (mg/L)	54	0	0	0	--	--	7.2	8.3	9.2	11.2	12.5
Dissolved oxygen, % saturation	54	0	0	0	--	--	92	99	102	104	113
pH (standard units)	54	0	0	0	--	--	7.1	7.7	8.0	8.2	9.1
Specific conductance (µS/cm at 25 °C)	54	0	0	0	--	--	750	3,858	5,805	7,085	10,500
Temperature, water (°C)	54	0	0	0	--	--	5.9	10.3	19.4	25.1	30.2
Secchi depth (m)	46	0	0	0	--	--	0.24	0.45	0.50	0.60	0.90
Turbidity (NTRU)	55	0	0	0	--	--	5.2	7.2	11	18	42
Total suspended solids (mg/L)	55	22	40.0	8	15	75	<15	23	32	52	120
Ammonia, diss. (mg/L as N)	55	16	29.1	1	0.01	0.01	<0.01	<0.01	0.01	0.04	0.10
Ammonia + organic N, total (mg/L as N)	55	0	0	0	--	--	0.58	0.95	1.1	1.3	1.9
Nitrate + nitrite (mg/L as N)	55	40	72.7	3	0.01	0.04	<0.01	<0.01	<0.01	0.01	0.25
Phosphorus, total (mg/L as P)	55	0	0	0	--	--	0.027	0.040	0.050	0.064	0.094
Total nitrogen (mg/L as N)	55	0	0	0	--	--	0.58	0.97	1.14	1.30	1.90
Enterococci (MPN/100 mL)	46	32	69.6	2	10	100	<10	<10	<10	10	65
E. coli (MPN/100 mL)	46	34	73.9	2	10	100	<10	<10	<10	10	71
Chlorophyll *a* (µg/L)	15	0	0	0	--	--	14.1	19.9	21.4	36.4	70.3
Aluminum, diss. (µg/L)	55	31	56.4	12	6.0	170	<6.0	<6.0	7.9	16.3	180
Aluminum, total (µg/L)	55	1	1.8	1	95	95	41.2	87.1	183	418	887
Chromium, total (µg/L)	55	30	54.5	7	0.90	2.5	0.70	0.70	0.93	1.4	60.8
Copper, total (µg/L)	54	35	64.8	10	0.8	4.2	0.6	0.7	1.0	1.5	3.95

Table 9. Statistical summary of water-quality properties and constituents for sampling stations in Currituck Sound, North Carolina, 2011–18.—Continued

[mg/L, milligrams per liter; diss., dissolved; µg/L, micrograms per liter; %, percent; µS/cm @ 25 °C, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; m, meter; NTRU, nephelometric turbidity ratio units; diss., dissolved; N, nitrogen; P, phosphorus; MPN/100 mL, most probable number per 100 milliliters; –, not applicable]

Constituent or property name (unit)	Number of observations	Number censored	Percent censored	Number censoring levels	Minimum censor level	Maximum censor level	Minimum value	25th percentile	50th percentile (median)	75th percentile	Maximum value
Iron, diss. (µg/L)	55	36	65.5	11	4.0	60.0	<4.0	<4.0	6.4	14.9	342
Iron, total (µg/L)	55	0	0	0	--	--	101	182	318	588	1,240
Lead, diss. (µg/L)	55	42	76.4	12	0.040	1.50	<0.040	--	--	--	1.59
Lead, total (µg/L)	55	2	3.6	2	1.00	3.60	0.30	0.53	0.99	1.53	3.47
Manganese, diss. (µg/L)	55	10	18.2	6	0.80	13.0	<0.80	1.41	2.57	3.35	11.7
Manganese, total (µg/L)	55	0	0	0	–	–	10.0	21.7	38.0	54.2	89.4
Nickel, diss. (µg/L)	54	13	24.1	8	0.40	9.0	0.33	0.48	0.58	0.77	5.4
Nickel, total (µg/L)	54	20	37.0	8	0.40	12	<0.40	0.40	0.75	0.98	16.9
Arsenic, diss. (µg/L)	55	1	1.8	1	2.2	2.2	0.79	1.0	1.2	1.5	2.1
Arsenic, total (µg/L)	55	1	1.8	1	1.1	1.1	1.0	1.3	1.6	2.0	4.4
Selenium, diss. (µg/L)	20	11	55.0	5	0.10	0.45	<0.10	0.10	0.11	0.11	0.29
Selenium, total (µg/L)	20	6	30.0	3	0.1	0.3	<0.1	0.1	0.1	0.1	0.25
Total cylindrospermopsins (µg/L)	15	7	46.7	1	0.05	0.05	<0.05	<0.05	0.07	0.12	0.94
Total microcystins + nodularins (µg/L)	15	3	20.0	1	0.10	0.10	<0.10	0.20	0.39	1.70	2.20
Cylindrospermopsin (µg/L)	15	11	73.3	1	0.10	0.10	<0.10	<0.10	<0.10	0.11	1.2
Microcystin WR (µg/L)	15	11	73.3	1	0.30	0.30	0.35	<0.30	<0.30	0.35	0.45
3.5-mile station											
Dissolved oxygen (mg/L)	85	0	0	0	–	–	7.0	8.4	9.2	11.2	12.6
Dissolved oxygen, % saturation	85	0	0	0	–	–	84	97	100	104	116
pH (standard units)	85	0	0	0	–	–	7.1	7.7	8.0	8.2	9.0
Specific conductance (µS/cm at 25 °C)	85	0	0	0	–	–	723	3,940	5,700	7,190	9,730
Temperature, water (°C)	85	0	0	0	–	–	5.9	9.9	18.2	24.8	30.0
Secchi depth (m)	45	0	0	0	–	–	0.20	0.40	0.50	0.60	0.80
Turbidity (NTRU)	85	0	0	0	–	–	4.3	7.7	9.9	16	48
Total suspended solids (mg/L)	85	30	35.3	10	15	75	<15	20	34	48	108
Ammonia, diss. (mg/L as N)	85	37	43.5	1	0.01	0.01	<0.01	<0.01	0.01	0.02	0.09
Ammonia + organic N, total (mg/L as N)	85	0	0	0	–	–	0.52	0.95	1.2	1.4	1.8
Nitrate + nitrite (mg/L as N)	85	60	70.6	3	0.01	0.04	<0.01	<0.01	<0.01	0.02	0.64
Phosphorus, total (mg/L as P)	85	0	0	0	–	–	0.027	0.040	0.048	0.059	0.115
Total nitrogen (mg/L as N)	85	0	0	0	–	–	0.53	0.97	1.20	1.40	1.82
Enterococci (MPN/100 mL)	45	31	68.9	2	10	100	<10	<10	<10	10	180

Table 9. Statistical summary of water-quality properties and constituents for sampling stations in Currituck Sound, North Carolina, 2011–18.—Continued

[mg/L, milligrams per liter; diss., dissolved; µg/L, micrograms per liter; %, percent; µS/cm @ 25 °C, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; m, meter; NTRU, nephelometric turbidity ratio units; diss., dissolved; N, nitrogen; P, phosphorus; MPN/100 mL, most probable number per 100 milliliters; –, not applicable]

Constituent or property name (unit)	Number of observations	Number censored	Percent censored	Number censoring levels	Minimum censor level	Maximum censor level	Minimum value	25th percentile	50th percentile (median)	75th percentile	Maximum value
E. coli (MPN/100 mL)	45	38	84.4	2	10	100	<10	–	–	–	55
Chlorophyll *a* (µg/L)	9	0	0	0	–	–	7.0	10.2	21.2	26.6	38.9
Aluminum, diss. (µg/L)	85	48	56.5	11	6.0	27	<6.0	<6.0	6.6	15.4	159
Aluminum, total (µg/L)	85	0	0	0	–	–	37.7	85.3	159	328	1,150
Chromium, total (µg/L)	85	55	64.7	11	0.60	2.5	<0.60	0.70	0.70	1.1	8.3
Copper, total (µg/L)	85	54	63.5	12	0.8	7	0.6	0.7	1.1	1.7	390
Iron, diss. (µg/L)	85	52	61.2	12	3.2	50.0	<3.2	<3.2	7.1	19.9	309
Iron, total (µg/L)	85	0	0	0	–	–	91.0	183	272	546	1,620
Lead, diss. (µg/L)	85	64	75.3	11	0.040	0.200	<0.040	–	–	–	0.740
Lead, total (µg/L)	85	0	0	0	–	–	0.33	0.59	1.01	1.34	3.73
Manganese, diss. (µg/L)	85	12	14.1	5	0.80	3.60	<0.80	1.57	2.69	4.04	39.4
Manganese, total (µg/L)	85	0	0	0	–	–	10.5	17.3	35.4	55.9	86.5
Nickel, diss. (µg/L)	82	25	30.5	7	0.40	1.8	0.34	0.46	0.55	0.68	1.6
Nickel, total (µg/L)	82	41	50.0	11	0.40	1.9	<0.40	0.50	0.69	0.84	2.5
Arsenic, diss. (µg/L)	85	1	1.2	1	0.45	0.45	<0.45	1.0	1.2	1.5	2.7
Arsenic, total (µg/L)	85	2	2.4	2	1.7	2.2	0.96	1.2	1.5	1.9	4.5
Selenium, diss. (µg/L)	29	15	51.7	5	0.10	0.45	0.09	0.10	0.11	0.13	0.30
Selenium, total (µg/L)	29	11	37.9	3	0.1	0.3	<0.1	0.1	0.1	0.1	0.25
4.5-mile station											
Dissolved oxygen (mg/L)	47	0	0	0	–	–	6.8	8.5	9.5	11.4	12.4
Dissolved oxygen, % saturation	47	0	0	0	–	–	91	97	101	106	115
pH (standard units)	47	0	0	0	–	–	7.1	7.8	8.0	8.2	9.0
Specific conductance (µS/cm at 25 °C)	47	0	0	0	–	–	822	3,860	5,710	6,980	10,800
Temperature, water (°C)	47	0	0	0	–	–	6.1	9.7	18.1	24.4	30.2
Secchi depth (m)	45	0	0	0	–	–	0.25	0.40	0.50	0.60	1.00
Turbidity (NTRU)	47	0	0	0	–	–	4.0	7.7	9.4	14	36
Total suspended solids (mg/L)	47	18	38.3	7	25	75	15	20	29	42	94
Ammonia, diss. (mg/L as N)	47	16	34.0	1	0.01	0.01	<0.01	<0.01	0.01	0.02	0.09
Ammonia + organic N, total (mg/L as N)	47	0	0	0	–	–	0.5	0.98	1.2	1.4	1.9
Nitrate + nitrite (mg/L as N)	47	34	72.3	3	0.01	0.04	<0.01	<0.01	<0.01	0.01	0.19
Phosphorus, total (mg/L as P)	47	0	0	0	–	–	0.028	0.040	0.046	0.057	0.100

Table 9. Statistical summary of water-quality properties and constituents for sampling stations in Currituck Sound, North Carolina, 2011–18.—Continued

[mg/L, milligrams per liter; diss., dissolved; µg/L, micrograms per liter; %, percent; µS/cm @ 25 °C, microsiemens per centimeter at 25 degrees Celsius; °C, degrees Celsius; m, meter; NTRU, nephelometric turbidity ratio units; diss., dissolved; N, nitrogen; P, phosphorus; MPN/100 mL, most probable number per 100 milliliters; –, not applicable]

Constituent or property name (unit)	Number of observations	Number censored	Percent censored	Number censoring levels	Minimum censor level	Maximum censor level	Minimum value	25th percentile	50th percentile (median)	75th percentile	Maximum value
Total nitrogen (mg/L as N)	47	0	0	0	–	–	0.51	1.01	1.20	1.41	1.92
Enterococci (MPN/100 mL)	45	24	53.3	2	10	100	<10	<10	<10	10	160
E. coli (MPN/100 mL)	45	33	73.3	2	10	100	<10	<10	<10	10	71
Chlorophyll *a* (µg/L)	15	0	0	0	–	–	13.5	18.2	22.4	38.0	71.4
Aluminum, diss. (µg/L)	47	24	51.1	10	6.6	170	<6.6	6.7	8.1	14.5	142
Aluminum, total (µg/L)	47	0	0	0	–	–	33.9	78.6	143	288	852
Chromium, total (µg/L)	47	31	66.0	9	0.60	2.5	<0.60	<0.6	0.78	0.94	27.3
Copper, total (µg/L)	47	34	72.3	10	0.6	4.2	<0.6	0.7	0.8	1.2	3.05
Iron, diss. (µg/L)	47	28	59.6	10	4.0	40.0	<4.0	<4.0	6.2	21.1	273
Iron, total (µg/L)	47	0	0	0	–	–	87.2	172	269	406	1,150
Lead, diss. (µg/L)	47	38	80.9	12	0.040	1.50	<0.040	–	–	–	1.03
Lead, total (µg/L)	47	1	2.1	1	1.00	1.00	0.28	0.61	0.93	1.25	2.43
Manganese, diss. (µg/L)	47	6	12.8	5	0.80	13.0	<0.80	2.39	3.00	3.69	16.5
Manganese, total (µg/L)	47	0	0	0	–	–	10.2	18.2	36.5	58.8	104
Nickel, diss. (µg/L)	44	11	25.0	7	0.40	9.0	0.35	0.49	0.57	0.66	5.3
Nickel, total (µg/L)	44	21	47.7	6	0.40	1.1	<0.40	0.50	0.64	0.78	2.7
Arsenic, diss. (µg/L)	47	1	2.1	1	2.2	2.2	0.68	1.0	1.3	1.6	2.6
Arsenic, total (µg/L)	47	1	2.1	1	2.8	2.8	0.94	1.3	1.6	2.0	2.75
Selenium, diss. (µg/L)	15	8	53.3	5	0.10	0.40	0.07	0.09	0.11	0.12	0.27
Selenium, total (µg/L)	15	3	20.0	2	0.1	0.2	<0.1	0.1	0.1	0.1	0.20
Total cylindrospermopsins (µg/L)	15	7	46.7	1	0.05	0.05	<0.05	<0.05	0.06	0.18	1.10
Total microcystins + nodularins (µg/L)	15	1	6.7	1	0.10	0.10	<0.10	0.16	0.55	1.80	3.20
Cylindrospermopsin (µg/L)	15	12	80.0	1	0.10	0.10	<0.10	–	–	–	1.1
Microcystin WR (µg/L)	15	9	60.0	1	0.30	0.30	0.38	<0.30	<0.30	0.40	0.48

Table 10. Summary results of the nonparametric Kruskal-Wallis tests on the ranked values of selected physical property measurements, chemical-constituent concentrations, and phytoplankton group densities between sampling events and among sampling sites and seasons for Currituck Sound, North Carolina, 2011–18.

[The null hypothesis was that the mean ranks of each distribution were the same. *, indicates signficant difference (P<0.05); –, not analyzed]

Chemical constituent or property	Kruskal-Wallis test for sampling event type	Kruskal-Wallis test for sampling sites	Kruskal-Wallis test for sampling seasons
	P-value	P-value	P-value
Physical property or chemical constituent			
Temperature, water	0.208	0.994	<0.001*
Dissolved oxygen	0.934	0.904	<0.001*
pH	0.255	0.964	<0.001*
Specific conductance, field	0.002*	0.999	<0.001*
Turbidity, unfiltered	0.001*	0.599	<0.001*
Ammonia plus organic nitrogen, unfiltered	0.061	0.957	<0.001*
Total nitrogen, computed	0.054	0.937	<0.001*
Phosphorus, unfiltered	0.007*	0.151	<0.001*
Aluminum, unfiltered recoverable	0.018*	0.390	<0.001*
Arsenic, unfiltered	0.029*	0.272	<0.001*
Iron, unfiltered recoverable	0.062	0.521	<0.001*
Lead, unfiltered recoverable	0.010*	0.705	<0.001*
Manganese, unfiltered recoverable	0.501	0.950	<0.001*
Chlorophyll *a*	–	0.437	<0.001*
Total cylindrospermopsins	–	0.919	<0.001*
Total microcystins plus nodularins	–	0.541	<0.001*
Phytoplankton group			
Total cyanobacteria	–	0.799	<0.001*
Total diatoms	–	0.473	0.660
Total green algae	–	0.666	0.078
Total cryptophytes	–	0.499	0.001*

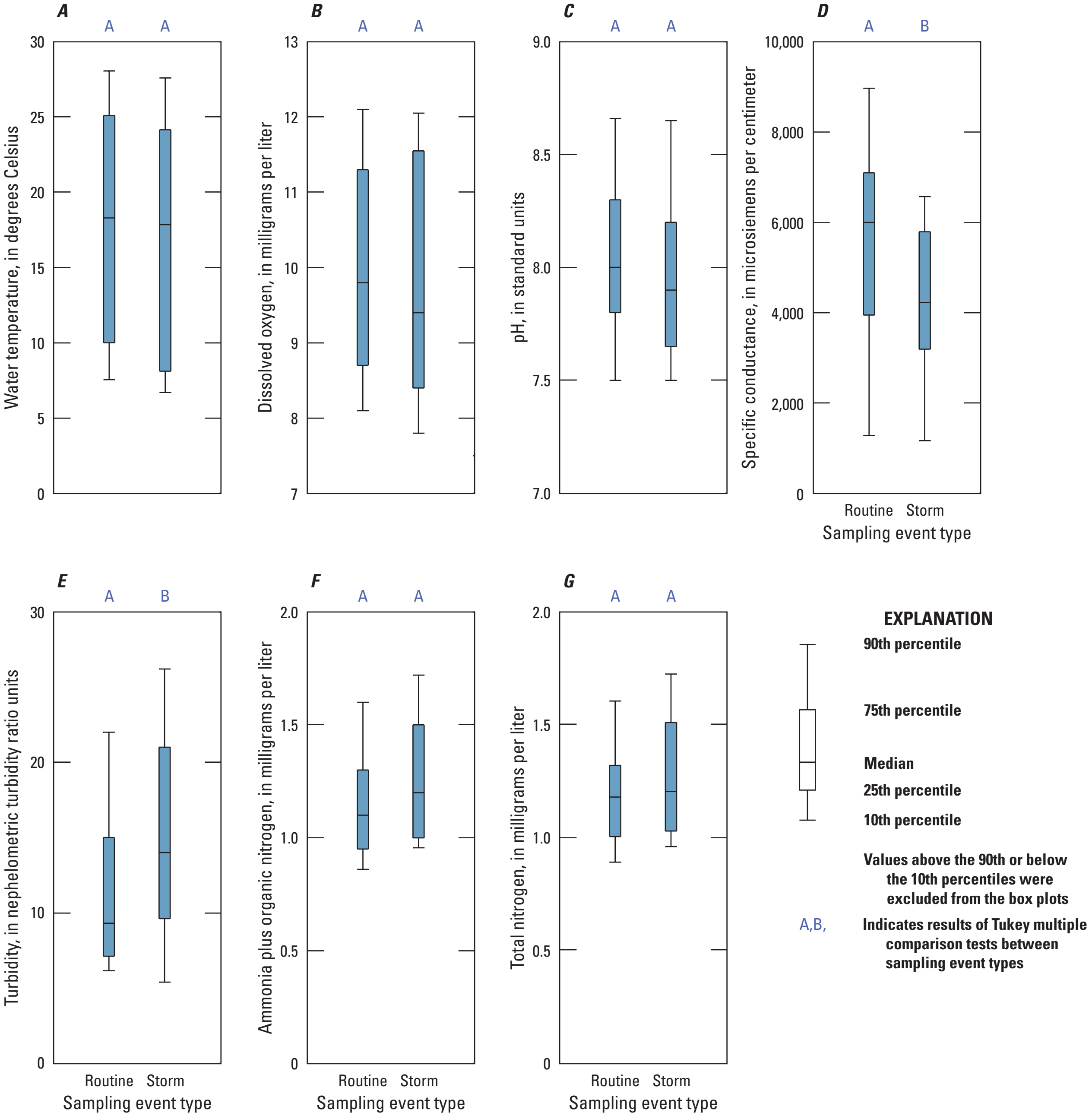

Figure 2. Plots showing distributions of (*A*) water temperature, (*B*) dissolved oxygen, (*C*) pH, (*D*) specific conductance, (*E*) turbidity, (*F*) ammonia plus organic nitrogen, (*G*) total nitrogen, (*H*) total phosphorus, (*I*) total aluminum, (*J*) total arsenic, (*K*) total iron, (*L*) total lead, and (*M*) total manganese for top depth samples at all study sites based on sampling event type. For a given constituent, if a sampling event type contains the same letter above it as another sampling event type, Kruskal Wallis and Tukey tests did not identify a statistical difference between them at the 95 percent confidence level.

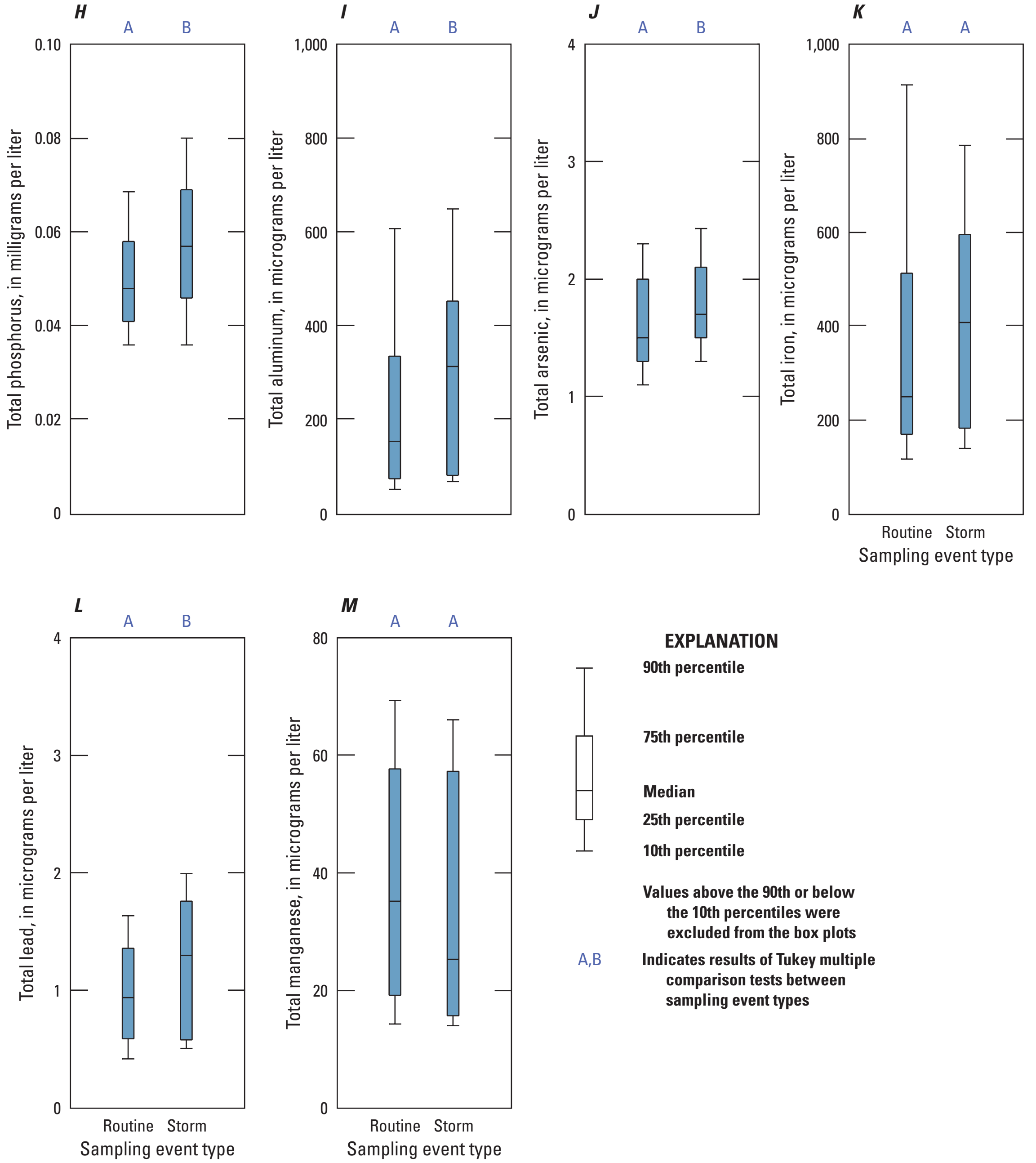

Figure 2. Plots showing distributions of (*A*) water temperature, (*B*) dissolved oxygen, (*C*) pH, (*D*) specific conductance, (*E*) turbidity, (*F*) ammonia plus organic nitrogen, (*G*) total nitrogen, (*H*) total phosphorus, (*I*) total aluminum, (*J*) total arsenic, (*K*) total iron, (*L*) total lead, and (*M*) total manganese for top depth samples at all study sites based on sampling event type. For a given constituent, if a sampling event type contains the same letter above it as another sampling event type, Kruskal Wallis and Tukey tests did not identify a statistical difference between them at the 95 percent confidence level.—Continued

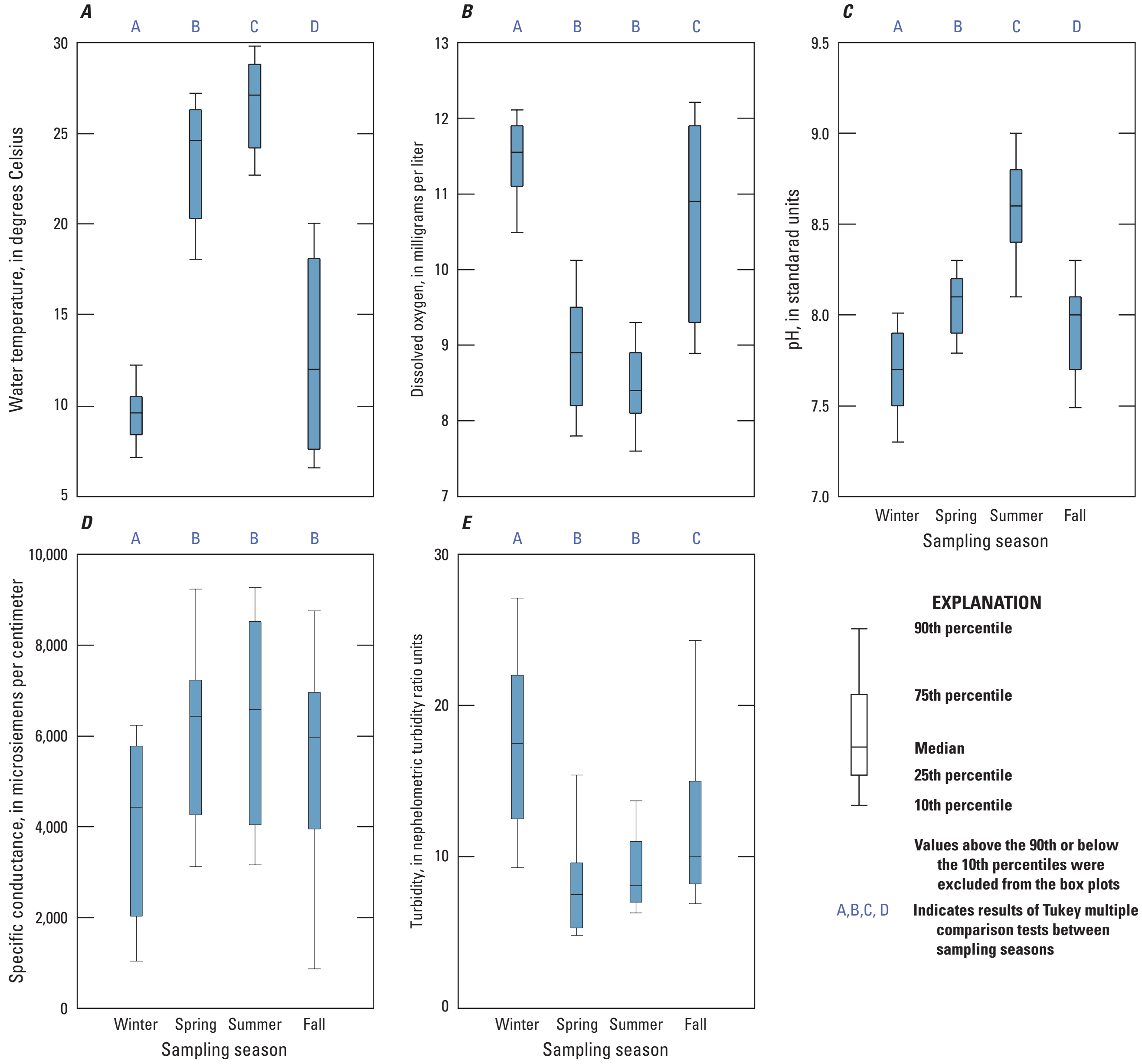

Figure 3. Plots showing distributions of (*A*) water temperature, (*B*) dissolved oxygen, (*C*) pH, (*D*) specific conductance, (*E*) turbidity, (*F*) ammonia plus organic nitrogen, (*G*) total nitrogen, (*H*) total phosphorus, (*I*) total aluminum, (*J*) total arsenic, (*K*) total iron, (*L*) total lead, (*M*) total manganese, (*N*) chlorophyll *a*, (*O*) total cylindrospermopsins, and (*P*) total microcystins plus nodularins for all study sites based on sampling season. For a given constituent, if a sampling season contains the same letter above it as another sampling season, Kruskal Wallis and Tukey tests did not identify a statistical difference between them at the 95 percent confidence level.

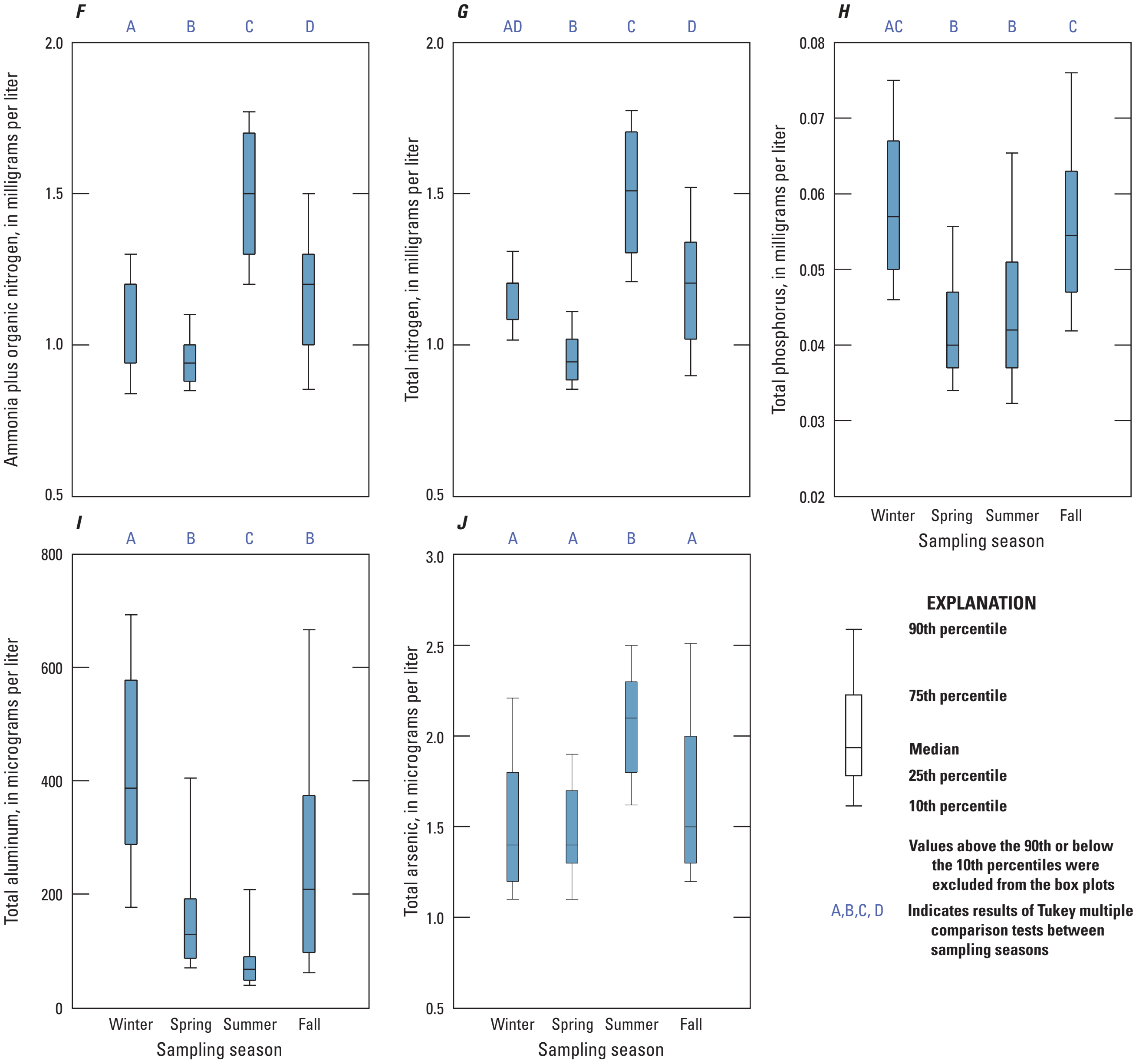

Figure 3. Plots showing distributions of (*A*) water temperature, (*B*) dissolved oxygen, (*C*) pH, (*D*) specific conductance, (*E*) turbidity, (*F*) ammonia plus organic nitrogen, (*G*) total nitrogen, (*H*) total phosphorus, (*I*) total aluminum, (*J*) total arsenic, (*K*) total iron, (*L*) total lead, (*M*) total manganese, (*N*) chlorophyll *a*, (*O*) total cylindrospermopsins, and (*P*) total microcystins plus nodularins for all study sites based on sampling season. For a given constituent, if a sampling season contains the same letter above it as another sampling season, Kruskal Wallis and Tukey tests did not identify a statistical difference between them at the 95 percent confidence level.—Continued

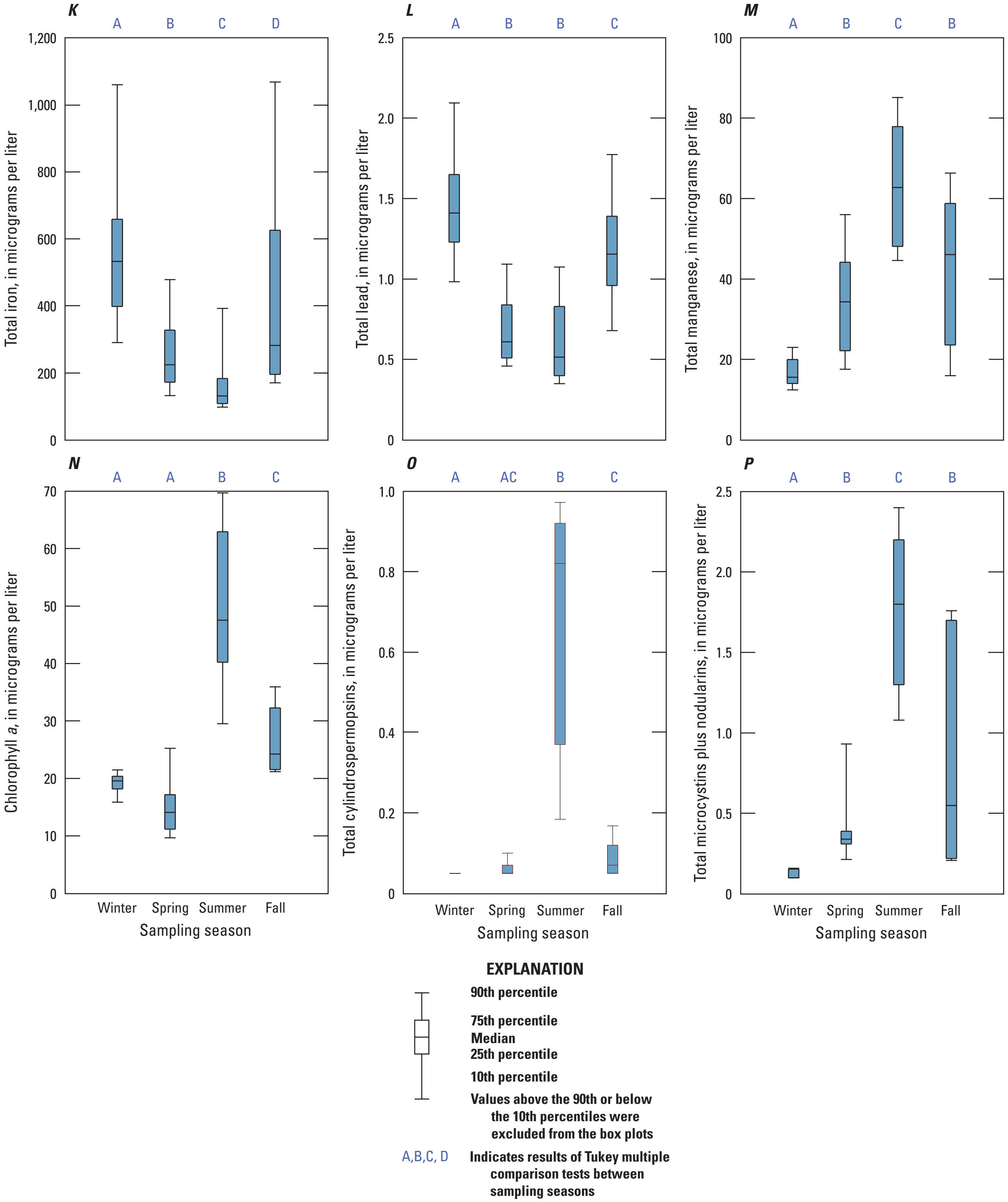

Figure 3. Plots showing distributions of (*A*) water temperature, (*B*) dissolved oxygen, (*C*) pH, (*D*) specific conductance, (*E*) turbidity, (*F*) ammonia plus organic nitrogen, (*G*) total nitrogen, (*H*) total phosphorus, (*I*) total aluminum, (*J*) total arsenic, (*K*) total iron, (*L*) total lead, (*M*) total manganese, (*N*) chlorophyll *a*, (*O*) total cylindrospermopsins, and (*P*) total microcystins plus nodularins for all study sites based on sampling season. For a given constituent, if a sampling season contains the same letter above it as another sampling season, Kruskal Wallis and Tukey tests did not identify a statistical difference between them at the 95 percent confidence level.—Continued

Phytoplankton Taxonomic Data

In a recent study of water quality in Albemarle Sound, chlorophyll *a* concentrations exceeded the water-quality threshold of 40 µg/L, and cyanobacterial densities exceeded recreational health alert levels, particularly in Currituck Sound (Moorman and others, 2016). Chlorophyll *a* is a measurement of the main photosynthetic pigment found in plants and algae and is typically used as an estimate of the total phytoplankton biomass (Boyer and others, 2009). Elevated levels of chlorophyll *a* are a sign of eutrophication and can result from nutrient enrichment (Bricker and others, 2007). Cyanobacteria are commonly associated with harmful algal blooms, which can cause a multitude of water-quality concerns and have the potential to produce the cyanotoxins implicated in human and animal illnesses and death (Graham, 2007). Cyanobacteria accounted for 97 percent of the community when phytoplankton densities were greater than 100,000 cells/mL in the Albemarle Sound study (Moorman and others, 2016). Because cyanotoxins are an emerging water-quality concern in the Albemarle Sound region, particularly the Currituck Sound, water samples were collected during field period 2 of this study (including the 0.25-mi, 2.1-mi, and 4.5-mi stations) for an analysis of phytoplankton taxonomy, as well as chlorophyll *a* and cyanotoxin concentrations.

As is noted for the water-quality properties and constituents, no statistically significant differences among sampling sites (n=3) were identified for any of the primary phytoplankton groups—total cyanobacteria, total diatoms, total green algae, and total cryptophytes—based on the KW test evaluations (table 10). However, KW tests identified significant differences among seasons for two of the phytoplankton groups (table 10). Distributions, by sampling season, of the original (nonranked transformed) data for the phytoplankton group densities are displayed in figure 4. Tukey test results indicated that cyanobacteria densities were highest in the summer, intermediate during the spring and fall, and lowest during the winter (fig. 4*A*). Total cryptophyte densities were higher in the winter than they were during the spring through fall period (fig. 4*D*). No significant differences were noted among seasons for the total diatom and total green algae densities (figs 4*B* and 4*C*, respectively).

The mean densities, by sampling event, of the total phytoplankton, total cyanobacteria, total diatoms, total green algae, and total cryptophytes are displayed together in figure 5 to highlight the temporal variability in the phytoplankton community during field period 2. Total phytoplankton densities increased from June through August 2017 and remained relatively high through December 2017. Cyanobacteria were the most abundant group from May through December 2017, then decreased in January 2018 to levels like those noted during fall 2016 and winter 2017. A mix of diatoms, green algae, and cryptophytes accounted for most of the remaining phytoplankton.

Although multiple genera of potential toxin-producing cyanobacteria (Graham and others, 2010; Loftin and others, 2016b; Paerl and others, 2016) were identified in phytoplankton samples collected during the study (Cain and others, 2020), three species capable of producing toxins dominated the cyanobacteria community: *Cylindrospermopsis raciborskii* (*C. raciborskii*), *Planktolyngbya limnetica*, and *Planktolyngbya* cf. *contorta*. As previously discussed, *Planktolyngbya* cf. *contorta* represents a combined grouping of several coiled organisms (*Planktolyngbya contorta*, *Pseudanabaena contorta*, and *Dactylococcopsis irregularis*) identified within the cyanobacteria group for this study (Cain and others, 2020). Trends in the densities of the three cyanobacteria were like those for chlorophyll *a* and two of the cyanotoxin classes (total cylindrospermopsins and total microcystins plus nodularins) analyzed by ELISA (fig. 6). The densities of these three species rapidly increased between May and June, reached peak levels in August, and then declined in November and December before dropping below pre-June levels (fig. 6*A*). Chlorophyll *a* concentrations increased in early summer, peaked in August, and then slowly waned through the fall (fig. 6*B*). Average chlorophyll *a* concentrations exceeded the water-quality threshold of 40 µg/L (table 8) between July and September.

By September, *C. raciborskii* had formed akinetes, or "over-wintering" cells, although a few complete filaments were observed in the December 2017 samples.[2] *C. raciborskii* was absent from the samples collected between December 2016 and March 2017; *Planktolyngbya limnetica* and *Planktolyngbya* cf. *contorta* were absent from the February and March 2017 samples (fig. 6*A*). Among these three organisms, only *C. raciborskii* can fix N and synthesize the toxins detected during the study. For the cyanotoxins, trends in the total concentrations of cylindrospermopsins and microcystins plus nodularins (fig. 6*B*) were similar to those for the cyanobacteria (fig. 6*A*), with the highest concentrations typically occurring in the summer when the abundance of cyanobacteria was also high. No concentrations of cylindrospermopsins or microcystins plus nodularins in samples collected during field period 2 exceeded the recommended water-quality thresholds (table 8).

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[2] *C. raciborskii* is a tropical species expanding into nutrient-replete, hyposaline environments in the temperate zone worldwide (Calandrino and Paerl, 2011).

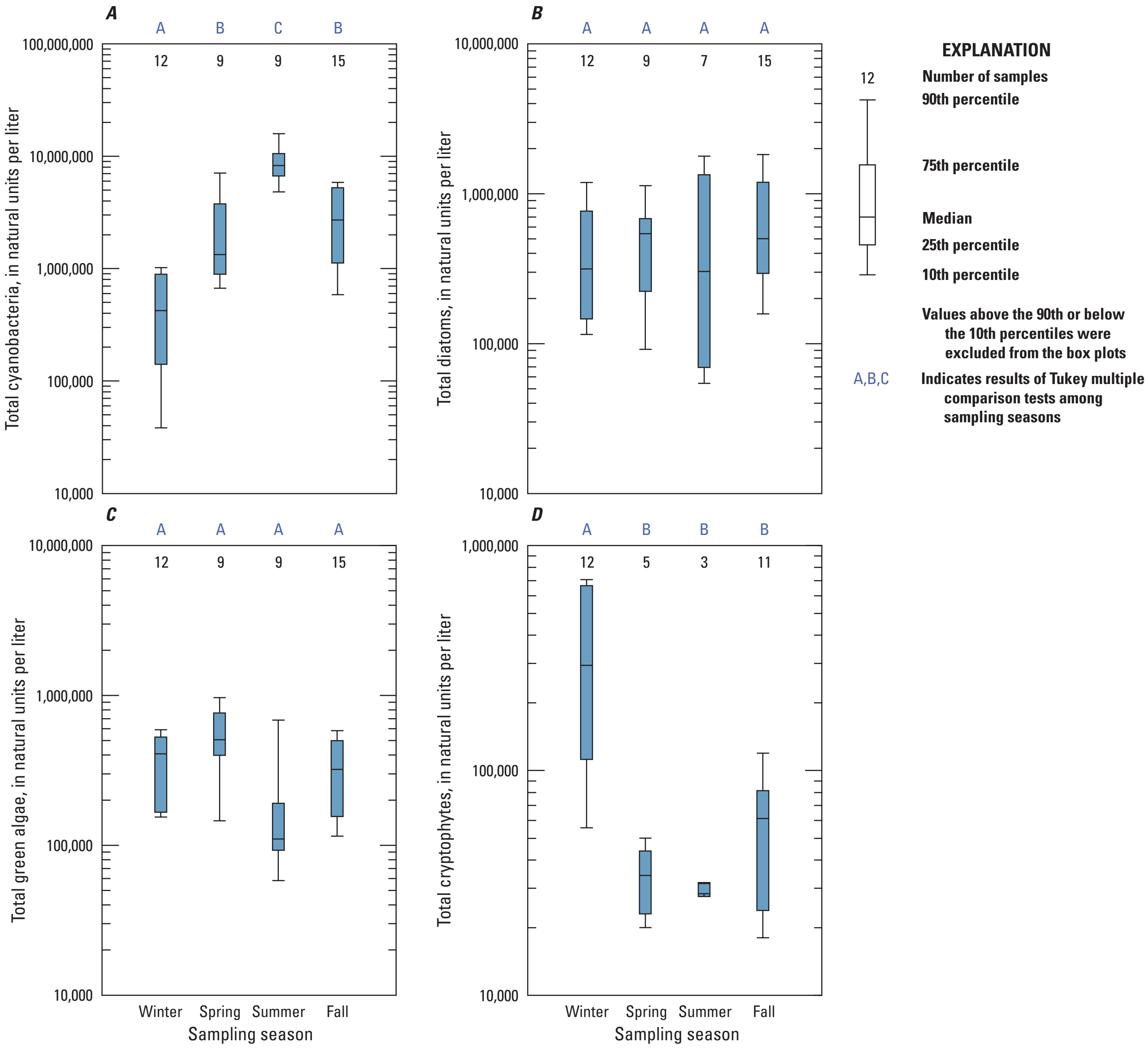

Figure 4. Plots showing distributions of phytoplankton density for four taxonomic groups—(*A*) total cyanobacteria, (*B*) total diatoms, (*C*) total green algae, and (*D*) total-cryptophytes—for three study sites based on sampling season. For a given phytoplankton group, if a sampling season contains the same letter above it as another sampling season, Kruskal Wallis and Tukey tests did not identify a statistical difference between them at the 95 percent confidence level.

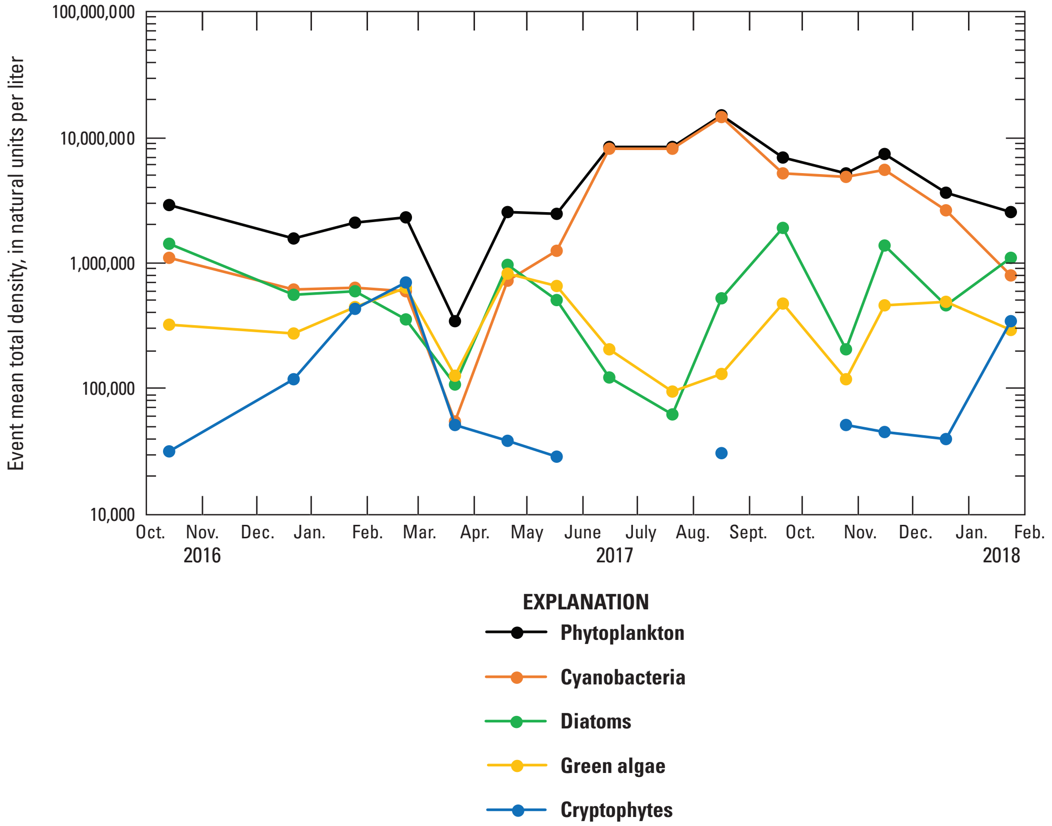

Figure 5. Graph showing mean total densities of the primary phytoplankton groups for sampling events during field period 2 in Currituck Sound, North Carolina, October 2016–January 2018.

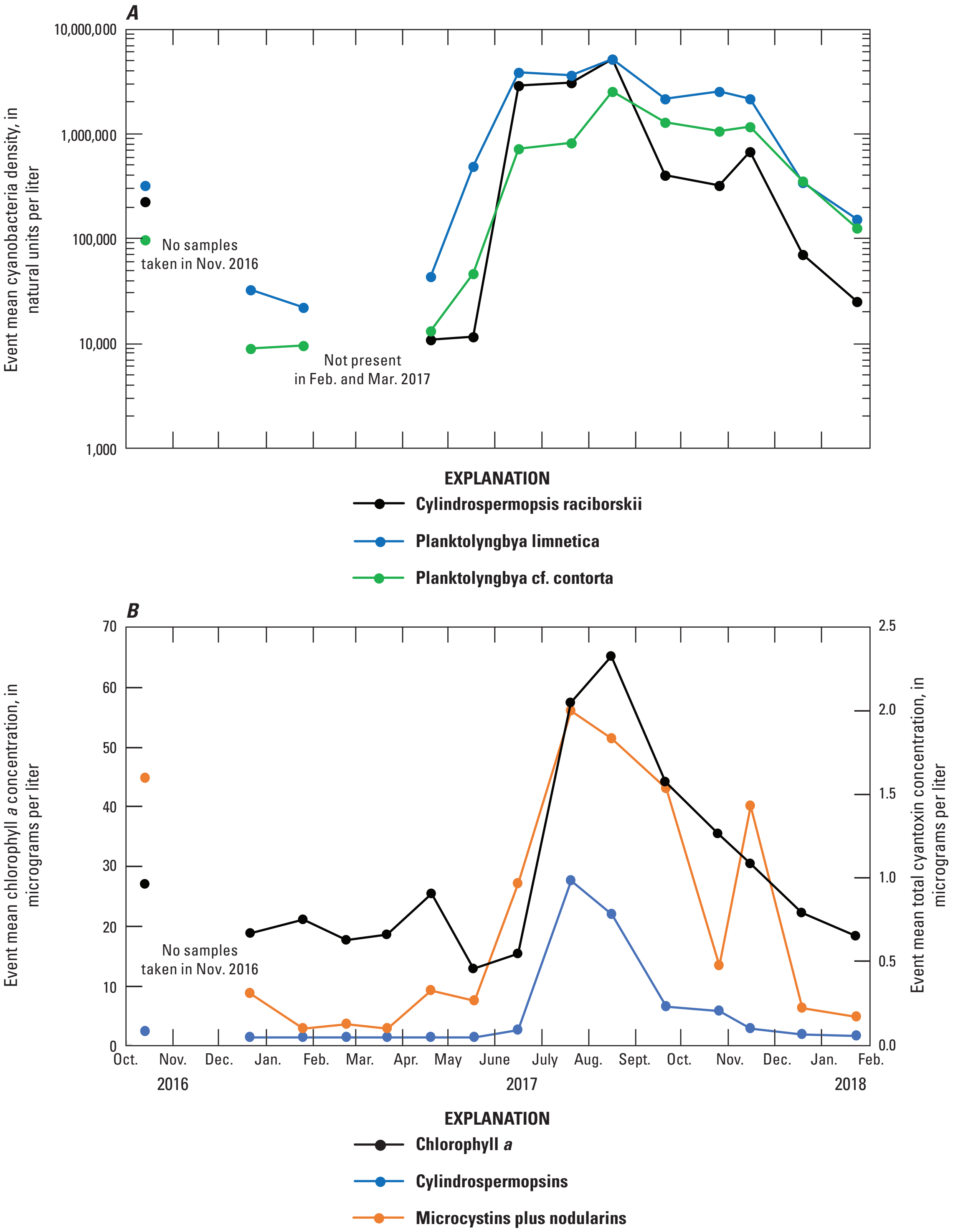

Figure 6. Graphs showing mean of (*A*) cyanobacteria density and (*B*) chlorophyll *a* and total cyanotoxin concentrations for sampling events during field period 2 in Currituck Sound, North Carolina, October 2016–January 2018. The results for *Planktolyngbya* cf. *contorta* represent the combined densities for *Planktolyngbya contorta*, *Pseudanabaena contorta*, and *Dactylococcopsis irregularis*.

Correlation of Wind Speed and Direction to Water Quality

Given that the most appreciable changes in water quality were hypothesized to probably occur during wind events (Caldwell, 2001; Fine, 2008), summary statistics were compiled for gage height (or water level) during sampling and wind speed and direction data for the 24- and 72-hour periods before water-quality sampling (table 11), which can be used for correlation with water-quality conditions. The water-level data and wind speed-direction data were compiled from the USGS gaging station (02043433) and the USGS meteorological station (362228075500401), respectively, located on the east bank of Currituck Sound near Corolla, North Carolina (fig. 1). An initial graphical review of the wind data did not indicate an apparent relation between wind speeds and wind directions. Examination of the median 24-hour and 72-hour antecedent wind directions indicated that the most common wind direction leading up to the sampling events was from the southwest, followed by the northeast and southeast. Southwestern winds were most common during spring through fall and northeastern winds were most common in fall and winter.

The median 72-hour wind directions were compared with the mean gage height, specific conductance, and turbidity data for the sampling events (fig. 7) to examine potential relations between wind direction and water-quality conditions in Currituck Sound. Winds from a more northerly direction tended to push water out of the Sound, thereby decreasing water levels (fig. 7*A*) and conductivity-salinity (fig. 7*B*). Winds from a more southerly direction tended to push water up into the Sound, thereby increasing water levels (fig. 7*A*) and conductivity-salinity (fig. 7*B*). In contrast, mean turbidity concentrations (fig. 7*C*) tended to be higher during the more brackish conditions at lower water levels and lower during the more saline conditions at higher water levels.

It is likely that higher turbidity levels reflect the increased resuspension of bottom materials from higher wave action during periods of shallower water depths. The wind-driven effects on turbidity levels are also reflected in particle-reactive constituents, as illustrated by the comparisons of turbidity to total P (fig. 8*A*), total iron (fig. 8*B*), and total lead (fig. 8*C*). Positive linear relations are noted among the constituents where increases in turbidity concentrations had corresponding increases in the total P, total iron, and total lead concentrations. The study results indicate that wind conditions are an important, influential factor on hydrologic and water-quality conditions in Currituck Sound.

Table 11. Summary statistics of gage height during sampling, and wind speed and direction 24 and 72 hours prior to water-quality sampling events in Currituck Sound, North Carolina, 2011–18.

[mph, mile per hour; h, hour; std dev, standard deviation; deg, degrees; —, no data available; S, south; W, west; N, north; E, east; SW, southwest; SE, southeast, NE, northeast; NW, northwest]

Sample date	Median sample time	Sampling event type	Season	Mean gage height (feet)	24-h antecedent wind speed (mph)			72-h antecedent wind speed (mph)			24-h antecedent wind direction			72-h antecedent wind direction		
					Mean	Median	Std dev	Mean	Median	Std dev	Mean	Median	Std dev (deg. from 0, N)	Mean	Median	Std dev (deg. from 0, N)
08/30/11	1215	Storm	Summer	0.77	—	—	—	—	—	—	—	—	—	—	—	—
09/28/11	1145	Routine	Summer	0.97	7.95	7.90	3.45	—	—	—	SSW	S	32.18	—	—	—
10/18/11	1120	Routine	Fall	0.79	11.33	11.40	2.97	13.59	13.10	4.96	SW	SW	24.14	WSW	SW	35.95
11/15/11	1015	Routine	Fall	0.40	15.52	15.35	2.73	13.36	13.30	3.23	SW	SW	13.19	SW	SW	13.54
12/20/11	0955	Routine	Fall	0.06	11.95	12.15	2.31	10.57	11.50	3.85	SW	SW	25.28	SSE	SW	128.91
01/24/12	1200	Routine	Winter	−0.14	8.46	8.40	3.14	11.83	12.00	4.84	SSW	SW	46.74	ESE	NE	121.20
02/22/12	1245	Routine	Winter	−0.13	10.55	11.30	3.13	13.46	12.20	7.53	SW	SW	38.12	ESE	NE	115.36
03/06/12	1315	Storm	Winter	−0.57	16.54	15.80	5.54	14.05	14.20	5.71	E	N	139.83	SSE	SW	129.86
03/21/12	1115	Routine	Winter	−0.01	8.42	8.50	2.76	6.89	6.50	3.41	SSE	SE	31.39	E	E	83.29
04/17/12	1345	Routine	Spring	0.31	13.76	13.85	3.37	15.67	15.90	3.05	SW	SW	70.62	SW	SW	44.32
05/31/12	1230	Storm	Spring	0.77	12.02	12.25	3.38	13.89	14.10	3.62	SSE	W	127.50	SSW	SW	81.98
06/20/12	1215	Routine	Spring	0.80	8.86	8.80	3.07	7.12	7.10	3.09	SSW	SW	58.49	SE	SE	88.63
07/18/12	1345	Routine	Summer	0.95	13.68	13.45	2.91	13.21	13.60	2.98	SW	SW	6.46	WSW	SW	22.32
08/15/12	1330	Routine	Summer	1.08	11.09	11.60	2.84	8.23	8.10	3.72	SSW	SW	44.74	S	SW	65.30
09/12/12	1215	Routine	Summer	−0.19	6.67	5.75	3.09	9.46	9.30	3.80	NE	NE	24.14	NE	N	84.07
10/09/12	1345	Storm	Fall	−0.70	12.53	12.40	3.42	12.15	12.20	3.28	NNE	NE	38.53	ENE	NE	88.69
10/10/12	0945	Storm	Fall	−0.30	10.03	10.20	2.25	11.75	11.60	3.29	SSE	W	150.87	E	NE	120.19
11/15/12	1130	Routine	Fall	−0.93	12.80	12.30	2.74	13.26	13.45	4.00	NNE	N	22.60	ENE	N	78.31
12/18/12	1200	Routine	Fall	0.73	11.06	11.15	4.78	7.19	6.45	4.53	SW	SW	40.64	S	S	73.63
01/17/13	1115	Routine	Winter	−0.07	6.02	5.05	3.51	6.99	6.15	4.41	E	NE	89.31	E	NE	95.46
02/27/13	0930	Storm	Winter	0.13	12.68	11.00	5.62	9.41	8.80	5.46	S	S	63.81	ESE	E	105.01
03/20/13	0915	Routine	Winter	−0.08	10.50	9.35	4.61	—	—	—	SSW	W	116.51	—	—	—
04/09/13	1115	Routine	Spring	0.25	13.58	13.50	1.78	11.30	11.40	3.48	SW	SW	22.12	SSE	S	72.99
05/30/13	1030	Routine	Spring	0.42	14.98	15.10	3.83	14.02	13.90	3.28	SSW	SW	20.10	SSW	S	30.36
06/10/13	1045	Routine	Spring	0.59	12.39	12.15	3.10	14.15	12.20	8.04	S	S	55.64	SSE	S	70.65
06/26/13	1130	Routine	Spring	0.78	14.82	14.90	2.15	14.85	14.80	2.53	SW	SW	13.19	SW	SW	20.07
07/24/13	1015	Routine	Summer	0.82	12.57	11.75	4.17	12.79	13.30	3.99	SW	SW	19.81	SW	SW	30.11

Table 11. Summary statistics of gage height during sampling, and wind speed and direction 24 and 72 hours prior to water-quality sampling events in Currituck Sound, North Carolina, 2011–18.—Continued

[mph, mile per hour; h, hour; std dev, standard deviation; deg, degrees; —, no data available; S, south; W, west; N, north; E, east; SW, southwest; SE, southeast, NE, northeast; NW, northwest]

Sample date	Median sample time	Sampling event type	Season	Mean gage height (feet)	24-h antecedent wind speed (mph)			72-h antecedent wind speed (mph)			24-h antecedent wind direction			72-h antecedent wind direction		
					Mean	Median	Std dev	Mean	Median	Std dev	Mean	Median	Std dev (deg. from 0, N)	Mean	Median	Std dev (deg. from 0, N)
08/15/13	1300	Routine	Summer	-0.22	8.69	8.40	2.38	10.28	10.05	4.09	ENE	NE	33.72	SE	SE	86.40
09/11/13	1145	Routine	Summer	0.28	8.62	8.50	2.20	6.41	7.00	3.16	S	S	42.05	SE	SE	62.79
10/23/13	0900	Routine	Fall	0.76	10.19	10.00	2.40	7.50	7.00	3.45	SW	SW	18.08	SSE	SE	101.26
11/21/13	1200	Routine	Fall	−1.06	11.88	12.35	3.30	12.35	12.95	3.71	NE	NE	9.28	SE	NE	114.52
12/19/13	1115	Routine	Fall	0.10	9.25	9.35	3.85	9.97	9.75	4.44	SW	SW	67.58	SSW	SW	78.13
01/25/15	1115	Storm	Winter	0.77	16.23	16.80	5.34	11.87	10.30	5.95	WNW	W	21.90	SSE	S	116.87
10/13/16	1215	Storm	Fall	1.31	5.99	5.45	1.96	8.43	8.10	3.04	ESE	NE	118.12	ENE	NE	79.78
12/21/16	1100	Routine	Fall	−0.79	10.01	9.00	3.78	14.59	15.40	5.04	W	NW	78.35	SSE	E	115.68
01/25/17	1030	Routine	Winter	0.17	14.83	15.45	5.53	13.02	12.30	6.09	W	W	29.35	SW	W	101.36
02/22/17	1115	Routine	Winter	−0.39	7.26	7.15	2.11	7.28	7.10	2.90	E	E	54.53	E	NE	84.75
03/21/17	1145	Routine	Winter	−0.72	8.38	8.85	2.75	11.33	10.00	6.19	SSE	S	70.62	SSW	SW	100.01
04/19/17	1230	Routine	Spring	−0.57	11.12	10.80	1.99	13.71	13.10	5.20	NE	NE	8.04	SE	NE	88.30
05/17/17	1100	Routine	Spring	0.68	8.57	8.50	2.37	10.26	9.70	4.37	SSE	S	49.72	SSW	S	81.12
06/15/17	1145	Routine	Spring	0.14	7.31	7.40	2.64	11.22	11.40	3.78	ESE	E	91.75	S	SW	71.95
07/20/17	1130	Routine	Summer	0.23	9.50	9.55	3.88	9.16	9.40	3.31	SSW	SW	55.39	SSW	SW	52.67
08/16/17	1045	Storm	Summer	0.48	7.70	7.20	3.97	6.60	5.80	2.92	ESE	E	66.34	E	E	62.66
09/20/17	1000	Routine	Summer	−0.47	16.64	16.00	3.97	15.89	15.35	4.07	W	NW	102.75	SE	NE	125.93
10/25/17	1130	Routine	Fall	0.81	10.83	9.95	5.40	12.09	10.35	6.48	WSW	W	50.36	SSE	S	67.09
11/15/17	1115	Routine	Fall	−0.87	13.57	13.60	2.16	11.83	12.85	4.45	SSE	SE	109.30	SSE	E	123.91
12/19/17	1045	Routine	Fall	−0.21	6.66	6.80	2.23	6.26	6.45	2.22	SW	S	50.71	SW	SW	40.85
01/24/18	1145	Routine	Winter	−0.11	9.84	10.70	4.38	8.62	8.50	5.33	WSW	W	60.01	SSW	S	61.60

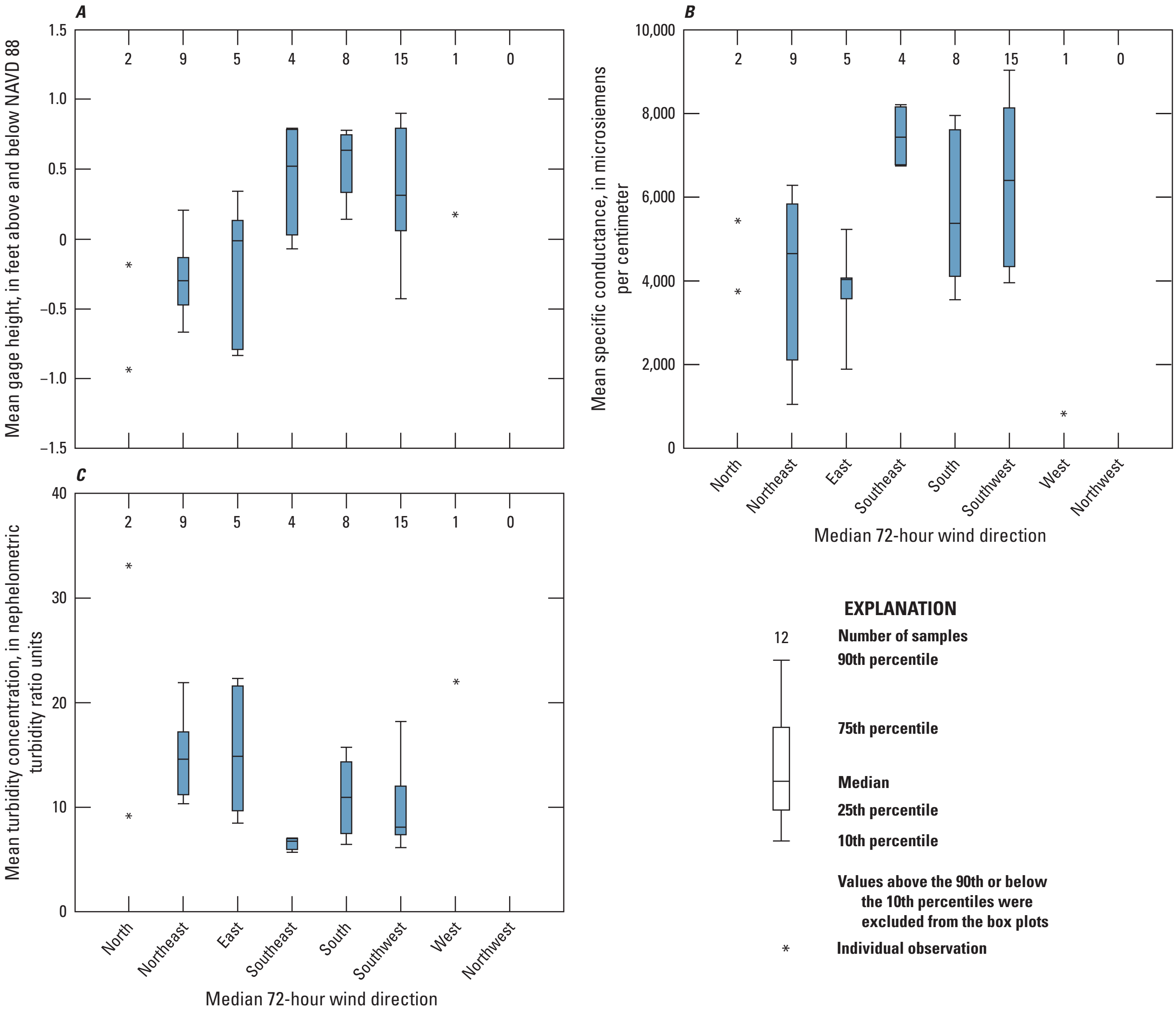

Figure 7. Plots showing relations of mean values for (*A*) gage height, (*B*) specific conductance, and (*C*) turbidity concentrations during water-quality sampling events to median wind direction 72 hours prior to the sampling events in Currituck Sound, North Carolina, 2011–18.

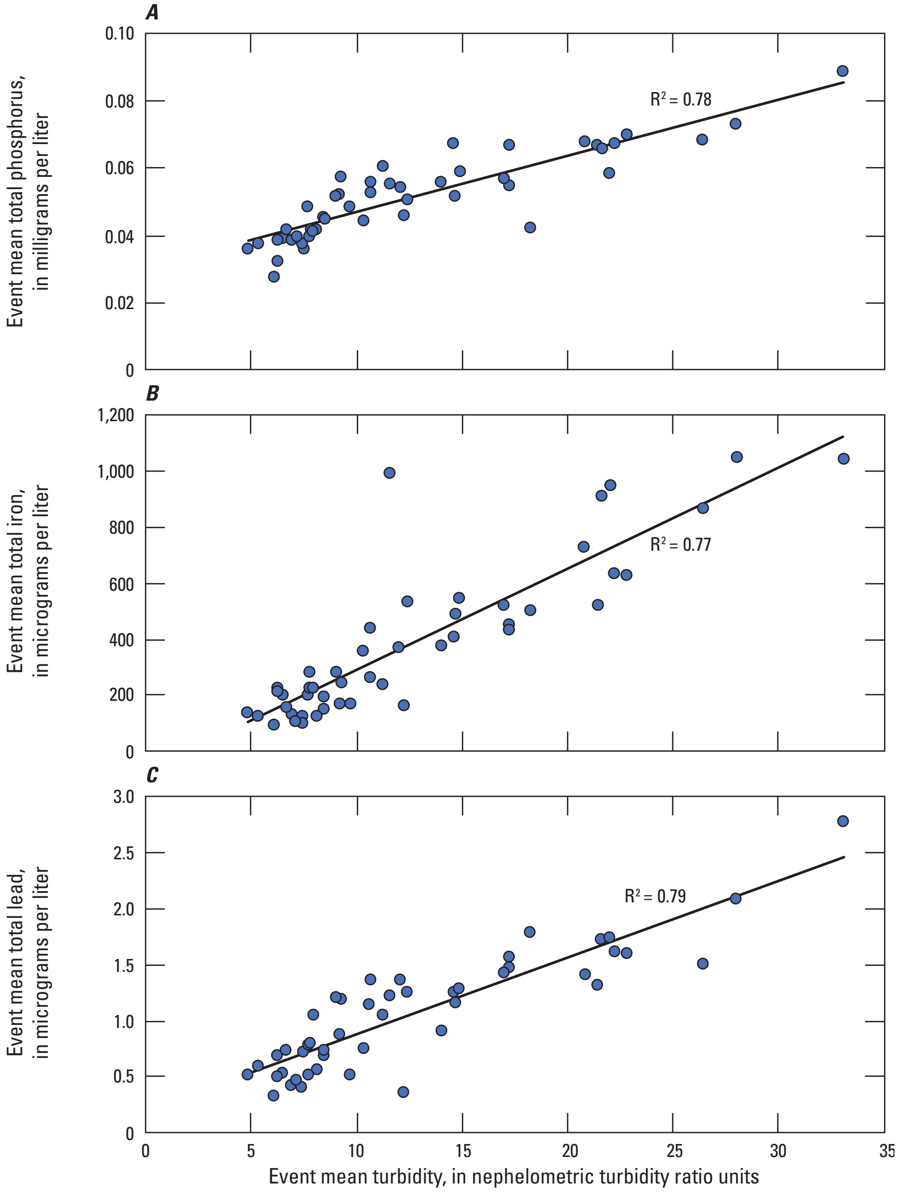

Figure 8. Graphs showing comparison between event mean concentrations of turbidity and (*A*) total phosphorus, (*B*) total iron, and (*C*) total lead in Currituck Sound, North Carolina, 2011–18.

Summary of Water-Velocity Data

The transect velocity data collected during field periods 1 and 2 and the stationary velocity profile data collected during period 2 are summarized in this section. The ADCP three-dimensional velocity data collected along the transect of the water-quality stations (fig. 1) were used to compute the spatial mean of depth-averaged water velocity magnitudes and directions at each sampling location as summarized, by sampling event, in table 12. Except for the 0.25-mile station, the mean depth-averaged water velocity magnitudes and directions were determined over 400-ft sections along the transect, which were centered on each of the other 4 sites (1.2-, 2.1-, 3.5-, and 4.5-mile stations).

The prevalence of SAV and shallow water depths in the vicinity of the 0.25-mile site limited the availability of the data needed to compute the mean velocity magnitude and direction over the 400-ft section centered on this site. Conditions were such that no transect velocity data were collected on the east side of the 0.25-mile site. Velocity data were collected westward of the site as conditions improved toward the 1.2-mile site. On some occasions, the closest available measurements varied from within tens or hundreds of feet to more than 1,000 feet away from the site. Consequently, the mean velocity magnitudes and directions determined for the 0.25-mile site (table 12) were based on available data across a 200-ft interval located no more than 0.2 miles (about 1,050 ft) from the site. These mean velocity values for the 0.25-mile site are considered estimates and assumed to be representative of the general water-velocity conditions during sampling events at this location.

The relatively high standard deviations shown in table 12 indicate that the water-velocity magnitudes and directions are highly variable both spatially and temporally in the vicinity of the planned Mid-Currituck Bridge. Based on these data, the mean water velocities at the sites were typically less than 0.5 feet per second (ft/s) and rarely exceeded 1 ft/s during the sampling events. The median of the mean velocities determined for each event, across all sites, ranged from 0.07 to 1.36 ft/s. Water-flow directions were most frequently toward the south and southwest during the sampling events.

An example of how the transect velocity data can be visually displayed is provided in figure 9, which shows the depth-averaged velocity vectors, averaged over 100-m (328-ft) windows, along the transect of the sampling stations on October 13, 2016. During this sampling event, velocity magnitudes tended to be lower, with an easterly to southerly flow in the eastern side of the Sound. Conversely, velocity magnitudes tended to be higher in the western side of the Sound, with flows toward the west.

The stationary velocity profile data collected during the sampling events in field period 2 were used to compute the depth-averaged water speed and velocity at each site (table 13). The depth-averaged speed represents the average velocity in any direction at any point throughout the water column. The depth-averaged velocity magnitude and direction represent the overall (net) average velocity of the entire water column along with its direction of flow.

The median of the depth-averaged speeds determined for each site, across all events, tended to increase from east to west across the Sound, ranging from a low of 0.12 ft/s at the 0.25-mile site to a high of 0.43 ft/s at the 3.5-mile site. The median of the depth-averaged velocity magnitudes followed a similar trend, ranging from a low of 0.05 ft/s at the 0.25-mile site to a high of 0.19 ft/s at the 3.5-mile site. The median of the average velocity directions indicated that overall flow directions were typically toward the south (1.2 and 2.1-mi sites) and southwest (3.5 and 4.5-mi sites), while flow at the 0.25-mi site was predominantly toward the northwest.

An example of how the stationary velocity profile data can be visually displayed is provided in figure 10, which shows the 25th, median, and 75th percentiles of all easting and northing velocity magnitudes measured at each depth throughout the water column for each site on October 13, 2016. For the east velocity data, positive values indicate an eastward component to overall velocity while negative values indicate a westward component. Similarly, for the north velocity data, positive values indicate a northward component to overall velocity while negative values indicate a southward component.

These data illustrate how velocity magnitudes and directions can be quite variable throughout the water column at each location. For instance, the east and north velocity data at the 0.25-mi site indicate a more westerly and southerly component to flow in the upper water column and a more easterly and northerly component to flow in the lower water column (fig. 10). On October 13, 2016, the depth-averaged speed at any point, without regard to direction, was 0.08 ft/s at the 0.25-mi site (table 13). The net average velocity of the overall water column was 0.02 ft/s toward the east. Although beyond the scope of this report, the ADCP velocity data can be used to characterize and compare the circulation dynamics and how they relate to water quality in the study area before the construction of the Mid-Currituck Bridge.

Summary of Bed-Sediment Sample Results

Examination of the chemical results for bed sediment included a comparison of sample constituent concentrations to applicable sediment quality guidelines (SQGs) for marine sediment (Buchman, 2008). The SQGs can be used as a preliminary screening tool to identify potential risks from contaminated water, sediment, or soil and possible effects on coastal resources and habitats; these guidelines do not constitute official criteria or cleanup levels. For the comparison done here, the constituent concentrations were screened against biological-based effect levels, including threshold effect levels (TEL), the 50 percent probability level of observing sediment toxicity (T_{50}), and the probable effect level (PEL). As described by Hübner and others (2009), the TEL and PEL indicate three ranges in threshold concentrations, whereby the likelihood of adverse effects are (1) rare for concentrations less than TEL, (2) occasional for concentrations between the TEL and PEL, and (3) frequent for concentrations greater than the PEL. When present, estimated "E" concentration values were included in the comparisons.

The bed-sediment constituents with 1 or more of the applicable TEL, T_{50}, and PEL screening values include 12 metals and 10 SVOCs (table 14). These screening values are based on bulk sediment in concentrations of micrograms per kilogram (µg/kg, or parts per billion) dry weight. Because the analysis of bed-sediment samples collected during field period 1 was based on the fine fraction, the concentrations reported for the period 1 samples had to first be multiplied by the percent fraction of fines in the overall samples to adjust the concentrations to a bulk-sediment basis before they were compared with the screening levels. Concentrations for the period 2 samples were determined directly on bulk sediment and were, therefore, directly comparable to the screening thresholds.

The overall number of samples with constituent concentrations exceeding the sediment screening levels was minimal. Of the 12 metals, 4 had concentrations, in 1 or more samples, above the most conservative TEL screening value (table 14). Of these, arsenic and nickel each had one sample that exceeded the TEL, but neither exceeded either the T_{50} or PEL values. Barium and tin exceeded the TEL in six and ten samples, respectively; no T_{50} or PEL values were available for these constituents. None of the 10 SVOCs had detected concentrations above any of the applicable screening levels. However, many of the SVOCs, particularly anthracene and naphthalene, had samples with left-censored results where the LRLs were higher than their lowest corresponding threshold, and, therefore, it could not be determined whether those samples were above or below the threshold (table 14). This examination of sediment constituent results with applicable SQGs provides useful baseline information that can be used to evaluate potential (future) changes in sediment quality that may occur during and after construction of the Mid-Currituck Bridge.

Statistical summaries of bed-sediment results based on fine-fraction analyses for period 1 samples (collected during 2011–13) and bulk-sediment analyses for period 2 samples (collected during 2017) are provided in tables 15 and 16, respectively.[3] For the SVOCs, both datasets had high numbers of constituents in which all sample results were left-censored below their respective LRLs and were, therefore, excluded from the tables. The censoring levels associated with individual SVOCs for the fine fraction tended to be higher and more variable than for the bulk sediment due to the smaller mass of fine material available for some sample analyses. Often, individual SVOCs were detected in some samples at concentrations lower than the LRLs for left-censored results reported for some of the other samples.

Of the 38 SVOCs analyzed for bed-sediment, 15 were detected in 1 or more samples for the fine fraction (table 15), and only 4 were detected in the bulk sediment samples (table 16). The four SVOCs identified in bulk sediment (2,6-dimethlnaphthalene, 9,10-anthraquinone, fluoranthene, and perylene) were also present in the fine fraction. Bis(2-ethylhexyl) phthalate was detected in half (five of ten) of the fine-fraction samples with some measured concentrations well above LRLs for this compound. Diethyl phthalate was measured at a relatively high concentration (1,700 µg/kg) in 1 fine-fraction sample but was not present above LRLs in the other 9 samples (table 14). During field period 1, sporadic contamination of these common plasticizers may have occurred as a part of sample collection-processing or laboratory analysis, and these constituent results should be interpreted with caution. Neither of these compounds was identified in the bulk-sediment samples analyzed during field period 2.

Most metals (27 of 30) analyzed for the fine fraction were detected above LRLs, except for silver, thallium, and uranium, which were all censored and, therefore, excluded from table 15. All 38 metals analyzed for the bulk sediment were detected above LRLs for most of the samples (table 16). Median concentrations for the metals and nutrients were higher for the fine fraction relative to the bulk sediment. The lower bulk sediment concentrations reflect the dilutive effects of the coarser sand fraction. Although constituent concentrations varied between the fine fraction and bulk sediment, those nutrients and metals with the higher and lower median concentrations were similar across both datasets. For example, P, barium, and manganese had the highest median concentrations, and mercury, cadmium, and total N had the lowest median concentrations in both the fine fraction (table 15) and the bulk sediment (table 16). The organic carbon fraction constituted most of the total carbon in both the fine-fraction and bulk-sediment samples.

Additional examination of the nutrient and metal data indicated that the largest proportion of constituents with the lowest concentrations, for both the fine fraction and bulk sediment (tables 15 and 16), occurred at the shallowest site (0.25-mile station; average depth of 1.9 ft) closest to the east bank of Currituck Sound. The largest proportion of constituents with the highest concentrations, for the fine fraction, occurred at the second shallowest site (4.5-mile station; average depth of 4.4 ft), which was closest to the west bank of Currituck Sound. In contrast, most constituents with the highest concentrations for bulk sediment occurred at the second deepest site (2.1-mile station; average depth of 6.3 ft), which was near the middle of the Sound.

Trace-element concentrations in bulk sediments are well-correlated with the concentration of fines and the total surface area of sediments (Horowitz and Elrick, 1987). Therefore, bulk-sediment total concentrations of elements not associated with the mineral lattice are largely controlled by the proportion of fines. The weight percent of fines in bed sediments sampled during the study varied spatially and temporally (fig. 11). The concentration of fines ranged from less than 1 percent at the shallower sites near the shoreline (0.25-mile and 4.5-mile stations) to more than 60 percent at the deeper transect sites (2.1-mile and 3.5-mile stations) in the Sound. Construction of the Mid-Currituck Bridge could influence water-circulation dynamics along with the transport, deposition, and resuspension patterns of sediment particles near the study sites. These physical processes, combined with sediment, debris, and chemical inputs from bridge runoff, could also potentially alter the chemical composition of bed sediments in the vicinity of the bridge alignment.

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[3] The weight percent fine (< 63 µm) fraction values for bed sediment listed for both periods were determined on whole bulk-sediment samples.

Table 12. Summary of spatially averaged and depth-averaged water-velocity magnitude and direction along the transect of water-quality sampling stations in Currituck Sound, North Carolina, 2011–18.

[ft/s, foot per second; std dev, standard deviation; deg, degrees; —, insufficient velocity data available; GPS, global positioning system]

Date	362103075493801 0.25 miles from east bank of Currituck Sound[1]				362048075504901 1.2 miles from east bank of Currituck Sound[1]				362035075514301 2.1 miles from east bank of Currituck Sound[1]			
	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)
08/30/11	0.06	0.08	33.3	54.2	0.14	0.26	94.4	69.6	0.20	0.26	189.1	78.5
09/28/11	No valid GPS data											
10/18/11	0.03	0.41	324.9	103.7	0.19	0.39	225.9	89.8	0.11	0.43	39.8	61.4
11/15/11	—	—	—	—	0.32	0.21	311.5	62.2	0.20	0.35	326.7	76.2
12/20/11	—	—	—	—	0.20	0.15	250.8	52.4	0.13	0.12	242.3	77.4
01/24/12	0.42	0.43	62.8	50.2	0.09	0.17	310.9	85.5	0.15	0.15	0.7	44.8
02/22/12	0.21	0.19	191.1	80.9	0.28	0.18	292.0	48.9	0.16	0.18	342.9	62.6
03/06/12	0.34	0.26	127.4	51.9	0.05	0.21	62.7	70.6	0.06	0.31	114.8	86.8
03/21/12	0.21	0.14	13.2	23.4	0.06	0.28	12.7	56.3	0.10	0.33	75.9	74.1
04/17/12	0.45	0.28	172.4	41.8	0.08	0.13	158.4	74.2	0.11	0.09	157.4	72.4
05/31/12	0.32	0.15	181.9	39.8	0.05	0.31	162.5	82.6	0.09	0.34	65.4	68.4
06/20/12	0.43	0.21	62.6	47.1	0.17	0.22	246.6	76.7	0.08	0.17	279.5	85.3
07/18/12	—	—	—	—	0.04	0.31	255.1	91.2	0.10	0.17	74.8	70.1
08/15/12	—	—	—	—	0.13	0.26	294.2	76.8	0.13	0.51	40.5	56.2
09/12/12	0.39	0.14	49.9	42.0	0.30	0.18	46.4	42.3	0.13	0.18	27.7	55.0
10/10/12	—	—	—	—	0.12	0.18	260.4	87.0	0.24	0.22	319.0	66.8
11/15/12	0.26	0.08	165.1	26.0	0.18	0.38	148.3	76.8	0.52	0.94	201.4	70.6
12/18/12	No valid GPS data											
01/17/13	—	—	—	—	0.07	0.58	55.2	63.4	0.08	0.43	119.8	86.7
02/27/13	—	—	—	—	—	—	—	—	0.29	0.17	330.3	49.2
03/20/13	—	—	—	—	0.12	0.19	351.2	90.2	0.06	0.23	273.0	96.1
04/09/13	No valid GPS data											
05/30/13	—	—	—	—	—	—	—	—	—	—	—	—
06/10/13	—	—	—	—	0.22	0.48	273.4	86.7	0.27	0.61	19.7	45.8
06/26/13	—	—	—	—	0.70	1.08	59.2	68.0	1.01	1.19	66.3	64.1
07/24/13	0.23	0.55	202.5	84.6	0.07	0.28	257.2	103.0	0.27	0.27	116.6	71.1
08/15/13	0.85	0.04	20.0	11.5	0.14	0.39	328.0	85.3	0.34	0.75	66.7	69.2
09/11/13	No valid GPS data											
10/23/13	No valid velocity data											
11/21/13	—	—	—	—	1.13	0.90	62.6	53.9	1.36	1.03	74.8	41.0
12/19/13	0.23	0.62	75.3	74.3	0.14	0.40	294.9	91.7	0.31	0.42	57.1	68.3
01/25/15	No valid GPS data											
10/13/16	0.13	0.43	6.0	48.3	0.05	0.28	60.4	67.2	0.28	0.75	199.5	83.5
12/21/16	0.24	0.24	37.4	55.7	0.09	0.29	263.5	100.1	0.13	0.24	319.2	87.1
01/25/17	0.09	0.40	281.4	103.1	0.07	0.36	186.1	94.4	0.20	0.55	327.1	90.9
02/22/17	0.54	0.39	272.7	55.8	0.19	0.23	283.3	81.4	0.15	0.36	9.8	49.4
03/21/17	0.62	0.43	214.4	51.3	0.31	0.24	238.4	60.7	0.16	0.27	357.8	45.6

Table 12. Summary of spatially averaged and depth-averaged water-velocity magnitude and direction along the transect of water-quality sampling stations in Currituck Sound, North Carolina, 2011–18.—Continued

[ft/s, foot per second; std dev, standard deviation; deg, degrees; —, insufficient velocity data available; GPS, global positioning system]

Date	362019075531301 3.5 miles from east bank of Currituck Sound[1]				362002075540401 4.5 miles from east bank of Currituck Sound[1]			
	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)
08/30/11	0.28	0.43	187.1	71.5	0.23	0.34	135.0	83.6
09/28/11	No valid GPS data							
10/18/11	0.20	0.23	155.2	75.1	0.05	0.19	175.3	94.1
11/15/11	0.37	0.19	190.4	49.6	0.39	0.28	297.6	55.9
12/20/11	0.07	0.12	300.7	85.1	0.20	0.24	205.9	77.7
01/24/12	0.26	0.10	334.9	22.7	0.12	0.15	231.2	82.5
02/22/12	0.31	0.13	337.5	28.5	0.17	0.16	289.7	74.2
03/06/12	0.18	0.34	86.4	72.6	0.14	0.29	108.9	76.9
03/21/12	0.30	0.45	75.2	69.3	0.14	0.26	330.5	85.6
04/17/12	0.38	0.14	159.0	27.2	0.12	0.13	198.4	56.4
05/31/12	0.10	0.21	344.2	79.7	0.14	0.17	202.6	83.0
06/20/12	0.07	0.19	188.5	85.3	0.19	0.21	211.5	77.2
07/18/12	0.04	0.15	172.2	100.1	0.13	0.17	304.6	79.5
08/15/12	0.08	0.16	1.4	46.7	0.35	0.25	235.7	54.4
09/12/12	0.21	0.33	14.8	48.1	0.29	0.41	48.8	58.8
10/10/12	0.36	0.14	337.7	26.2	0.13	0.15	298.6	82.6
11/15/12	0.33	0.65	294.9	64.0	0.44	0.11	91.4	30.2
12/18/12	No valid GPS data							
01/17/13	0.12	0.38	89.5	76.7	—	—	—	—
02/27/13	0.44	0.19	324.5	32.3	—	—	—	—
03/20/13	0.06	0.39	54.9	64.3	0.09	0.39	276.6	102.0
04/09/13	No valid GPS data							
05/30/13	0.75	0.56	168.3	62.7	0.51	0.39	133.5	58.5
06/10/13	0.01	0.25	109.7	78.8	—	—	—	—
06/26/13	0.78	0.88	70.4	55.6	0.01	0.29	127.5	89.7
07/24/13	0.38	0.19	150.7	40.9	0.24	0.27	121.1	74.1
08/15/13	0.28	0.42	31.1	54.3	0.42	0.31	328.4	59.4
09/11/13	No valid GPS data							
10/23/13	No valid velocity data							
11/21/13	1.41	0.99	51.0	40.5	—	—	—	—
12/19/13	1.99	1.51	250.4	54.4	0.75	0.40	37.4	36.9
01/25/15	No valid GPS data							
10/13/16	0.37	0.56	279.0	81.1	0.32	0.99	204.5	101.1
12/21/16	0.21	0.17	318.8	64.0	—	—	—	—
01/25/17	0.30	0.50	25.5	44.4	0.32	0.35	63.7	63.0
02/22/17	0.26	0.21	324.7	59.3	0.31	0.38	260.7	78.8
03/21/17	0.16	0.61	346.3	85.9	0.59	0.51	260.4	66.8

Table 12. Summary of spatially averaged and depth-averaged water-velocity magnitude and direction along the transect of water-quality sampling stations in Currituck Sound, North Carolina, 2011–18.—Continued

[ft/s, foot per second; std dev, standard deviation; deg, degrees; —, insufficient velocity data available; GPS, global positioning system]

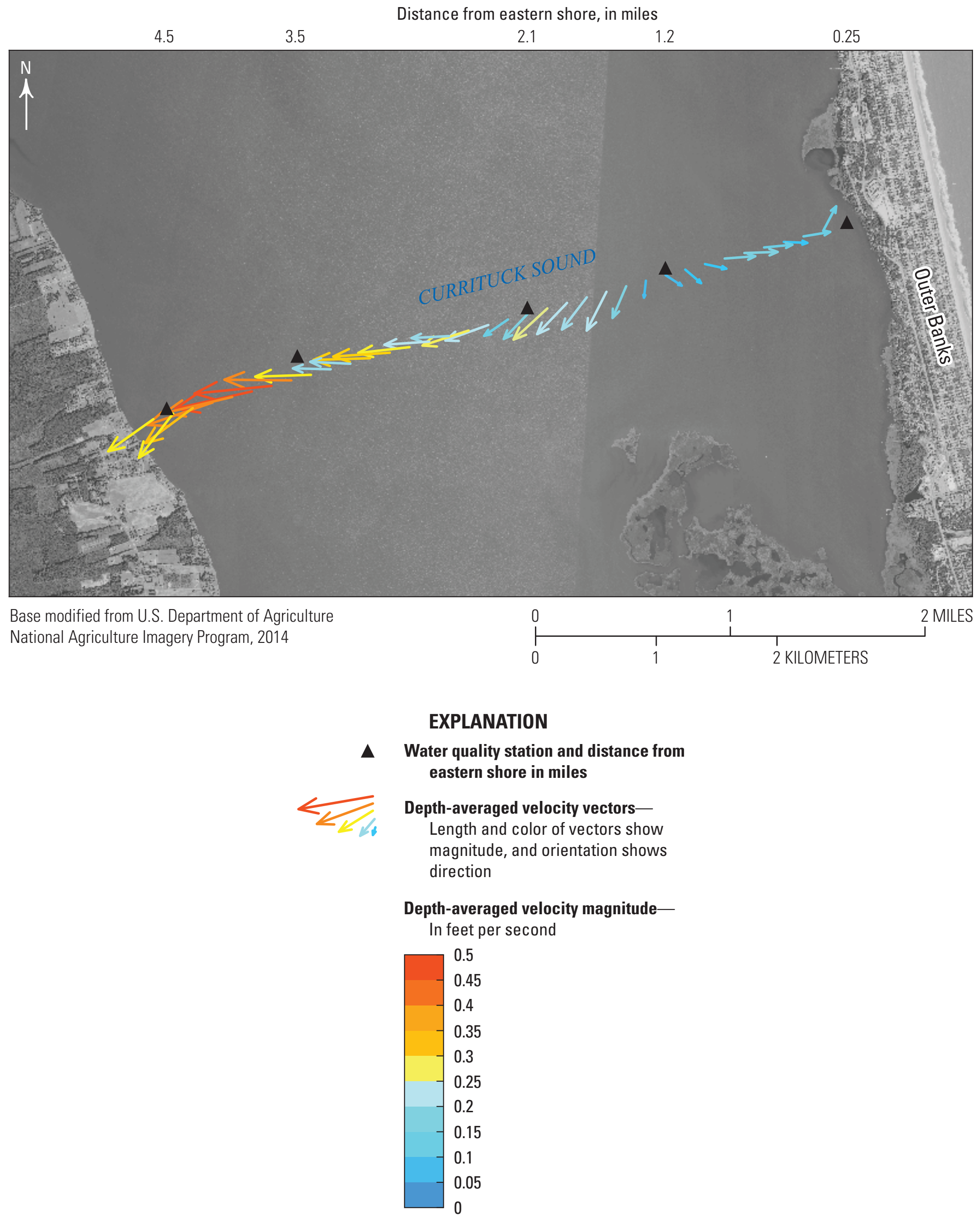
Date	362103075493801 0.25 miles from east bank of Currituck Sound[1]				362048075504901 1.2 miles from east bank of Currituck Sound[1]				362035075514301 2.1 miles from east bank of Currituck Sound[1]			
	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)
04/19/17	No valid GPS data											
05/17/17	0.29	0.17	250.6	58.5	0.19	0.24	237.9	86.4	0.07	0.15	188.0	70.6
06/15/17	0.06	0.17	27.1	48.6	0.14	0.37	66.4	65.2	0.10	0.26	163.0	91.0
07/20/17	0.27	0.49	81.1	80.4	0.83	0.80	58.3	50.1	0.58	0.60	76.5	57.1
08/16/17	0.14	0.22	242.1	54.5	0.38	0.29	160.2	60.5	0.41	0.31	177.8	52.6
09/20/17	0.43	0.34	218.7	67.7	0.15	0.23	197.3	84.8	0.17	0.25	306.6	88.0
10/25/17	0.34	0.20	205.9	54.0	0.36	0.27	197.1	53.5	0.42	0.20	190.3	19.1
11/15/17	—	—	—	—	0.26	0.26	215.3	70.7	0.24	0.30	217.5	72.8
12/19/17	0.39	0.39	257.9	68.0	0.10	0.58	310.0	84.4	0.11	0.21	315.8	85.0
01/24/18	0.17	0.29	219.8	60.3	0.32	0.24	211.2	57.1	0.27	0.23	186.3	59.6

Table 12. Summary of spatially averaged and depth-averaged water-velocity magnitude and direction along the transect of water-quality sampling stations in Currituck Sound, North Carolina, 2011–18.—Continued

[ft/s, foot per second; std dev, standard deviation; deg, degrees; —, insufficient velocity data available; GPS, global positioning system]

Date	362019075531301 3.5 miles from east bank of Currituck Sound[1]				362002075540401 4.5 miles from east bank of Currituck Sound[1]			
	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)	Mean velocity magnitude (ft/s)	Std dev velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Std dev velocity direction (deg from 0, north)
04/19/17	No valid GPS data							
05/17/17	0.10	0.15	176.2	78.8	0.24	0.27	263.0	63.3
06/15/17	0.15	0.22	147.7	75.7	0.15	0.26	177.7	76.8
07/20/17	0.23	0.22	122.7	49.0	0.16	0.27	223.0	75.9
08/16/17	0.33	0.24	156.8	58.9	0.37	0.29	157.3	63.7
09/20/17	0.45	0.27	330.2	48.1	0.46	0.42	215.5	55.4
10/25/17	0.56	0.12	175.3	11.9	0.44	0.30	179.1	46.3
11/15/17	0.17	0.21	200.7	87.1	0.51	0.44	222.1	61.0
12/19/17	0.16	0.11	202.3	49.5	0.45	0.36	255.2	57.8
01/24/18	0.28	0.20	171.3	27.0	0.42	0.37	216.6	49.6

[1] U.S. Geological Survey water-quality station number and name.



Base modified from U.S. Department of Agriculture
National Agriculture Imagery Program, 2014

Figure 9. Image showing the depth-averaged transect velocity data in the vicinity of the study sites in Currituck Sound, North Carolina, October 13, 2016.

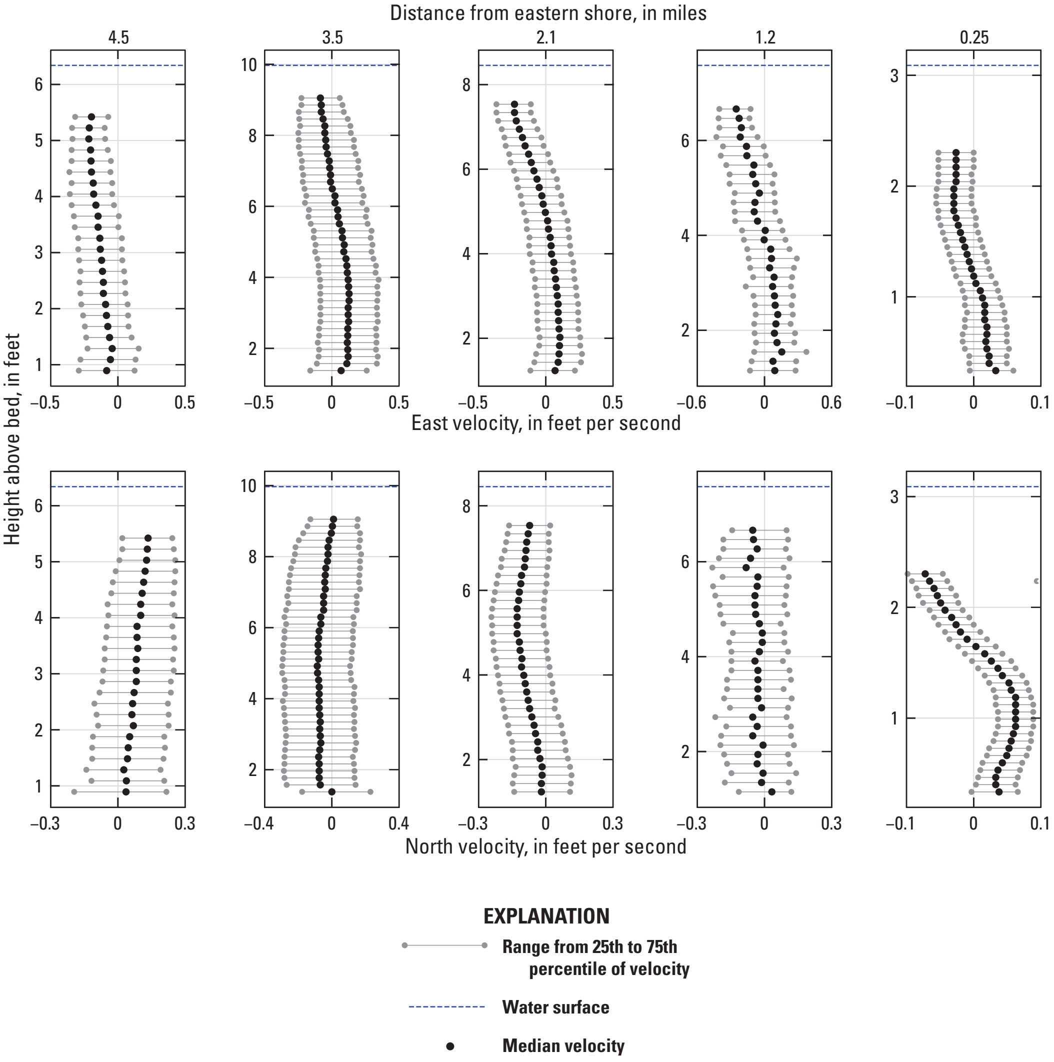


Figure 10. Profile velocity measurements at the study sites in Currituck Sound, North Carolina, October 13, 2016.

Table 13. Summary of depth-averaged water-velocity magnitude and direction for stationary profiles at the water-quality sampling locations in Currituck Sound, North Carolina, 2016–18.

[ft/s, foot per second; std dev, standard deviation; deg, degrees; GPS, global positioning system]

Date	362103075493801 0.25 miles from east bank of Currituck Sound[1]				362048075504901 1.2 miles from east bank of Currituck Sound[1]				362035075514301 2.1 miles from east bank of Currituck Sound[1]			
	Mean speed magnitude (ft/s)	Std dev speed magnitude (ft/s)	Mean velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Mean speed magnitude (ft/s)	Std dev speed magnitude (ft/s)	Mean velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Mean speed magnitude (ft/s)	Std dev speed magnitude (ft/s)	Mean velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)
10/13/16	0.08	0.08	0.02	99.8	0.42	0.32	0.01	169.6	0.36	0.27	0.07	257.5
12/21/16	0.05	0.02	0.03	334.3	0.17	0.16	0.06	309.5	0.29	0.23	0.14	359.2
01/25/17	0.14	0.13	0.05	350.6	0.45	0.32	0.12	0.7	0.50	0.34	0.16	7.0
02/22/17	0.20	0.12	0.15	322.9	0.36	0.30	0.08	45.0	0.41	0.29	0.10	30.8
03/21/17	0.07	0.04	0.01	137.2	0.34	0.32	0.06	279.3	0.38	0.28	0.11	4.1
04/19/17	No valid GPS data											
05/17/17	0.21	0.16	0.12	317.0	0.26	0.25	0.04	238.6	0.25	0.24	0.03	160.9
06/15/17	0.12	0.07	0.07	161.7	0.53	0.35	0.08	148.3	0.58	0.39	0.11	187.5
07/20/17	0.17	0.15	0.05	351.9	0.19	0.17	0.07	178.9	0.14	0.09	0.11	181.4
08/16/17	0.08	0.06	0.004	312.6	0.47	0.32	0.10	127.9	0.53	0.32	0.20	185.2
09/20/17	0.10	0.09	0.03	104.3	0.46	0.37	0.11	334.3	0.54	0.33	0.25	357.5
10/25/17	0.11	0.11	0.06	127.2	0.18	0.08	0.13	192.8	0.18	0.07	0.17	198.1
11/15/17	0.14	0.07	0.09	342.9	0.49	0.37	0.13	229.8	0.58	0.38	0.09	256.5
12/19/17	0.08	0.08	0.03	327.5	0.33	0.29	0.02	35.0	0.41	0.30	0.06	23.4
01/24/18	0.13	0.11	0.07	144.3	0.15	0.10	0.11	209.3	0.37	0.28	0.13	190.6

Table 13. Summary of depth-averaged water-velocity magnitude and direction for stationary profiles at the water-quality sampling locations in Currituck Sound, North Carolina, 2016–18.—Continued

[ft/s, foot per second; std dev, standard deviation; deg, degrees; GPS, global positioning system]

Date	362019075531301 3.5 miles from east bank of Currituck Sound[1]				362002075540401 4.5 miles from east bank of Currituck Sound[1]			
	Mean speed magnitude (ft/s)	Std dev speed magnitude (ft/s)	Mean velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)	Mean speed magnitude (ft/s)	Std dev speed magnitude (ft/s)	Mean velocity magnitude (ft/s)	Mean velocity direction (deg from 0, north)
10/13/16	0.42	0.26	0.07	309.2	0.44	0.36	0.17	149.9
12/21/16	0.34	0.24	0.22	334.4	0.09	0.05	0.05	298.9
01/25/17	0.43	0.27	0.21	335.1	0.10	0.07	0.04	354.1
02/22/17	0.42	0.27	0.20	339.1	0.27	0.19	0.11	310.4
03/21/17	0.51	0.29	0.26	335.6	0.27	0.15	0.16	316.6
04/19/17	No valid GPS data							
05/17/17	0.37	0.24	0.14	144.0	0.11	0.07	0.05	253.9
06/15/17	0.47	0.28	0.19	167.5	0.39	0.34	0.09	153.7
07/20/17	0.19	0.06	0.15	165.3	0.10	0.18	0.03	152.6
08/16/17	0.49	0.30	0.15	163.4	0.57	0.38	0.17	145.0
09/20/17	0.77	0.36	0.63	331.9	0.35	0.29	0.02	263.7
10/25/17	0.36	0.17	0.30	172.7	0.23	0.15	0.14	148.0
11/15/17	0.55	0.42	0.11	307.2	0.57	0.36	0.07	158.5
12/19/17	0.40	0.26	0.09	186.8	0.12	0.07	0.08	257.5
01/24/18	0.45	0.26	0.23	178.4	0.40	0.36	0.11	170.4

[1] U.S. Geological Survey water-quality station number and name.

Table 14. Sediment quality screening levels applicable to constituents measured in bed-sediment samples collected in Currituck Sound, North Carolina, 2011–17.

[TEL, thresholds effect level; T_{50}, 50 percent probability of observing sediment toxicity; PEL, probable effects level; µg/kg; micrograms per kiligram (or parts per billion); —, not available]

		Sediment quality screening level[1]						
Constituent	**Number of sample results**	**TEL (µg/kg)**	**Number of samples exceeding TEL**	**T_{50} (µg/kg)**	**Number of samples exceeding T_{50}**	**PEL (µg/kg)**	**Number of samples exceeding PEL**	**Number of samples where the reporting level exceeded the lowest screening level**
Antimony	15	—	—	2,400	0	—	—	0
Arsenic	15	7,240	1	20,000	0	41,600	0	0
Barium	15	130,100	6	—	—	—	—	0
Cadmium	14	680	0	1,400	0	4,210	0	0
Chromium	15	52,300	0	141,000	0	160,000	0	0
Copper	15	18,700	0	94,000	0	108,000	0	0
Lead	15	30,240	0	—	—	112,000	0	0
Mercury	15	130	0	480	0	700	0	0
Nickel	15	15,900	1	47,000	0	42,800	0	0
Silver	15	730	0	1,100	0	1,770	0	0
Tin	15	48	10	—	—	—	—	5
Zinc	15	124,000	0	245,000	0	271,000	0	0
1-Methylphenanthrene	15	—	—	112	0	—	—	2
2,6-Dimethlnaphthalene	15	—	—	133	0	—	—	0
Anthracene	12	46.9	0	290	0	245	0	9
Bis(2-ethylhexyl) phthalate	15	182	0	—	—	2,647	0	3
Chrysene	12	108	0	650	0	846	0	2
Fluoranthene	15	113	0	1,034	0	1,494	0	1
Naphthalene	12	34.6	0	217	0	391	0	9
Perylene	15	—	—	453	0	—	—	0
Phenanthrene	11	86.7	0	455	0	544	0	3
Pyrene	10	153	0	932	0	1,398	0	1

[1] Sediment quality screening levels obtained from Buchman (2008).

Table 15. Statistical summary of bed-sediment constituents measured on the fine fraction for samples collected during 2011–13 in Currituck Sound, North Carolina.

[%, percent; mg/kg, milligram per kilogram; µg/kg, microgram per kilogram; <, less than; —, not applicable; E, estimated concentration]

Constituent (unit)	Bed-sediment constituent concentrations based on fine fraction, 2011–2013							Station(s)[1] with minimum detected concentration	Station(s)[1] with maximum detected concentration
	Number of detected concentrations	Number of censored concentrations	Number of censoring levels	Minimum value	Mean value	Median value	Maximum value		
Nutrients, carbons, and physical properties									
Total nitrogen (%)	10	0	0	0.10	0.38	0.30	1.10	2.1	4.5
Phosphorus (mg/kg)	10	0	0	540	709	690	1,000	2.1	4.5
Total organic carbon (%)	10	0	0	1.1	2.79	2.35	7.0	2.1	4.5
Total carbon (%)	10	0	0	1.0	2.81	2.40	6.9	2.1	4.5
Bed sediment, <63 micrometers (weight %)	15	0	0	0.4	21.4	14.0	68	0.25	3.5
Metals									
Aluminum (%)	10	0	0	4.20	5.52	5.60	6.60	0.25	4.5
Antimony (mg/kg)	10	0	0	0.4	0.49	0.45	0.7	multiple	0.25
Arsenic (mg/kg)	10	0	0	3.3	6.5	6.5	10.0	0.25	2.1
Barium (mg/kg)	10	0	0	290	352	355	400	4.5	2.1/3.5
Beryllium (mg/kg)	10	0	0	1.2	1.54	1.55	1.9	0.25	4.5
Cadmium (mg/kg)	9	1	1	<0.1	0.25	0.25	0.4	0.25	3.5/4.5
Calcium (%)	10	0	0	0.5	0.8	0.8	1.1	4.5	0.25
Chromium (mg/kg)	10	0	0	34	55.4	56.0	79	0.25	4.5
Cobalt (mg/kg)	10	0	0	6	8.8	9.0	13	0.25	4.5
Copper (mg/kg)	10	0	0	5	13.1	11.0	29	0.25	0.25
Iron (%)	10	0	0	1.7	2.80	2.85	3.7	0.25	4.5
Lead (mg/kg)	10	0	0	16	51.5	27.0	210	2.1	0.25
Lithium (mg/kg)	10	0	0	22	44.9	46.0	72	0.25	4.5
Magnesium (%)	10	0	0	0.6	0.77	0.75	1.0	2.1	1.2
Manganese (mg/kg)	10	0	0	240	341	350	420	0.25	3.5
Mercury (mg/kg)	10	0	0	0.01	0.052	0.050	0.09	2.1	0.25/4.5
Molybdenum (mg/kg)	10	0	0	1	2.3	2.0	6	0.25/1.2	4.5
Nickel (mg/kg)	10	0	0	10	20.5	20.5	33	0.25	4.5
Potassium (%)	10	0	0	1.5	1.78	1.80	2.1	0.25	2.1
Selenium (mg/kg)	10	0	0	0.3	0.52	0.40	1.3	0.25/2.1	4.5
Sodium (%)	10	0	0	0.5	1.36	1.30	2.3	0.25	4.5
Strontium (mg/kg)	10	0	0	120	146	150	170	4.5	0.25
Sulfur (%)	10	0	0	0.36	1.09	1.10	1.7	0.25	4.5
Tin (mg/kg)	5	5	1	<1	—	—	3	all	3.5
Titanium (%)	10	0	0	0.43	0.548	0.540	0.68	0.25	3.5
Vanadium (mg/kg)	10	0	0	49	77.9	79.0	120	0.25	4.5
Zinc (mg/kg)	10	0	0	40	76.2	70.0	140	0.25	0.25
Semi-volatile organic compounds									
1,2-Dimethylnaphthalene (µg/kg)	1	9	9	E2.8	—	—	E2.8	2.1	2.1
1-Methylphenanthrene (µg/kg)	5	5	5	2.5	—	—	10.0	2.1	4.5
1-Methylpyrene (µg/kg)	1	9	9	3.4	—	—	3.4	2.1	2.1
2,6-Dimethlnaphthalene (µg/kg)	10	0	0	11	31.1	27.0	74	0.25	4.5

Table 15. Statistical summary of bed-sediment constituents measured on the fine fraction for samples collected during 2011–13 in Currituck Sound, North Carolina.—Continued

[%, percent; mg/kg, milligram per kilogram; µg/kg, microgram per kilogram; <, less than; —, not applicable; E, estimated concentration]

Constituent (unit)	Bed-sediment constituent concentrations based on fine fraction, 2011–2013							Station(s)[1] with minimum detected concentration	Station(s)[1] with maximum detected concentration
	Number of detected concentrations	Number of censored concentrations	Number of censoring levels	Minimum value	Mean value	Median value	Maximum value		
9,10-Anthraquinone (µg/kg)	4	5	5	11	—	—	23	2.1	1.2
Anthracene (µg/kg)	1	6	6	10	—	—	10	4.5	4.5
Benzo[def]fluorene (µg/kg)	2	8	8	2.5	—	—	3.4	3.5	2.1
Bis(2-ethylhexyl) phthalate (µg/kg)	5	5	5	<120	—	—	2,300	2.1	0.25
Chrysene (µg/kg)	1	7	7	14	—	—	14	4.5	4.5
Diethyl phthalate (µg/kg)	1	9	9	<26	—	—	1,700	2.1	0.25
Fluoranthene (µg/kg)	8	1	1	11	27	24	56	2.1	4.5
Naphthalene (µg/kg)	2	7	7	12	—	—	16	3.5	1.2
Perylene (µg/kg)	9	1	1	14	49	52	80	0.25	4.5
Phenanthrene (µg/kg)	3	4	4	13	—	—	58	1.2	4.5
Pyrene (µg/kg)	6	1	1	12	19.0	17.5	32	3.5	4.5

[1] Number of miles from the east bank of Currituck Sound near Corolla, North Carolina (see fig. 1).

Table 16. Statistical summary of bed-sediment constituents measured on bulk sediment for samples collected during 2017 in Currituck Sound, North Carolina.

[%, percent; mg/kg, milligram per kilogram; µg/kg, microgram per kilogram; <, less than; —, not applicable; E, estimated concentration]

Constituent (unit)	Bed-sediment constituent concentrations based on bulk sediment, 2017							Station(s)[1] with minimum detected concentration	Station(s)[1] with maximum detected concentration
	Number of detected concentrations	Number of censored concentrations	Number of censoring levels	Minimum value	Mean value	Median value	Maximum value		
				Nutrients, carbons, and physical properties					
Total nitrogen (%)	4	1	1	<0.02	0.048	0.030	0.09	0.25	3.5
Phosphorus (mg/kg)	5	0	0	40	252	180	540	0.25/4.5	2.1
Total organic carbon (%)	4	1	1	<0.1	0.36	0.30	0.7	0.25	3.5
Total carbon (%)	4	1	1	<0.1	0.44	0.30	0.8	0.25	2.1
Bed sediment, <63 micrometers (weight %)	5	0	0	1	21.4	7.0	71	0.25/4.5	2.1
				Metals					
Aluminum (%)	5	0	0	0.74	2.37	2.09	4.72	4.5	2.1
Antimony (mg/kg)	5	0	0	0.10	0.21	0.20	0.32	0.25	2.1
Arsenic (mg/kg)	5	0	0	0.9	3.6	2.3	8.6	0.25	2.1
Barium (mg/kg)	5	0	0	129	242	260	351	0.25	2.1
Beryllium (mg/kg)	5	0	0	0.19	0.75	0.68	1.59	4.5	2.1
Cadmium (mg/kg)	4	1	1	<0.02	0.046	0.030	0.09	0.25/4.5	2.1
Calcium (%)	5	0	0	0.17	0.48	0.42	0.92	4.5	2.1
Cerium (mg/kg)	5	0	0	13.6	37.2	35.2	65.5	0.25	2.1
Cesium (mg/kg)	5	0	0	0.18	0.97	0.60	2.59	0.25	2.1
Chromium (mg/kg)	5	0	0	6.4	16.1	10.6	36.3	0.25	2.1
Cobalt (mg/kg)	5	0	0	1.32	4.10	2.99	9.01	0.25	2.1
Copper (mg/kg)	5	0	0	2.4	6.2	5.7	10.2	0.25	2.1
Iron (%)	5	0	0	0.33	1.00	0.70	2.20	0.25	2.1
Lanthanum (mg/kg)	5	0	0	6.1	19.3	15.8	36.5	0.25	2.1
Lead (mg/kg)	5	0	0	4.7	9.5	8.0	14.3	0.25	2.1
Lithium (mg/kg)	5	0	0	5.5	14.4	10.9	30.6	0.25	2.1
Magnesium (%)	5	0	0	0.06	0.27	0.18	0.70	4.5	2.1
Manganese (mg/kg)	5	0	0	96	205	186	313	0.25	2.1
Mercury (mg/kg)	5	0	0	0.003	0.009	0.006	0.013	0.25	3.5
Molybdenum (mg/kg)	5	0	0	0.31	1.03	0.57	2.90	0.25	2.1
Nickel (mg/kg)	5	0	0	2.1	7.0	4.6	17.2	0.25	2.1
Potassium (%)	5	0	0	0.32	0.86	0.81	1.62	0.25	2.1
Rubidium (mg/kg)	5	0	0	11.9	38.4	33.1	81.5	0.25	2.1
Scandium (mg/kg)	5	0	0	1.3	3.7	2.8	7.7	0.25	2.1
Selenium (mg/kg)	2	3	1	<0.5	—	—	1.0	several	3.5
Silver (mg/kg)	5	0	0	0.17	0.23	0.20	0.30	0.25	3.5
Sodium (%)	5	0	0	0.17	0.61	0.59	1.08	4.5	2.1
Strontium (mg/kg)	5	0	0	34.3	84.9	87.3	138	4.5	2.1
Sulfur (%)	5	0	0	0.02	0.22	0.08	0.77	0.25	2.1
Tantalum (mg/kg)	5	0	0	0.20	0.46	0.48	0.64	0.25	3.5
Terbium (mg/kg)	5	0	0	0.13	0.43	0.34	0.84	0.25	2.1
Thallium (mg/kg)	5	0	0	0.06	0.19	0.17	0.38	0.25	2.1
Thorium (mg/kg)	5	0	0	1.2	4.2	3.2	8.0	0.25	2.1
Tin (mg/kg)	5	0	0	0.5	0.98	0.70	1.5	0.25	2.1/3.5

Table 16. Statistical summary of bed-sediment constituents measured on bulk sediment for samples collected during 2017 in Currituck Sound, North Carolina.—Continued

[%, percent; mg/kg, milligram per kilogram; µg/kg, microgram per kilogram; <, less than; —, not applicable; E, estimated concentration]

Constituent (unit)	Bed-sediment constituent concentrations based on bulk sediment, 2017							Station(s)[1] with minimum detected concentration	Station(s)[1] with maximum detected concentration
	Number of detected concentrations	Number of censored concentrations	Number of censoring levels	Minimum value	Mean value	Median value	Maximum value		
Titanium (%)	5	0	0	0.21	0.35	0.35	0.46	0.25	4.5
Uranium (mg/kg)	5	0	0	0.382	1.33	0.979	2.67	0.25	2.1
Vanadium (mg/kg)	5	0	0	9.4	26.7	18.4	57.0	0.25	2.1
Zinc (mg/kg)	5	0	0	7.4	24.2	16.3	51.8	0.25	2.1
Semi-volatile organic compounds									
2,6-Dimethlnaphthalene (µg/kg)	3	2	1	7.4	—	—	16	1.2	2.1
9,10-Anthraquinone (µg/kg)	1	4	1	28	—	—	28	2.1	2.1
Fluoranthene (µg/kg)	2	3	1	E11	—	—	E11	2.1/3.5	2.1/3.5
Perylene (µg/kg)	2	3	1	E16	—	—	58.0	3.5	2.1

[1] Number of miles from the east bank of Currituck Sound near Corolla, North Carolina (see fig. 1).

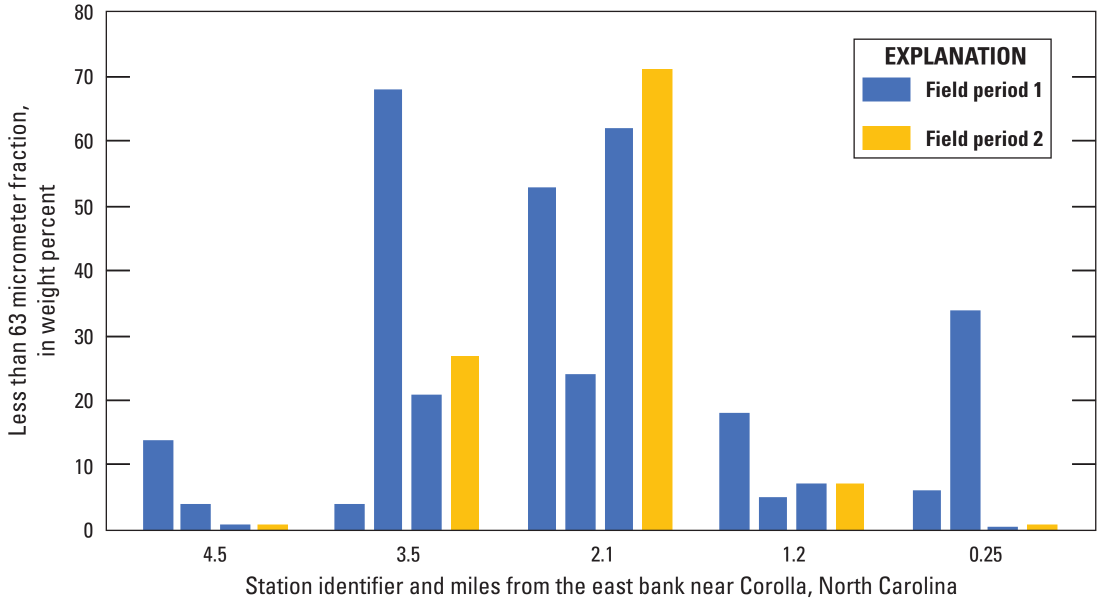


Figure 11. Graph showing summary of the less than 63-micrometer fraction of bed sediments measured at 5 sampling sites for samples collected during field periods 1 and 2 in Currituck Sound, North Carolina, 2011–18.

Summary

The North Carolina Turnpike Authority, a division of the North Carolina Department of Transportation, plans to improve transportation in the Currituck Sound area by constructing a two-lane bridge—the Mid-Currituck Bridge—from U.S. Highway 158, south of Coinjock, North Carolina, to North Carolina Highway 12 on the Outer Banks, south of Corolla, North Carolina. The results of the FEIS associated with the bridge project indicate potential impacts to water quality and biotic communities in Currituck Sound related to stormwater runoff, localized turbidity and sedimentation during construction, altered light levels, and the introduction of piles as hard substrate (Federal Highway Administration and North Carolina Turnpike Authority, 2012).

The primary objective of this study was to document baseline water-quality conditions and the bed-sediment chemistry of Currituck Sound in the vicinity of the planned Mid-Currituck Bridge, which can be used to evaluate potential effects associated with the bridge construction and bridge deck runoff from the completed bridge. Discrete water-quality samples were collected monthly and following selected storm events, at five locations in Currituck Sound from 2011 to 2018. All five locations were distributed along the planned alignment of the Mid-Currituck Bridge. Samples were analyzed for water quality physical properties and chemical constituents that are associated with bridge deck stormwater runoff and are important to estuarine waters. Bed-sediment samples were also collected for chemical analyses, on four occasions, at each sampling site.

The U.S. Geological Survey collected continuous water-level and wind-speed and direction data in Currituck Sound during the study period. The circulation dynamics in the vicinity of the planned bridge were measured during most sampling events using an ADCP. The ADCP velocity data can be used to characterize and compare the circulation dynamics and how they relate to water quality in the study area before construction of the Mid-Currituck Bridge.

The bias and precision of laboratory-derived constituent concentrations were assessed through various quality-control samples. Four constituents in water samples were deemed likely to have a positive bias: dissolved ammonia, dissolved and total zinc, and bis(2-ethyhexyl)phthalate. During the study, SVOCs were rarely detected in water samples; however, these results may have been influenced by matrix interference effects. The results for replicate sample pairs indicated acceptable reproducibility for most water-quality constituents.

Matrix-spike samples for bed sediment showed acceptable recoveries for most constituents, except for unacceptably low recoveries for 37 SVOCs in a 2012 matrix spike. These results indicate that SVOC concentrations determined on the fine fraction of samples during field period 1 may potentially be biased low. Better recoveries were noted in the 2017 matrix spike performed on bulk sediment, for which only 9 SVOCs had recoveries less than 75 percent. Analyses of field replicates indicated acceptable reproducibility for most constituents, but the variability of most SVOCs could not be assessed due to the prevalence of left-censored values in the sample sets.

This characterization of baseline water-quality conditions focused on physical properties and chemical constituents previously identified as POCs associated with bridge deck runoff in North Carolina. Other important water-quality properties and constituents, such as dissolved oxygen, specific conductance, turbidity, bacteria, chlorophyll *a*, and cyanotoxins, were also analyzed.

During the 2011 to 2018 study period, few water samples had constituent concentrations that exceeded water-quality thresholds (2.6 percent; 130 out of 5,107 constituent results). Concentrations above the thresholds were observed for 10 properties or constituents. Six of these properties and constituents had exceedances in 5 percent or more of the samples, including chlorophyll *a*, bis(2-ethylhexyl)phthalate, pH, turbidity, Enterococci, and pentachlorophenol. Several constituents, chiefly dissolved copper, dissolved silver, bis(2-ethylhexyl)phthalate, and pentachlorophenol, had high numbers of censored results with elevated LRLs such that it could not be determined whether those samples were above or below corresponding thresholds. The results for bis(2-ethylhexyl)phthalate should be used with caution because contamination of this compound may have occurred during field sampling or laboratory analysis.

Water-quality differences were evaluated among sampling-event types (routine and post-storm), stations, and seasons. Results indicated that water sampled along the planned bridge alignment was well mixed vertically and horizontally but varied temporally. No differences in water quality were observed among the five sampling sites or samples collected at top or bottom depths. Storm-related samples had lower specific conductance and higher concentrations of turbidity, total P, total aluminum, total arsenic, and total lead than routine, non-storm samples. Seasonal changes in water quality best explained the variations in water-quality conditions in Currituck Sound during the study period.

Water temperature, pH, specific conductance, total arsenic, total manganese, total cylindrospermopsins, and total microcystins plus nodularins tended to have higher values during warm seasons. Ammonia plus organic N, total N, and chlorophyll *a* also had higher concentrations during the summer, but lower concentrations tended to occur during the spring. Dissolved oxygen, turbidity, total P, total aluminum, total iron, and total lead tended to be higher during cool seasons.

The relative abundance of four phytoplankton groups—cyanobacteria, diatoms, green algae, and cryptophytes—was also similar among sites but varied among seasons. Total cyanobacteria densities were lower in the winter and higher during the spring through fall period, whereas total cryptophyte densities were higher in the winter and lower during the spring through fall period. Cyanobacteria constituted the most abundant group of phytoplankton.

Three organisms dominated the cyanobacterial community: *Cylindrospermopsis raciborskii*, *Planktolyngbya limnetica*, and *Planktolyngbya* cf. *contorta*. Trends in the densities of these species were like those observed for chlorophyll *a* and two of the cyanotoxin classes (total cylindrospermopsins and total microcystins plus nodularins). Total concentrations of cylindrospermopsins and microcystins plus nodularins were typically highest in the summer when the abundance of cyanobacteria was also high.

Antecedent wind speed and direction data were examined relative to water-quality conditions observed in Currituck Sound. Winds from a more northerly direction tended to push water out of the Sound, thereby decreasing water levels and conductivity-salinity. Winds from a more southerly direction tended to push water up into the Sound, thereby increasing water levels and conductivity-salinity. Conversely, turbidity and concentrations of total P, total iron, and total lead tended to be higher when water levels were lower, possibly reflecting the increased resuspension of bottom materials from wind-driven wave action. Results indicate that wind conditions are important, influential factors on hydrologic and water-quality conditions in Currituck Sound.

Water-velocity magnitudes and directions were highly variable, both spatially and temporally, in the study area. Mean water velocities at the sites were typically less than 0.5 ft/s and rarely exceeded 1 ft/s during sampling events. Water-flow directions were most frequently toward the south and southwest.

Bed-sediment chemistry was compared to sediment-quality guidelines for 12 metals and 10 SVOCs. Few samples contained concentrations that exceeded screening levels. Only 4 of the 12 metals (arsenic, barium, nickel, and tin) had concentrations in 1 or more samples above the most conservative screening value. None of the SVOCs had detected concentrations above any of the screening levels. However, many of the SVOCs had high numbers of censored results with elevated LRLs such that it could not be determined whether those samples were above or below the screening levels.

The weight percent of fines in bed sediments varied both spatially and temporally. The concentration of fines ranged from less than 1 percent at the shallower, nearshore sites to more than 60 percent at the deeper sites in the Sound. Construction of the Mid-Currituck Bridge could influence water circulation dynamics along with the transport, deposition, and resuspension patterns of sediment particles near the study sites. These physical processes, combined with sediment, debris, and chemical inputs from bridge runoff, could potentially alter the chemical composition of bed sediment in the vicinity of the bridge alignment.

The characterization of baseline water-quality and bed-sediment chemistry in Currituck Sound along the planned alignment of the Mid-Currituck Bridge, as summarized herein, provides a baseline to which comparisons can be made to determine if, and to what extent, bridge construction and bridge deck runoff from the completed bridge may affect environmental conditions in Currituck Sound.

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