Prepared in cooperation with the Georgia Environmental Protection Division, the South Carolina Department of Natural Resources, and the U.S. Environmental Protection Agency

Continuous Tidal Streamflow, Water Level, and Specific Conductance Data for Union Creek and the Little Back, Middle, and Front Rivers, Savannah River Estuary, November 2008 to March 2009

Open-File Report 2010–1169

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

Cover. Savannah River looking upstream at Georgia Highway 25, near Port Wentworth, Georgia. (Photo by USGS staff, January 2009.)

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KEN SALAZAR, Secretary

U.S. Geological Survey
Marcia K. McNutt, Director

U.S. Geological Survey, Reston, Virginia: 2010

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Suggested citation:
Lanier, T.H., and Conrads, P.A., 2010, Continuous tidal streamflow, water level, and specific conductance data for Union Creek and the Little Back, Middle, and Front Rivers, Savannah River Estuary, November 2008 to March 2009: U.S. Geological Survey Open-File Report 2010–1169, 25 p.

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Conversion Factors and Datums

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Flow rate	
foot per second (ft/s)	0.3048	meter per second (m/s)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

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

$$°F = (1.8 \times °C) + 32$$

Vertical coordinate information is referenced to the National Geodetic Vertical Datum of 1929 (NGVD 29).

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

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

Acronyms Used in this Report

ADCP acoustic Doppler current profiler

GPA Georgia Ports Authority

NWIS National Water Information System

NWR National Wildlife Refuge

R^2 coefficient of determination

TMDL total maximum daily load

USGS U.S. Geological Survey

3-D three dimensional

Continuous Tidal Streamflow, Water Level, and Specific Conductance Data for Union Creek and the Little Back, Middle, and Front Rivers, Savannah River Estuary, November 2008 to March 2009

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Abstract

In the Water Resource Development Act of 1999, the U.S. Congress authorized the deepening of the Savannah Harbor. Additional studies were then identified by the Georgia Ports Authority and other local and regional stakeholders to determine and fully describe the potential environmental effects of deepening the channel. One need that was identified was the validation of a three-dimensional hydrodynamic model developed to evaluate mitigation scenarios for a potential harbor deepening and the effects on the Savannah River estuary. The streamflow in the estuary is very complex due to reversing tidal flows, interconnections of streams and tidal creeks, and the daily flooding and draining of the marshes. The model was calibrated using very limited streamflow data and no continuous streamflow measurements.

To better characterize the streamflow dynamics and mass transport of the estuary, two index-velocity sites were instrumented with continuous acoustic velocity, water level, and specific conductance sensors on the Little Back and Middle Rivers for the 5-month period of November 2008 through March 2009. During the same period, a third acoustic velocity meter was installed on the Front River just downstream from U.S. Geological Survey streamgaging station 02198920 (Savannah River at GA 25, at Port Wentworth, Georgia) where water level and specific conductance data were being collected. A fourth index-velocity site was instrumented with continuous acoustic velocity, water level, and specific conductance sensors on Union Creek for a 2-month period starting in November 2008. In addition to monitoring the tidal cycles, streamflow measurements were made at the four index-velocity sites to develop ratings to compute continuous discharge for each site. The maximum flood (incoming) and ebb (outgoing) tides measured on Little Back River were –4,570 and 7,990 cubic feet per second, respectively. On Middle River, the maximum flood and ebb tides measured were –9,630 and 13,600 cubic feet per second, respectively. On Front River, the maximum flood and ebb tides were –34,500 and 43,700 cubic feet per second, respectively; and on Union Creek, the maximum flood and ebb tides were –2,390 and 4,610 cubic feet per second, respectively. During the 5-month instrumentation deployment, computed tidal streamflows on Little Back River ranged from –7,820 to 9,600 cubic feet per second for the flood and ebb tides, respectively. On Middle River, the computed tidal streamflows ranged from –17,500 to 22,500 cubic feet per second for the flood and ebb tides, respectively. The computed tidal streamflows on Front River ranged from –78,900 to 87,200 cubic feet per second, and from –3,850 to 6,130 cubic feet per second on Union Creek for the flood and ebb tides, respectively. The streamgages on the Little Back, Middle, and Front Rivers have continued in operation following the initial 5-month deployment.

Introduction

The Savannah River estuary, as with many major estuarine systems, meets many local and regional water-resource needs. The tidal reaches of the Savannah River provide water supply for coastal South Carolina and Georgia, an extensive freshwater marsh habitat, assimilative capacity for municipal and industrial dischargers, and navigational access for a major shipping terminal on the east coast (fig. 1). The shipping channel extends from the Savannah Harbor up to Port Wentworth, GA. Salinity intrudes to the area where I-95 crosses the Savannah River. Increasing industrial and residential development in Georgia and South Carolina is accompanied by competing and often conflicting interests in the water resources of the Savannah River.

Two important resources are located in the Savannah River estuary—the Savannah National Wildlife Refuge (NWR) and the Georgia Ports Authority (GPA; fig. 2). The tidal freshwater marsh is an essential part of the 29,000-acre Savannah NWR (U.S. Fish and Wildlife Service, 2009), which is located between river mile 18 and river mile 40 and is home to a diverse variety of wildlife and plant communities. Near the Savannah NWR is the GPA, which maintains two deep-water terminal facilities—Garden City Terminal and Ocean Terminal (fig. 2). To support navigation and the terminal activities of the GPA, the river channel and turning basins are

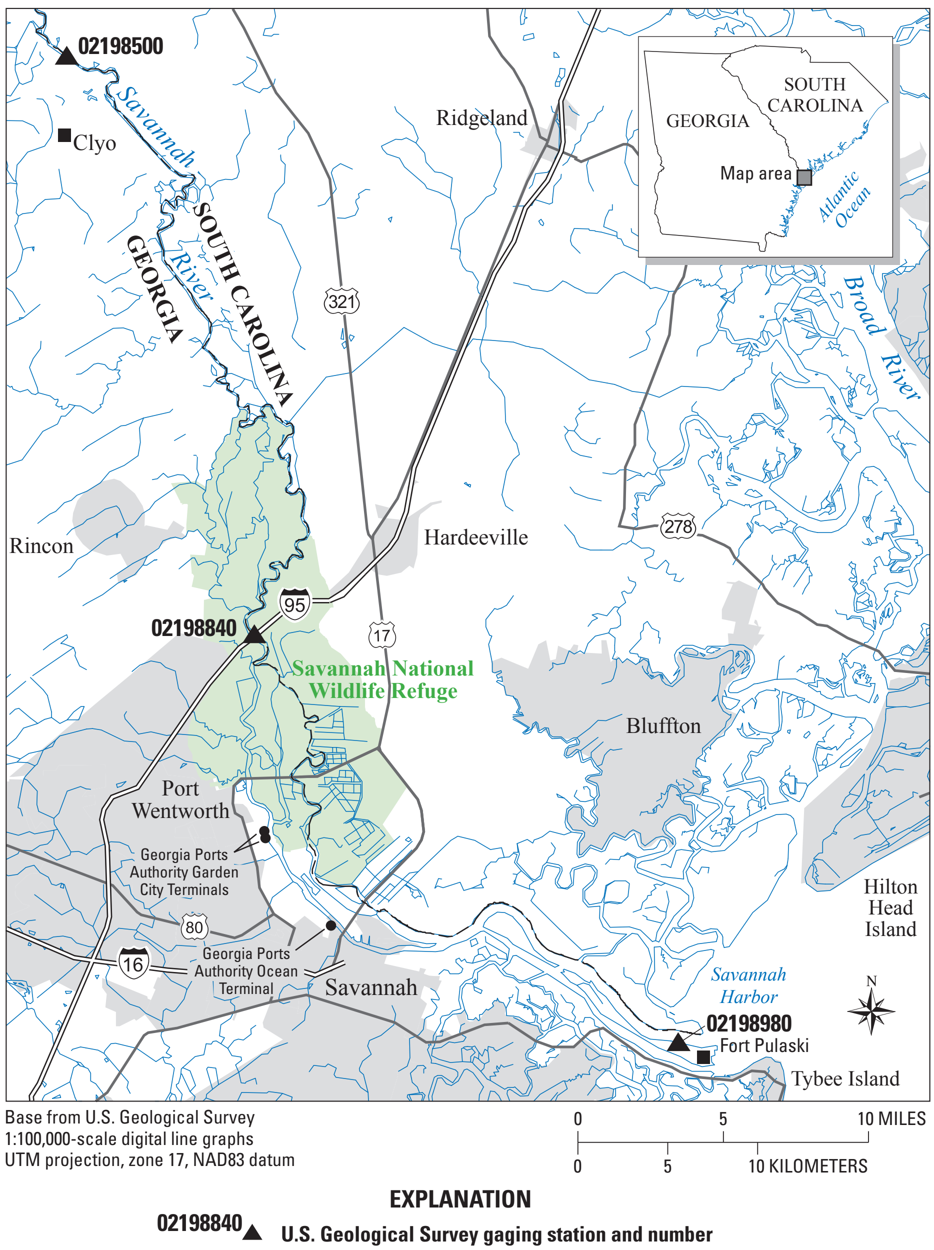

Figure 1. Location of the study area in the vicinity of the Savannah National Wildlife Refuge, in coastal South Carolina and Georgia.

maintained by dredging from below Houlihan Bridge on State route 25 (GA 25) to approximately 20 miles offshore from the harbor entrance.

Previous studies have shown that the salinity gradient is important in shaping the vegetative communities of a tidal marsh (Odum and others, 1984; Latham, 1990; Gough and Grace, 1998; Howard and Mendelsson, 1999). The freshwater-dominated parts of the tidal marsh may be the most sensitive of the tidal marshes to alterations of environmental gradients. Freshwater tidal marshes generally have a greater diversity of plant communities compared to saltwater tidal marshes. In the late 1970s, the tidal freshwater wetlands of the lower Savannah River were estimated to cover 5,538 acres (Tiner, 1977). Since that time, the amount of tidal freshwater marsh in the Savannah River estuary has been reduced by approximately 60 percent (3,269 acres) of its previously estimated size (E. EuDaly, retired, U.S. Fish and Wildlife Service, written commun., December 2009). The remaining tidal freshwater marsh is an essential part of the 29,000-acre Savannah NWR.

In the Water Resource Development Act of 1999, the U.S. Congress authorized the deepening of the Savannah Harbor. Additional studies were then identified by GPA and other local and regional stake holders which would determine and fully describe the potential environmental effects of deepening the channel. One need that was identified was the validation of the three-dimensional (3-D) model previously

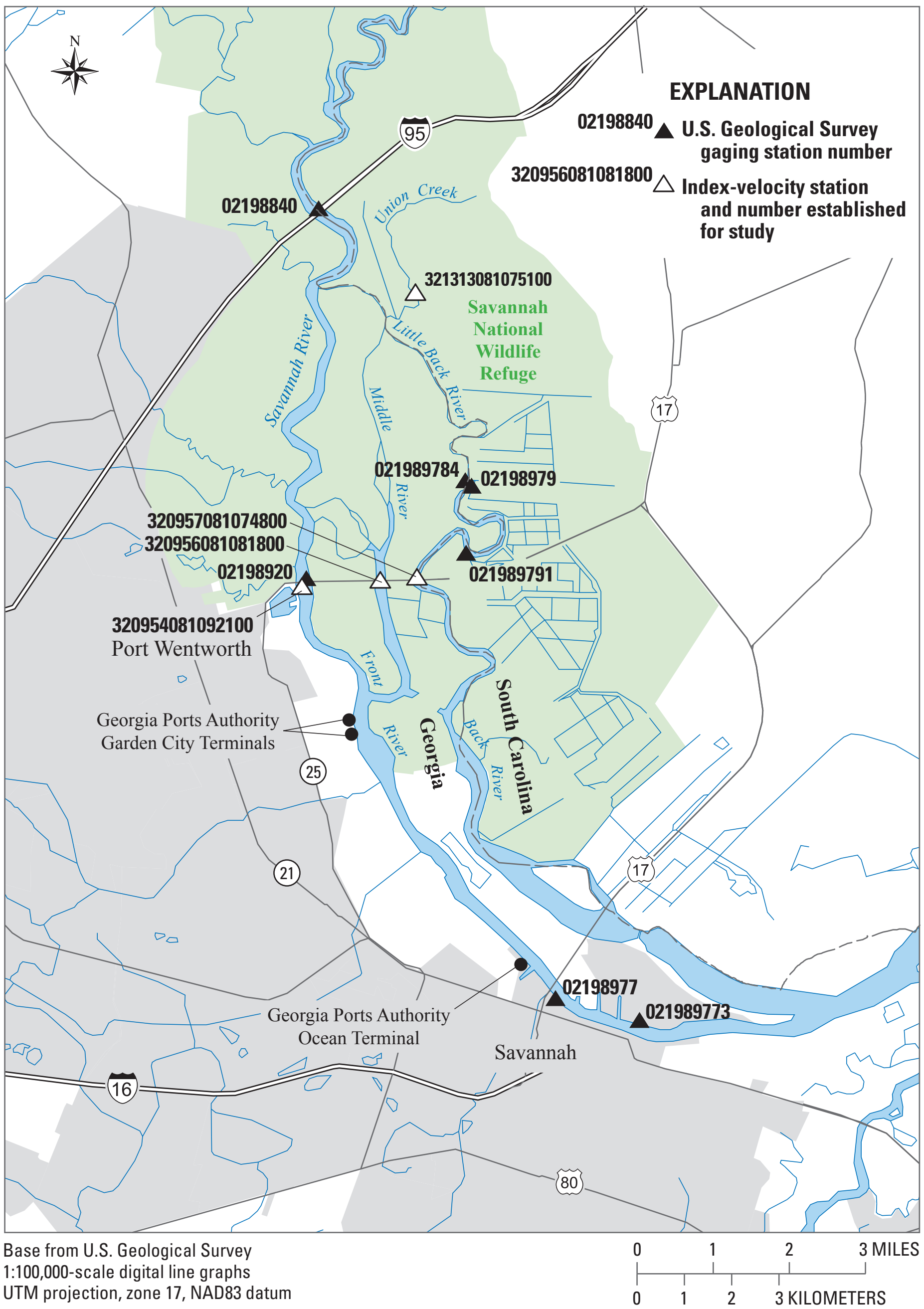

Figure 2. Location of index-velocity sites established for this study on Little Back River, Middle River, Front River, and Union Creek, along with the U.S. Geological Survey network of gages, in the vicinity of the Savannah National Wildlife Refuge.

Base from U.S. Geological Survey
1:100,000-scale digital line graphs
UTM projection, zone 17, NAD83 datum

developed to evaluate mitigation scenarios for the harbor deepening and its effects on the Savannah River estuary. The streamflow in the estuary is very complex due to reversing tidal flows, interconnections of streams and tidal creeks, and daily flooding and draining of the marshes. When the 3-D model was originally developed, it was calibrated with limited streamflow data collected in 1997 and 1999 (Tetra Tech, Inc., 2006) during 1 to 3 tidal cycles (7–14 hours) at 18 locations throughout the model domain. No continuous streamflow measurements were used in calibrating the model. At the beginning of this study (November 2008), only one U.S. Geological Survey (USGS) index-velocity site (station 021989773, fig. 2) was in operation in the study area, which is located at the U.S. Army Corps of Engineers dock. This station was established in May 2007. In 2008, the USGS in cooperation with Georgia Environmental Protection Division, the South Carolina Department of Natural Resources, and the U.S. Environmental Protection Agency initiated an investigation to better characterize the streamflow dynamics and the mass transport of the interconnected river system of the Savannah River estuary.

Purpose and Scope

An important part of the USGS mission is to provide scientific information for effective management of the Nation's water resources. To assess the quantity and quality of the Nation's surface water, the USGS collects hydrologic and water-quality data from rivers, lakes, estuaries, and wetlands using standardized methods, and maintains the data from these stations in a national database. This report documents the development of the four index velocity sites on the Lower Savannah River estuary for the measurement of continuous tidal streamflow. The geographical extents of the study are the four index velocity sites established on the Little Back River, Middle River, and Front River and on Union Creek. For this study, the Little Back, Middle, and Front River index-velocity sites were maintained from November 20, 2008, to March 24, 2009. The Union Creek site was maintained from November 25, 2008, to January 28, 2009. The three gages on the Little Back, Middle, and Front Rivers have continued in operation after the initial 5-month deployment and study.

Data Collection

The USGS has been monitoring the lower Savannah River since 1929 with the streamgage near Clyo, GA (station 02198500, fig.1). The data-collection network in the Savannah River estuary was established in the late 1980s on the Back and Front Rivers (fig. 2) and at Fort Pulaski (fig. 1). The USGS streamgages in the Savannah River estuary are part of the USGS National Water Information System (NWIS) database and are available in near real time on the Web (U.S. Geological Survey, 2008). The USGS maintains the NWIS database for the storage and retrieval of water data collected at approximately 1.5 million sites around the country as part of the USGS program for disseminating water data to the public. The locations of active streamgages during this study and inactive gages in the study area are listed in table 1 and shown in figures 1 and 2.

To compute continuous tidal streamflows, four index-velocity sites were instrumented with continuous acoustic velocity meters (AVM) in November 2008 and data were collected for 2–5 months for this study. Index velocity is a continuous measure of a portion (for example, a point or an integrated line measurement) of the velocity in a cross section. To compute continuous streamflow, the index velocity is converted to a mean velocity for the cross section. These index-velocity sites were located on Little Back River at the GA 25 bridge, Middle River at GA 25, Savannah (Front) River at GA 25, and Union Creek approximately 0.8 miles upstream from the confluence with Little Back River (fig. 2). The Front River site is the same location as USGS streamgaging station 02198920 (Savannah River at US 17, at Port Wentworth, GA). In addition to velocity, water level and specific conductance sensors were installed at the Union Creek, Little Back, and Middle River sites. Water level and specific conductance data from station 02198920 were used for the Front River index-velocity site.

At the Little Back and Middle River locations, instrumentation mounts for the acoustic velocity meters were attached to concrete bridge piers (figs. 3, 4). On the Front River, the mount was attached to the downstream right side of the pier fender, approximately 35 feet (ft) downstream from USGS station 02198920 (fig. 5). On Union Creek, the instrumentation mount was installed on the right bank (fig. 6).

In addition to tidal velocities, water level (hereafter referred to as stage) and specific conductance were monitored, and physical measurements of streamflow and channel geometry were made at the four index-velocity sites. A series of streamflow measurements were made on randomly selected days, twice during the monitoring period covering the entire tidal cycle at each of the sites. These measurements were used to develop the relation between the index velocity and mean velocity for each site. For the GA 25 bridge sites (Little Back, Middle, and Front Rivers), channel geometries were computed by measuring water surface and water depth from uniform positions along the downstream side of the bridge. For the Union Creek site, the streamflow measurements were used to determine the channel geometry. Once determined, the channel geometries were used to develop a stage–area relation at each site.

(Above) Figure 3. View of the instrumentation mount and housing at the Little Back River continuous index-velocity site, Lower Savannah River estuary, coastal South Carolina and Georgia (320957081074800; see fig. 2 for location).

(Right) Figure 4. View of the instrumentation mount and housing at the Middle River continuous index-velocity site, Lower Savannah River estuary, coastal South Carolina and Georgia (320956081081800; see fig. 2 for location).

(Above) Figure 5. View of the instrumentation mount and housing at the Front River continuous index-velocity site, Lower Savannah River estuary, coastal South Carolina and Georgia (320954081092100; see fig. 2 for location).

(Right) Figure 6. View of the instrumentation mount and housing at the Union Creek continuous index-velocity site, Lower Savannah River estuary, coastal South Carolina and Georgia (321313081075100; see fig. 2 for location).

Table 1. U.S. Geological Survey continuous river gaging network for the Lower Savannah River estuary, coastal South Carolina and Georgia, for the period of record.

[NAD 83, North American Datum of 1983; Q, flow; SC, specific conductance; V, velocity; WL, water level; USACE, U.S. Army Corp of Engineers; F & W, U.S. Fish and Wildlife; USFW, U.S. Fish and Wildlife]

Station number (fig. 2)	Station name	Station name used in this report	Physical properties	Period of record	Longitude (decimal degrees, NAD 83)	Latitude (decimal degrees, NAD 83)
02198500	Savannah River near Clyo, GA	Clyo	Q	October 1929 – 2010	–81.26888	32.52806
02198840	Savannah River near Port Wentworth, GA	I-95 Bridge	WL, SC	June 1986 – 2010	–81.15139	32.23555
02198920	Savannah River at GA 25, at Port Wentworth, GA	Front River at Houlihan Bridge	WL, SC	October 1987 – 2010	–81.15388	32.16583
02198977	Savannah River at Broad Street, at Savannah, GA	Front River at Broad Street	WL	October 1987 – September 2006	–81.09583	32.08388
021989773	Savannah River at USACE Dock, at Savannah, GA	Front River at USACE	V, SC, WL, Q	May 2007 – 2010	–81.08139	32.08083
021989784	L Back River above Lucknow Canal, near Limehouse, SC	Lucknow Canal	SC, WL	May 1990 – 2010	–81.11805	32.18555
02198979	Little Back River at Lucknow Canal, near Limehouse, SC	Limehouse	WL	June 1987 – 2010	–81.11722	32.18472
021989791	Little Back River at F & W Dock, near Limehouse, SC	USFW Dock	SC	October 1989 – 2010	–81.11833	32.17055
02198980	Savannah River at Fort Pulaski, GA	Fort Pulaski	WL	October 1987 – 2010	–80.90333	32.03388
320957081074800	Little Back River @ GA 25 near Port Wentworth, GA	Little Back River	V, SC , WL , Q	November 2008 – 2010	–81.13000	32.16583
320956081081800	Middle River @ GA 25 near Port Wentworth, GA	Middle River	V, SC, WL, Q	November 2008 – 2010	–81.13833	32.16555
320954081092100[a]	Savannah River @ GA 25 near Port Wentworth, GA	Front River	V, Q	November 2008 – 2010	–81.15583	32.16500
321313081075100	Union Creek below I-95 near Hardeeville, SC	Union Creek	V, SC, WL, Q	November 2008 – January 2009	–81.13083	32.22027

[a] Index-velocity station is located 35 feet downstream of station 02198920.

Continuous Velocity, Stage, and Specific Conductance Data

For this study, the Little Back, Middle, and Front River index-velocity sites were maintained from November 20, 2008, to March 24, 2009. The Union Creek site was maintained from November 25, 2008, to January 28, 2009. All four sites were instrumented with Argonaut-SL (side-looker) acoustic Doppler velocity meters (SonTek/YSI Inc., 2008). In addition, the Union Creek, Middle River, and Little Back River sites were instrumented with Aqua-TROLL® 100s for measuring stage and specific conductance (In-Situ, Inc., 2009).

At the Little Back River site, the velocity meter collected data in bin intervals from 6.6 to 39.4 ft (2–12 meters [m]) from the instrument. At the Middle River site, the bin intervals were from 3.3 to 14.8 ft (1–4.5 m). The bin intervals at the Front River site were 6.6 to 62.3 ft (2–19 m), and from 6.6 to 42.6 ft (2–13 m) from the instrument at the Union Creek site. At all four sites, a 100-second averaging interval was used prior to the 15-minute data-collection interval. The 15-minute time series of stage (figs. 7, 8), specific conductance (figs. 9, 10), and velocity (figs. 11, 12) are given for the Little Back, Middle, and Front Rivers and for Union Creek, respectively. The data indicate a typical semidiurnal tidal cycle of two low tides and two high tides per day. Because of equipment malfunction, velocity data are missing for Front River from December 18, 2008, to January 6, 2009 (fig. 11*C*).

During the data-collection period, the tidal range (elevation difference between one high and low tide) was 11.4 ft for Little Back River, 12.2 ft for Middle River, 12.6 ft for Front River, and 10.6 ft for Union Creek. The maximum flood-tide velocity (negative flow) was –1.6 feet per second (ft/s) on Little Back River, –2.2 ft/s on Middle River, –3.0 ft/s on Front River, and –1.5 ft/s on Union Creek. Maximum ebb-tide velocity (positive flow) was 2.0 ft/s on Little Back River, 2.9 ft/s on Middle River, 3.6 ft/s on Front River, and 2.8 ft/s on Union Creek. In addition, the maximum flood-tide specific conductance was 12,400 microsiemens per centimeter (µS/cm) on Little Back River, 22,300 µS/cm on Middle River, 27,400 µS/cm on Front River, and 835 µS/cm on Union Creek. The minimum ebb-tide specific conductance was 96 µS/cm on Little Back River, 89 µS/cm on Middle River, 76 µS/cm on Front River, and 79 µS/cm on Union Creek.

Discrete Streamflow Measurements

Twice during the deployment, tidal-cycle streamflow measurements were made during a 10- to 12-hour period at the four index-velocity sites using a 1,200-kilohertz Rio Grande acoustic Doppler current profiler (ADCP; Teledyne RD Instruments, 2008) or a 1,500-kilohertz RiverCAT ADCP (SonTek/YSI Inc., 2004). On Little Back River, Middle River, and Union Creek, these measurements were made on January 6 and 27, 2009. On Front River, the measurements were made on January 27 and March 23, 2009. Quality-assurance procedures described in Oberg and others (2005) were followed for the streamflow measurements, which are shown in figures 13–16. Stage measurements also are included in these figures to show where in the tidal cycle the streamflow measurements were made.

The maximum streamflows measured during flood tide and ebb tide occurred on January 27, 2009, at all four index-velocity sites (table 2). The maximum flood-tide and ebb-tide streamflows were –4,570 and 7,990 cubic feet per second (ft^3/s), respectively, on Little Back River; –9,630 and 13,600 ft^3/s, respectively, on Middle River; –34,500 and 43,700 ft^3/s, respectively, on Front River; and –2,390 and 4,610 ft^3/s, respectively, on Union Creek for two measurement periods.

Table 2. Maximum streamflow measured during flood and ebb tides at the index-velocity stations on Little Back River, Middle River, Front River, and Union Creek, Lower Savannah River estuary, coastal South Carolina and Georgia, January 6 and 27, 2009, and March 23, 2009.

[ft^3/s, cubic feet per second; N/A, not applicable]

Location	January 6, 2009		January 27, 2009		March 23, 2009	
	Flood tide (ft^3/s)	Ebb tide (ft^3/s)	Flood tide (ft^3/s)	Ebb tide (ft^3/s)	Flood tide (ft^3/s)	Ebb tide (ft^3/s)
Little Back River	–3,970	6,850	–4,570	7,990	N/A	N/A
Middle River	–9,030	4,000	–9,630	13,600	N/A	N/A
Front River	N/A	N/A	–34,500	43,700	–32,400	24,400
Union Creek	–1,850	1,590	–2,390	4,610	N/A	N/A

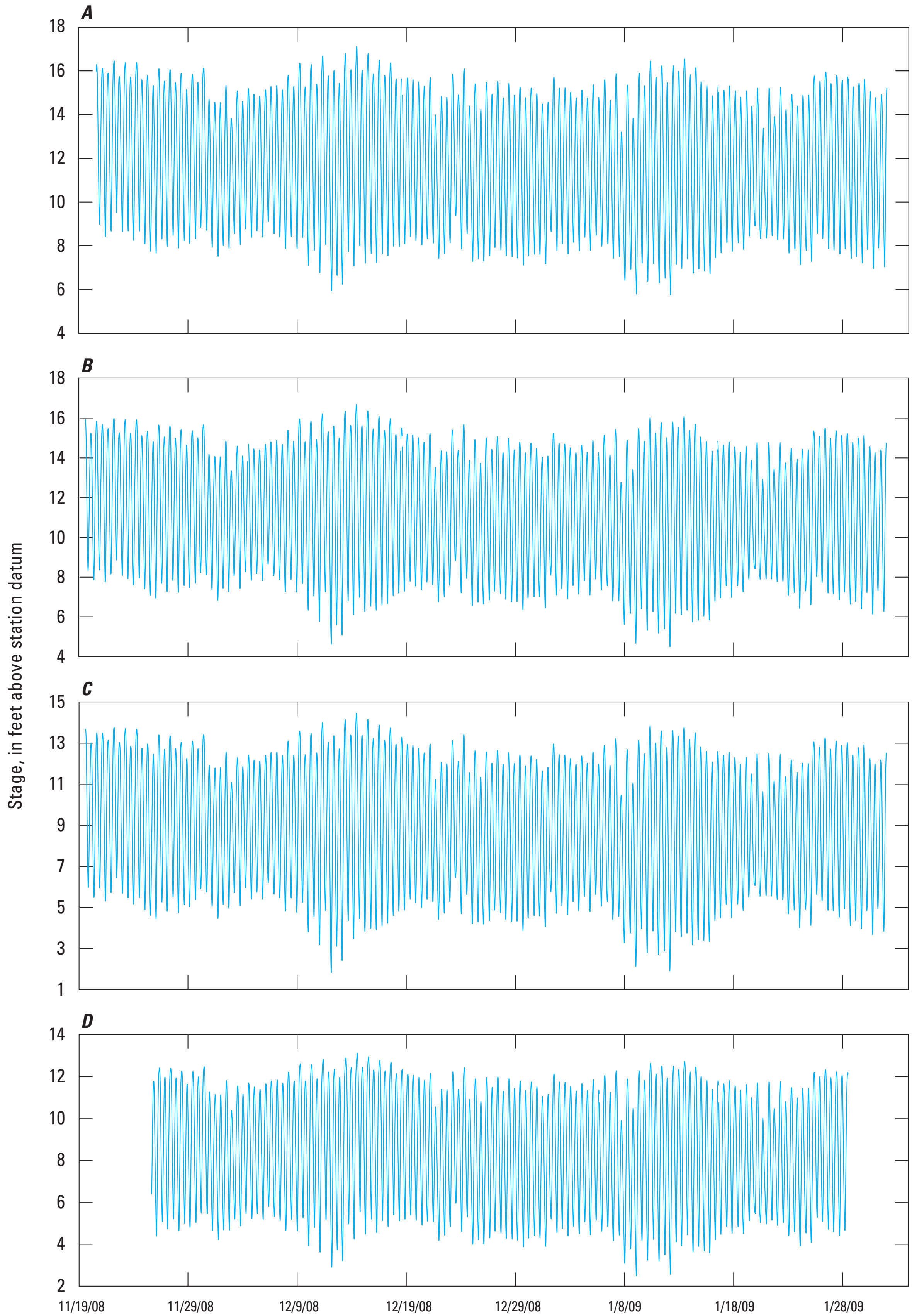

Figure 7. Stage for *(A)* Little Back River, *(B)* Middle River, *(C)* Front River, and *(D)* Union Creek, Lower Savannah River estuary, coastal South Carolina and Georgia, November 20, 2008, to January 30, 2009.

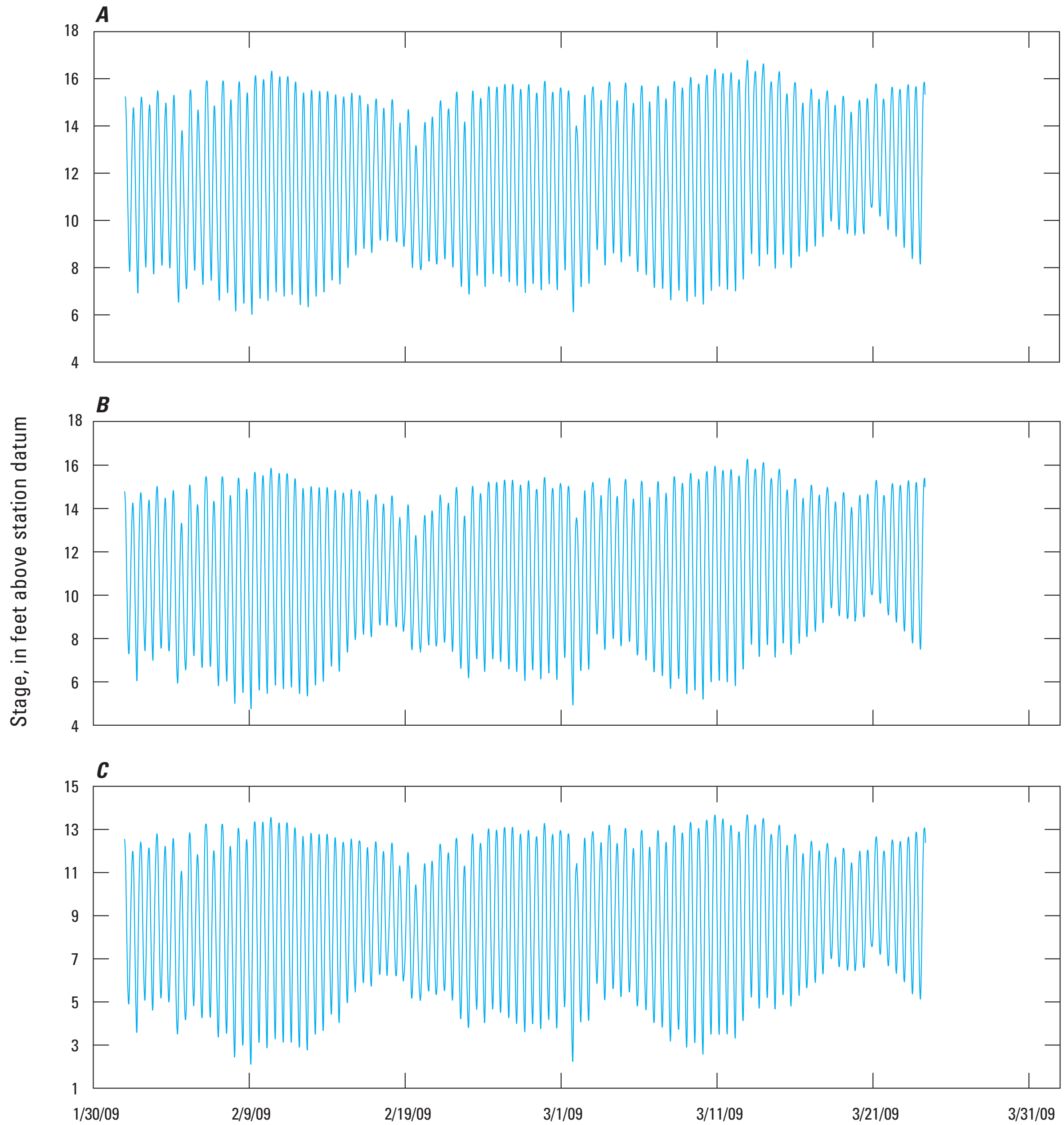

Figure 8. Stage for *(A)* Little Back River, *(B)* Middle River, and *(C)* Front River, Lower Savannah River estuary, coastal South Carolina and Georgia, February 1 to March 24, 2009.

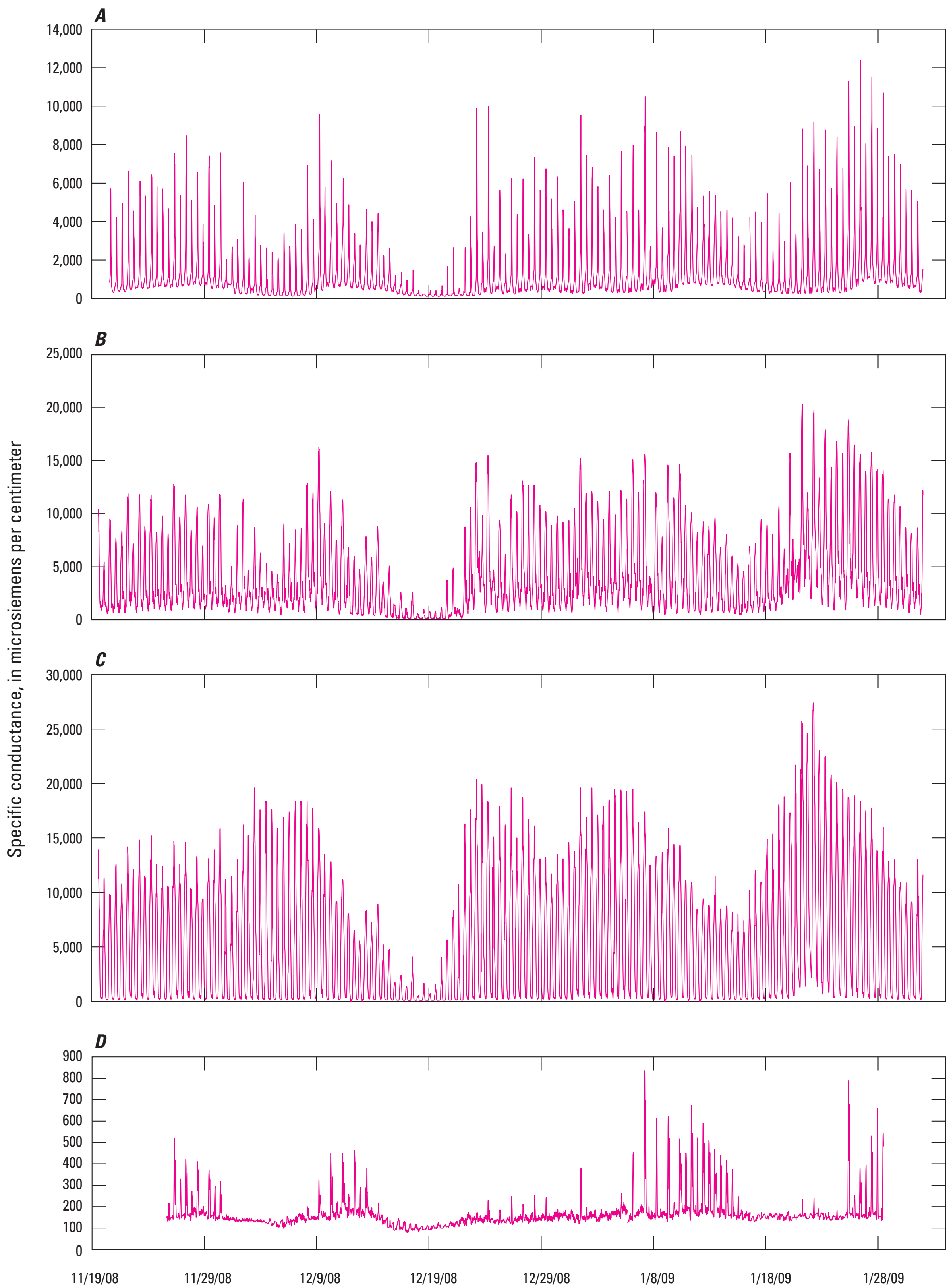

Figure 9. Specific conductance for *(A)* Little Back River, *(B)* Middle River, *(C)* Front River, and *(D)* Union Creek, Lower Savannah River estuary, coastal South Carolina and Georgia, November 20, 2008, to January 30, 2009.

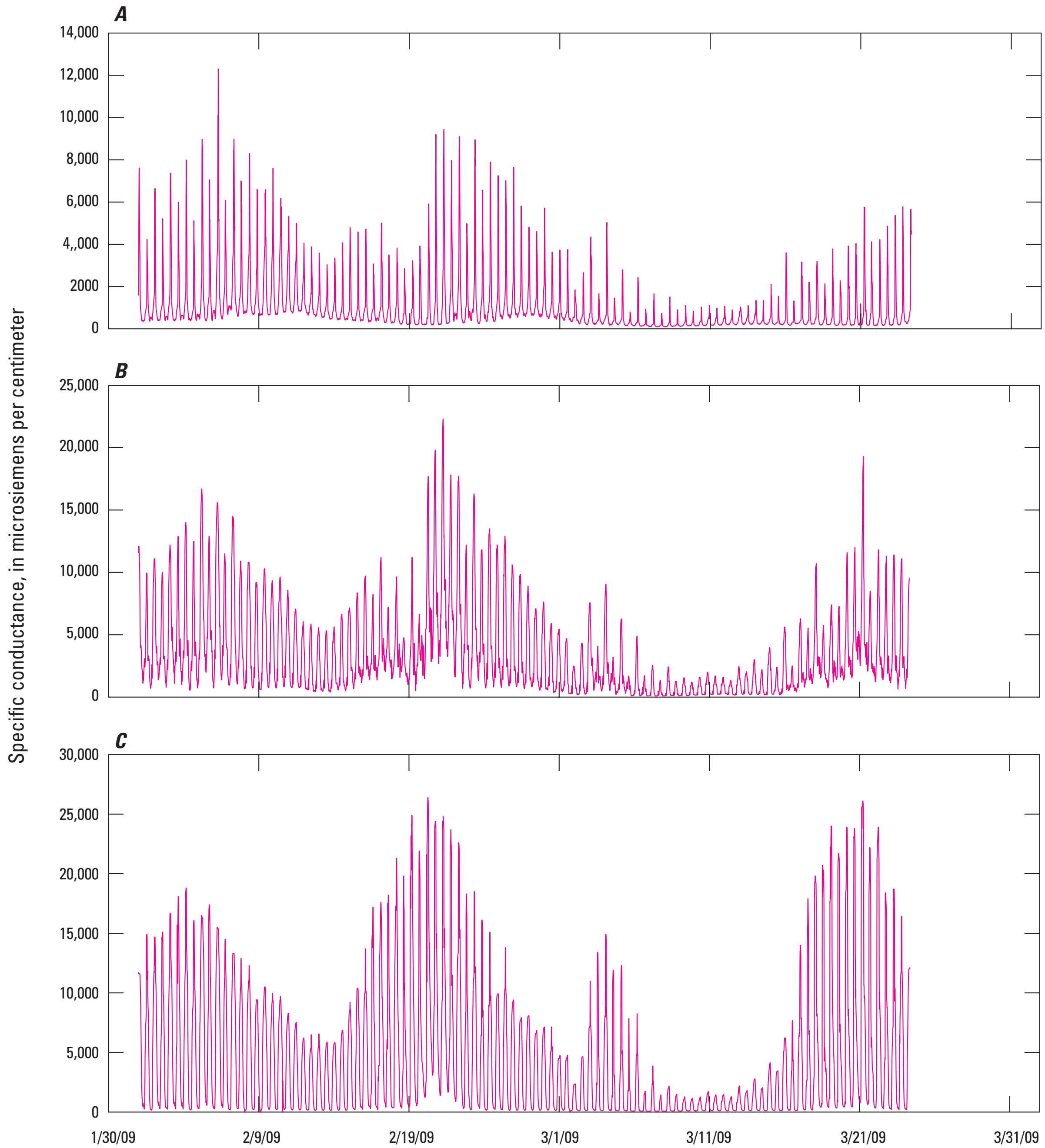

Figure 10. Specific conductance for *(A)* Little Back River, *(B)* Middle River, and *(C)* Front River, Lower Savannah River estuary, coastal South Carolina and Georgia, February 1 to March 24, 2009.

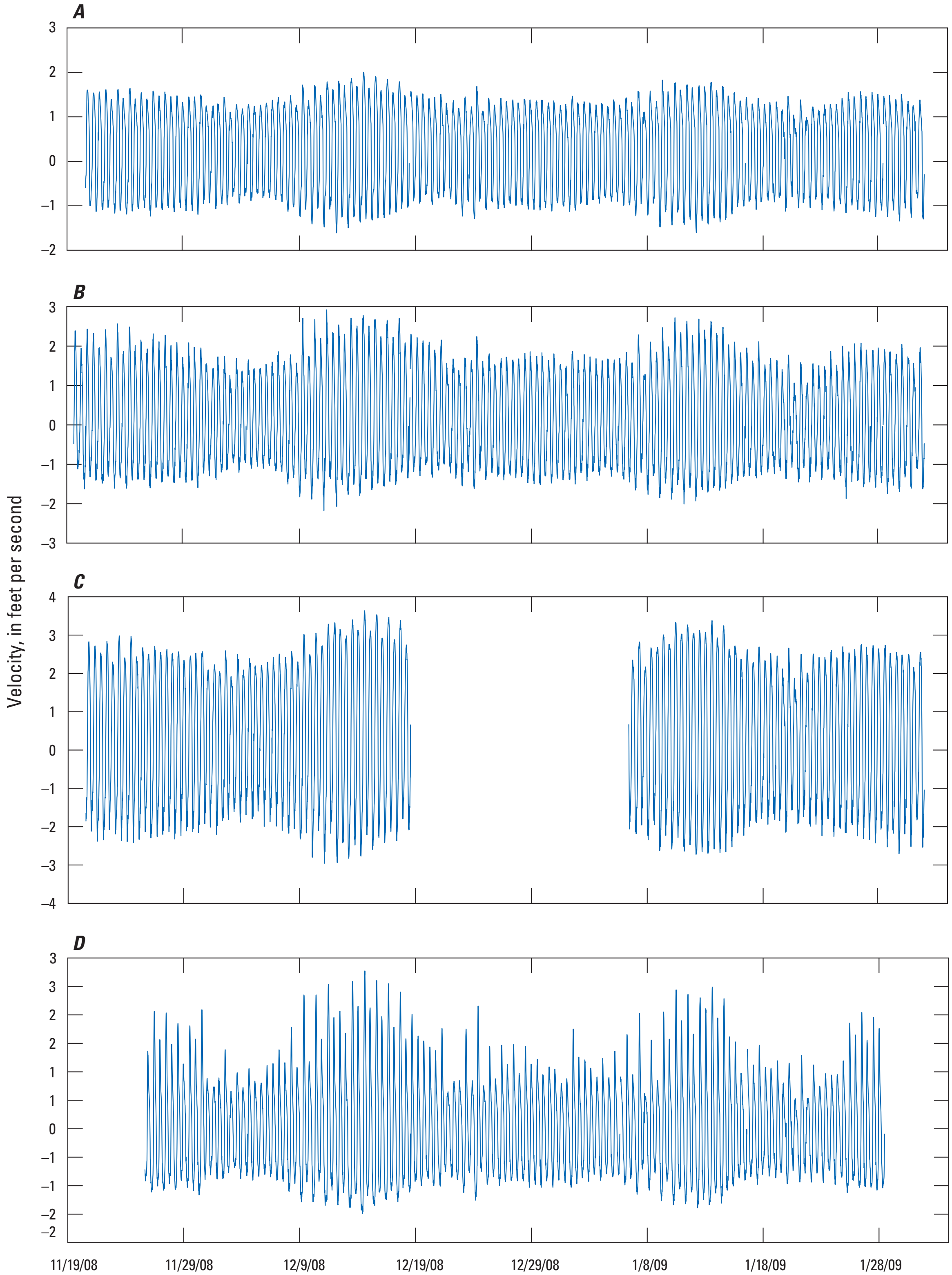

Figure 11. Velocity for *(A)* Little Back River, *(B)* Middle River, *(C)* Front River, and *(D)* Union Creek, Lower Savannah River estuary, coastal South Carolina and Georgia, November 20, 2008, to January 30, 2009.

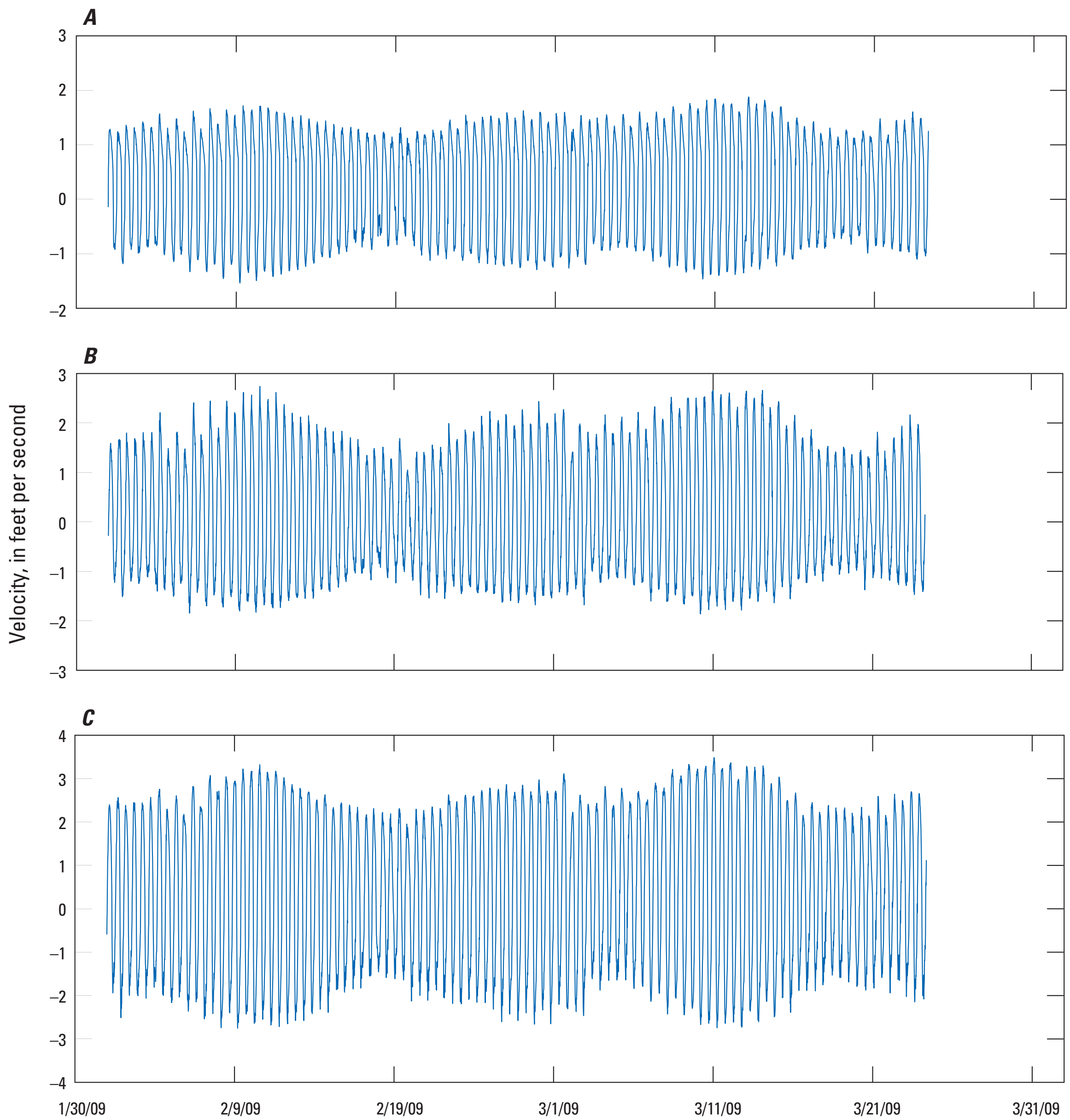

Figure 12. Velocity for *(A)* Little Back River, *(B)* Middle River, and *(C)* Front River, Lower Savannah River estuary, coastal South Carolina and Georgia, February 1 to March 24, 2009.

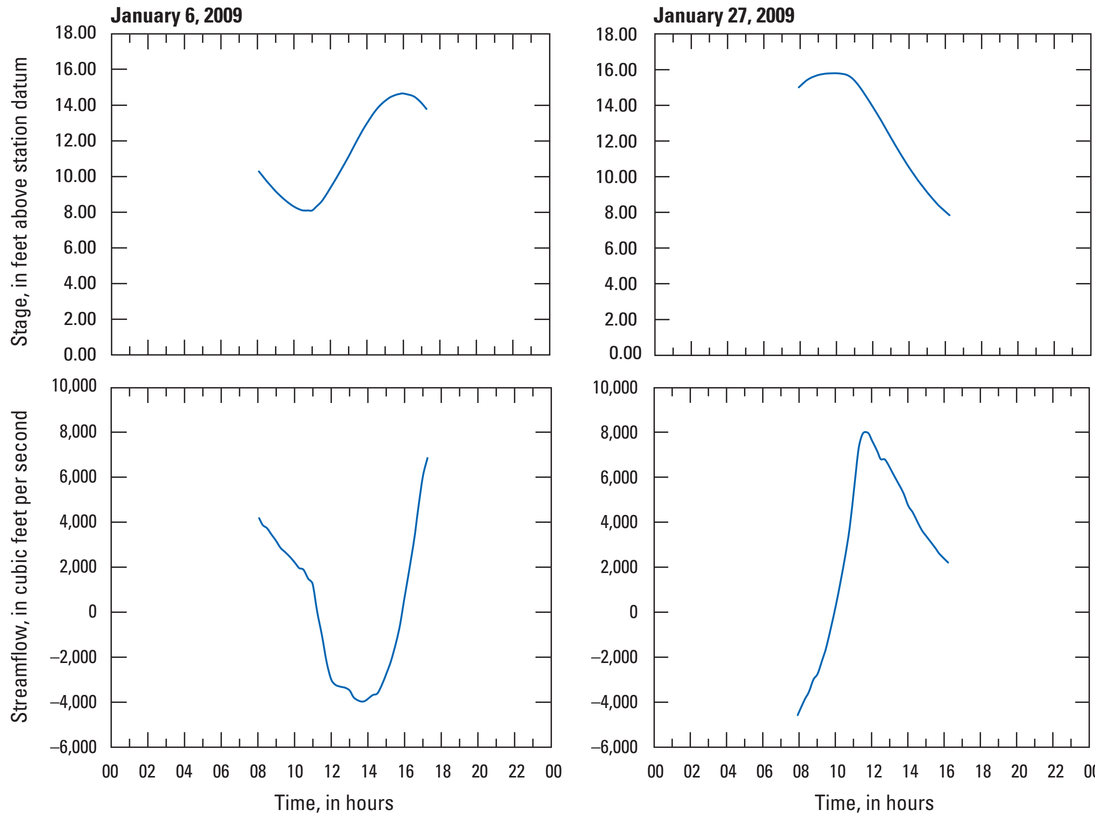

Figure 13. Measured stage and streamflow for the Little Back River at GA25 near Port Wentworth, GA, January 6 and 27, 2009.

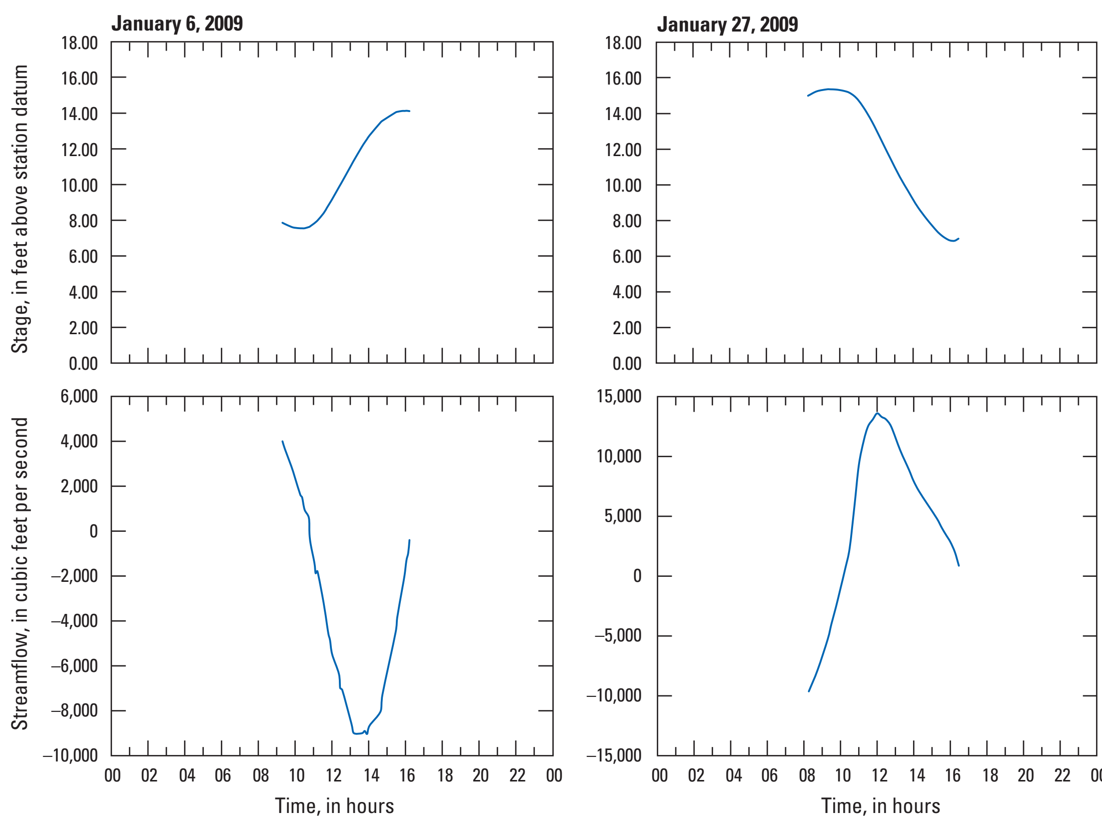

Figure 14. Measured stage and streamflow for the Middle River at GA25 near Port Wentworth, GA, January 6 and 27, 2009.

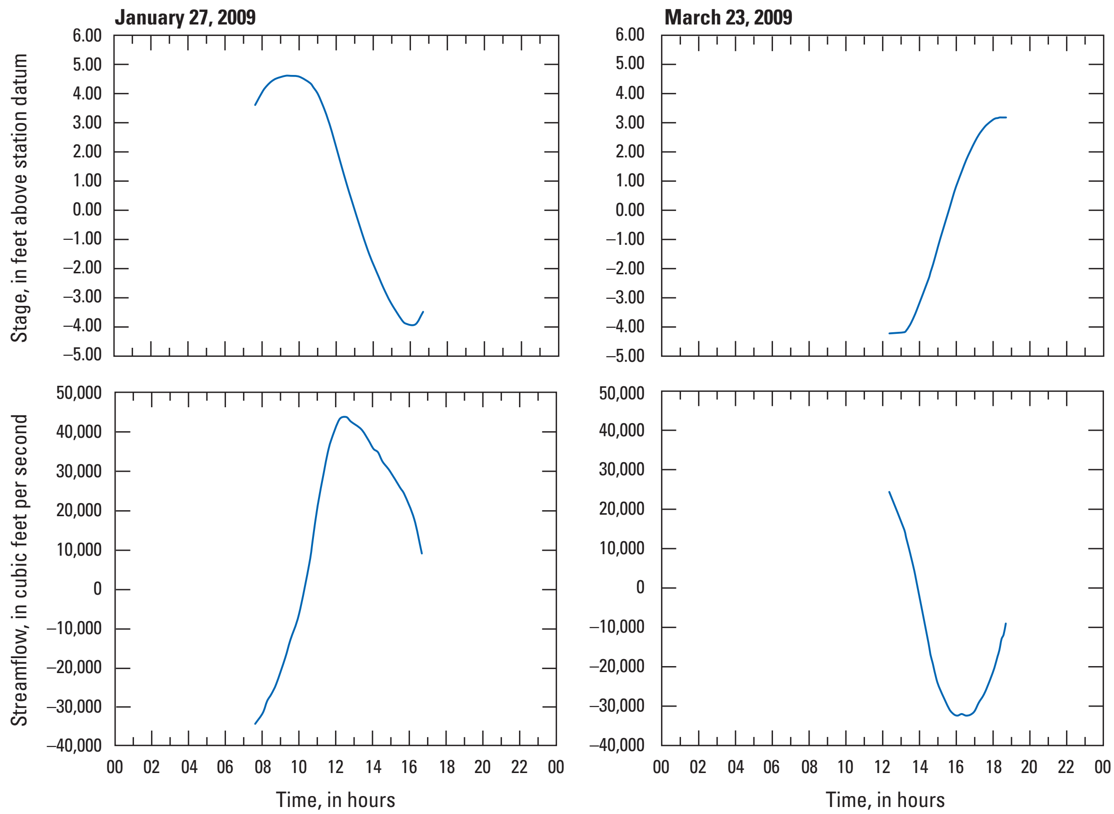

Figure 15. Measured stage and streamflow for the Front River at GA25 near Port Wentworth, GA, January 27 and March 23, 2009.

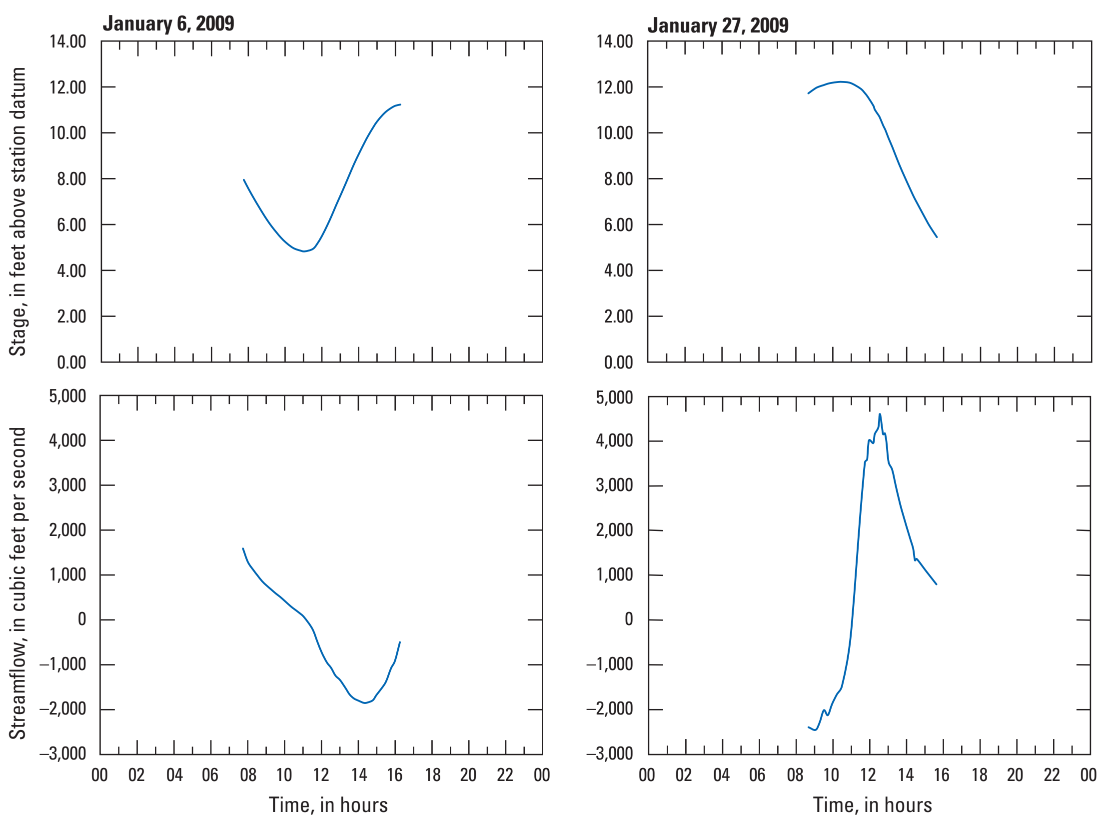

Figure 16. Measured stage and streamflow for Union Creek below I-95 near Hardeeville, SC, January 6 and 27, 2009.

Computation of Continuous Streamflow Data

The computation of continuous streamflow data at the index-velocity sites was accomplished in three steps (Ruhl and Simpson, 2005). The first step was to develop stage-area curves to establish the relation between the tidal stage at each site and the cross-sectional area. The second step was to develop velocity ratings to convert the continuous index-velocity readings to continuous mean velocity readings for the cross sections. The first two steps were accomplished by using the tidal-cycle streamflow measurements and cross-sectional data gathered at each site. The final step was to compute the streamflow by multiplying the cross-sectional area (determined by the stage-area curve) by the mean velocity (computed by the velocity rating).

Development of Stage-Area Curves

On January 26, 2009, cross-sectional data were gathered for the index-velocity sites mounted to bridges crossing the Little Back, Middle, and Front Rivers. These data included the distance from the bridge deck to the water surface and streambed at 20–30 measured points along the downstream side of the bridge. In addition, the time each measurement was made was recorded. Using the time of each measurement and the 15-minute measured stage data collected at the site, the water-surface elevation was determined at each of the measuring points. From these data, a cross-sectional profile of the downstream side of each bridge was computed for the three bridge sites.

At the index-velocity site on Union Creek, a different approach was used to develop the stage-area relation because this site has no bridge structure. During the January 6, 2009, streamflow measurements, one ADCP transect was made near the peak stage. The distance and depth data from the ADCP transect data file were extracted. A cross-sectional profile was determined by using the distance and depth data, the start and end times of the transect, and the 15-minute measured stage data collected at the site.

The cross-sectional profiles determined for each site were used to develop a stage-area curve for each site. These curves correlate the stage data to cross-sectional area (fig. 17).

Development of Index-Velocity Ratings

Index-velocity meters measure an integrated sample volume velocity in a particular part of the water column. In order to compute continuous streamflow at the index-velocity sites, the index velocities must be converted to the mean velocity for the cross section. Mean measured velocities were computed from the tidal-cycle streamflow measurements made on January 6 and 27, 2009, and March 23, 2009 (figs. 13–16), by dividing the measured streamflow by the area determined from the stage-area curve. Linear regression was used to correlate the index velocity to the mean measured velocity for each of the four cross sections.

At the Little Back River and Middle River sites, the velocity rating covers a range of index velocities from 2.2 to –1.2 ft/s and 2.2 to –1.6 ft/s, respectively. The plot of index velocity relative to mean measured velocity at both sites shows similar slopes for the ebb (outgoing) and flood (incoming) tides; thus, the ebb and flood tides were analyzed together. The coefficient of determination (R^2) for the Little Back and Middle River velocity ratings is greater than 0.98 and 0.99, respectively (figs. 18, 19).

At the Front River site, the velocity rating covers a range of index velocities from 3.6 to –1.9 ft/s. The plot of index velocity relative to mean measured velocity indicates that the slope for the ebb tide is different from the slope for the flood tide. Thus, the two were analyzed separately. The R^2 for the ebb tide portion of the velocity rating is greater than 0.98, which indicates that the regression explains about 98 percent of the variability between the index and mean measured velocity at this site. The R^2 for the flood tide is greater than 0.89 (fig. 20).

At the Union Creek site, the velocity rating covers a range of index velocities from 2.4 to –0.9 ft/s. As with the Front River site, the plots of the index and mean measured velocities indicate that the slopes for the ebb tide and flood tide are different; thus, the two portions of the tidal cycle were analyzed separately. The R^2 for the ebb tide portion of the velocity rating is greater than 0.99; the R^2 for the flood tide portion is 0.93 (fig. 21).

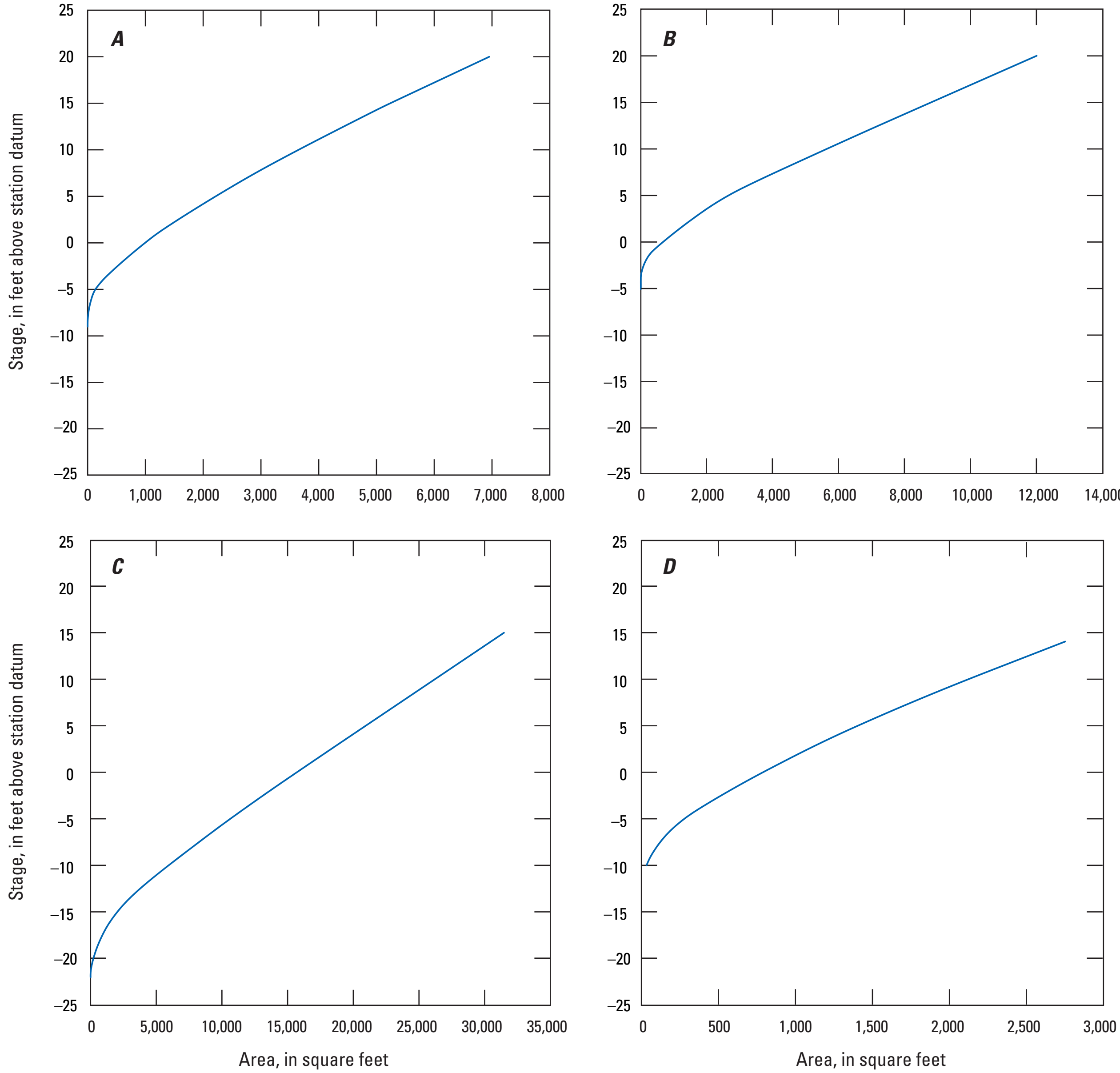

Figure 17. Stage area curves for stations on *(A)* Little Back River, *(B)* Middle River, and *(C)* Front River, complied from data collected on January 26, 2009, and *(D)* Union Creek, complied from data collected on January 6, 2009, Lower Savannah River estuary, South Carolina and Georgia.

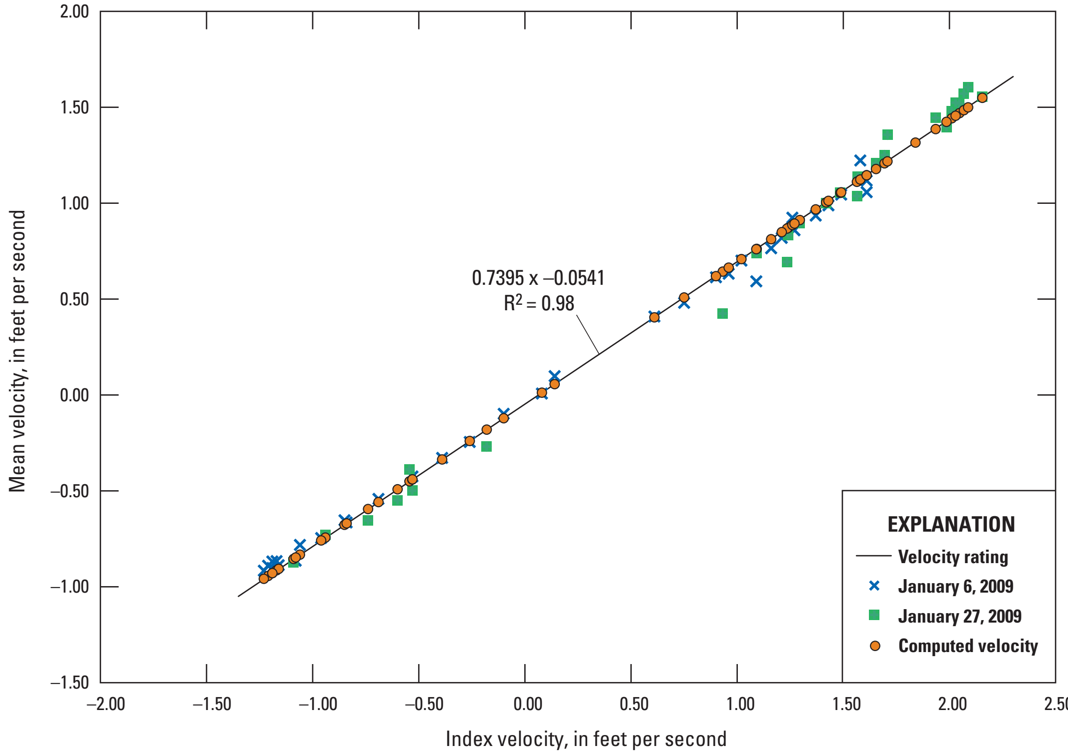

Figure 18. Velocity rating curve for the index-velocity station Little Back River at GA25 near Port Wentworth, GA, developed using measurements made on January 6 and 27, 2009.

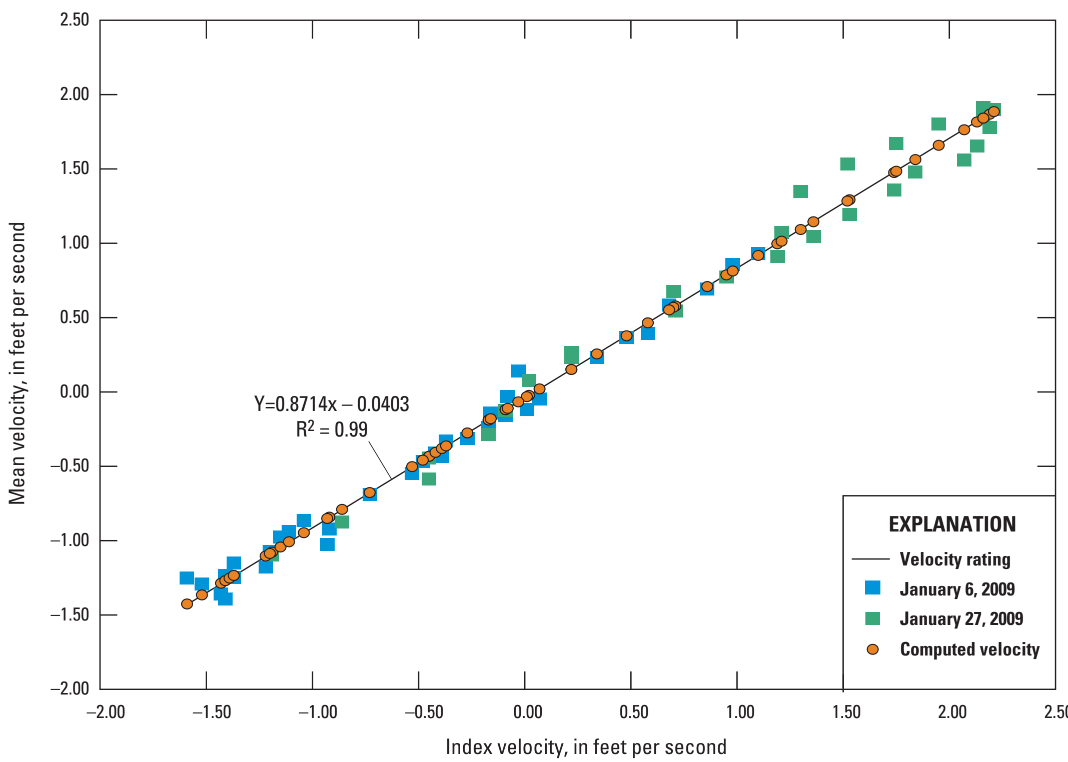

Figure 19. Velocity rating curve for the index-velocity station Middle River at GA25 near Port Wentworth, GA, developed using measurements made on January 6 and 27, 2009.

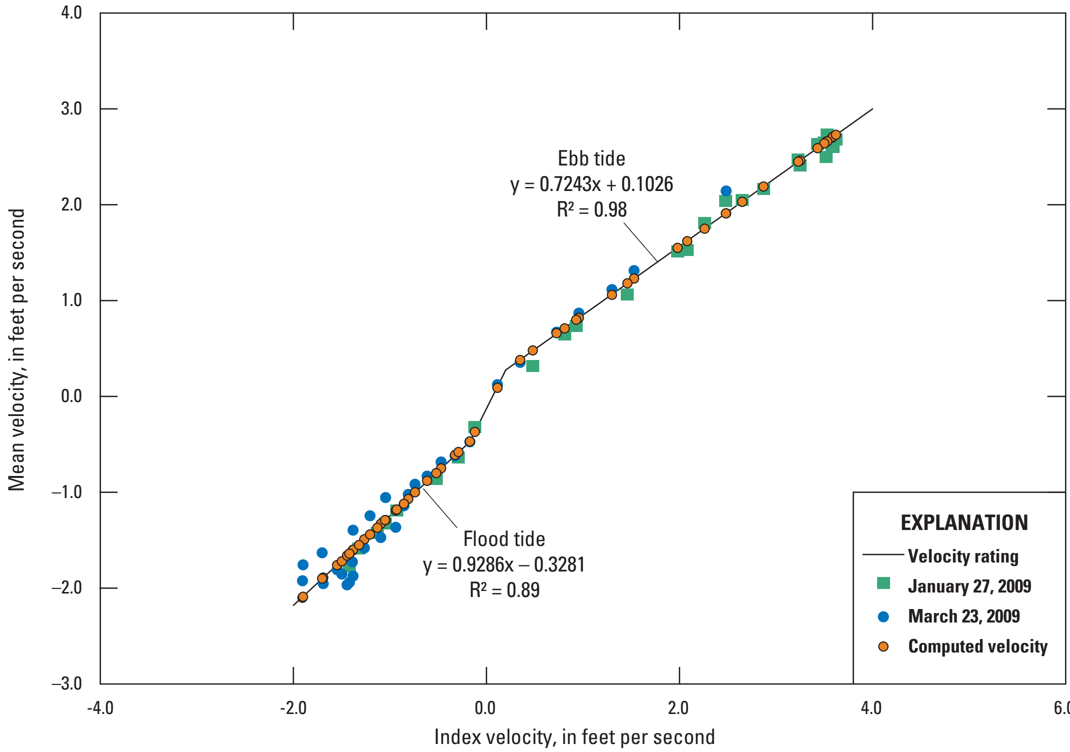

Figure 20. Velocity rating curve for the index-velocity station Front River at GA25 near Port Wentworth, GA, developed using measurements made on January 27 and March 23, 2009.

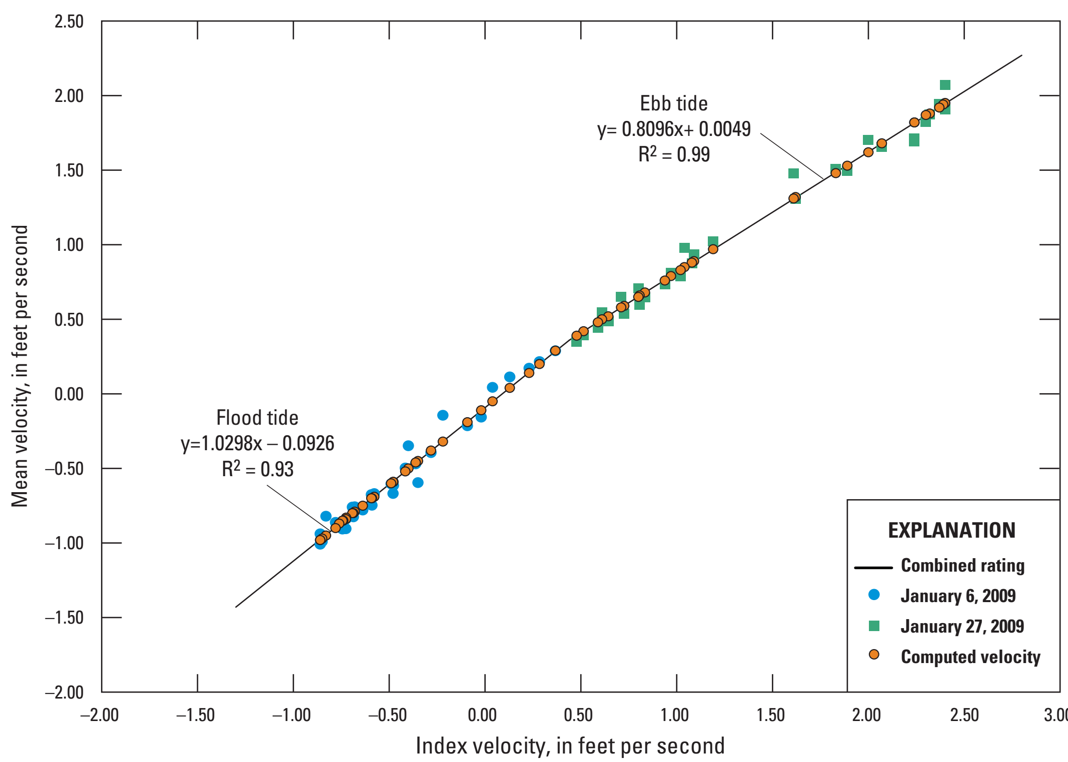

Figure 21. Velocity rating curve for the index-velocity station Union Creek below I-95 near Hardeeville, SC, developed using measurements made on January 6 and 27, 2009.

The results of the development of the velocity rating can be seen in the graph of the measured (measured streamflow divided by rated area), index (velocity from AVM), and computed velocities for Little Back River for January 6, 2009 (fig. 22). The index-velocity meter measured higher ebb (positive) velocities and lower flood (negative) velocities than the measured mean velocities. To adjust the index-velocity to the mean cross-sectional velocity, the velocity rating (linear regression) was computed for the Little Back River (fig. 18) to determine the mean cross-sectional velocity for the site.

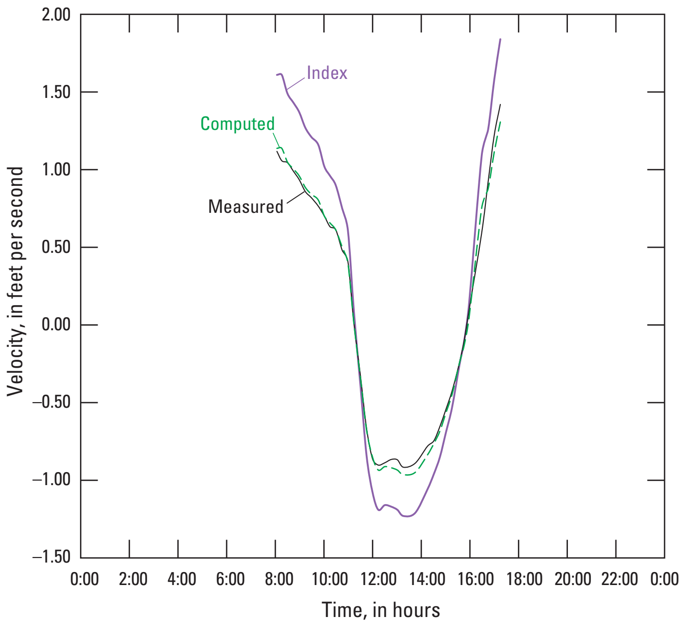

Figure 22. Measured, indexed, and computed velocity for Little Back River at GA25 near Port Wentworth, GA, January 6, 2009.

Continuous Streamflow and Specific Conductance Record

The continuous (15-minute interval) streamflow data at the index-velocity sites are a product of the mean velocity and the cross-sectional area. The mean velocity is calculated from the 15-minute index-velocity data, and the cross-sectional area is computed from the 15-minute stage data. Streamflow hydrographs for the Little Back River, Middle River, Front River, and Union Creek are shown in figures 23 and 24. The maximum flood-tide streamflow was –7,820 ft^3/s for the Little Back River, –17,500 ft^3/s for Middle River, –78,900 ft^3/s for Front River, and –3,850 ft^3/s for Union Creek, which occurred on December 12, 2008, at Middle River and Front River; on January 12, 2009, at Little Back River; and on December 14, 2008 at Union Creek. The maximum ebb-tide streamflow was 9,600 ft^3/s for Little Back River, 22,500 ft^3/s for Middle River, 87,200 ft^3/s for Front River, and 6,130 ft^3/s for Union Creek, which occurred on December 12, 2008, at Middle River, and on December 14, 2008, at Little Back River, Front River, and Union Creek (table 3).

In tidally influenced environments, simple averaging of 15-minute values over a 24-hour period does not produce a true daily value. Computing a 24-hour average with data that contain an 8-hour tidal cycle introduces a cyclical variation, or alias. These variations can be attributed to the changing 24-hour portion of the tidal cycle average, not actual variations in the data. These tidal effects were removed by using the Godin filter (Godin, 1972), which removes frequencies that have periods less than 30 hours (astronomical tides have periods around 12 and 24 hours). The Godin filter uses at least 71 continuous hours of data to create a filtered value at the 35th hour. Thus, the filter drops exactly 35 hourly data points at the beginning and end of the input series. The residual of the filter represents the net downstream streamflow (figs. 23, 24).

Table 3. Maximum and minimum instantaneous and daily filtered flood and ebb tides at the index-velocity stations on Little Back River, Middle River, Front River, and Union Creek, Lower Savannah River estuary, coastal South Carolina and Georgia, 2008 and 2009.

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

Location	Maximum instantaneous flow				Maximum daily tidally filtered flow			
	Flood tide (ft^3/s)	Date	Ebb tide (ft^3/s)	Date	Flood tide (ft^3/s)	Date	Ebb tide (ft^3/s)	Date
Little Back River	–7,820	1/12/2009	9,600	12/14/2008	–662	1/12/2009	1,530	3/7/2009
Middle River	–17,500	12/12/2008	22,500	12/11/2008	–289	1/21/2009	1,820	12/17/2009
Front River	–78,900	12/12/2008	87,200	12/14/2008	–4,470	2/13/2009	14,700	3/7/2009
Union Creek	–3,850	12/14/2008	6,130	12/14/2008	–40	1/16/2009	182	12/15/2009

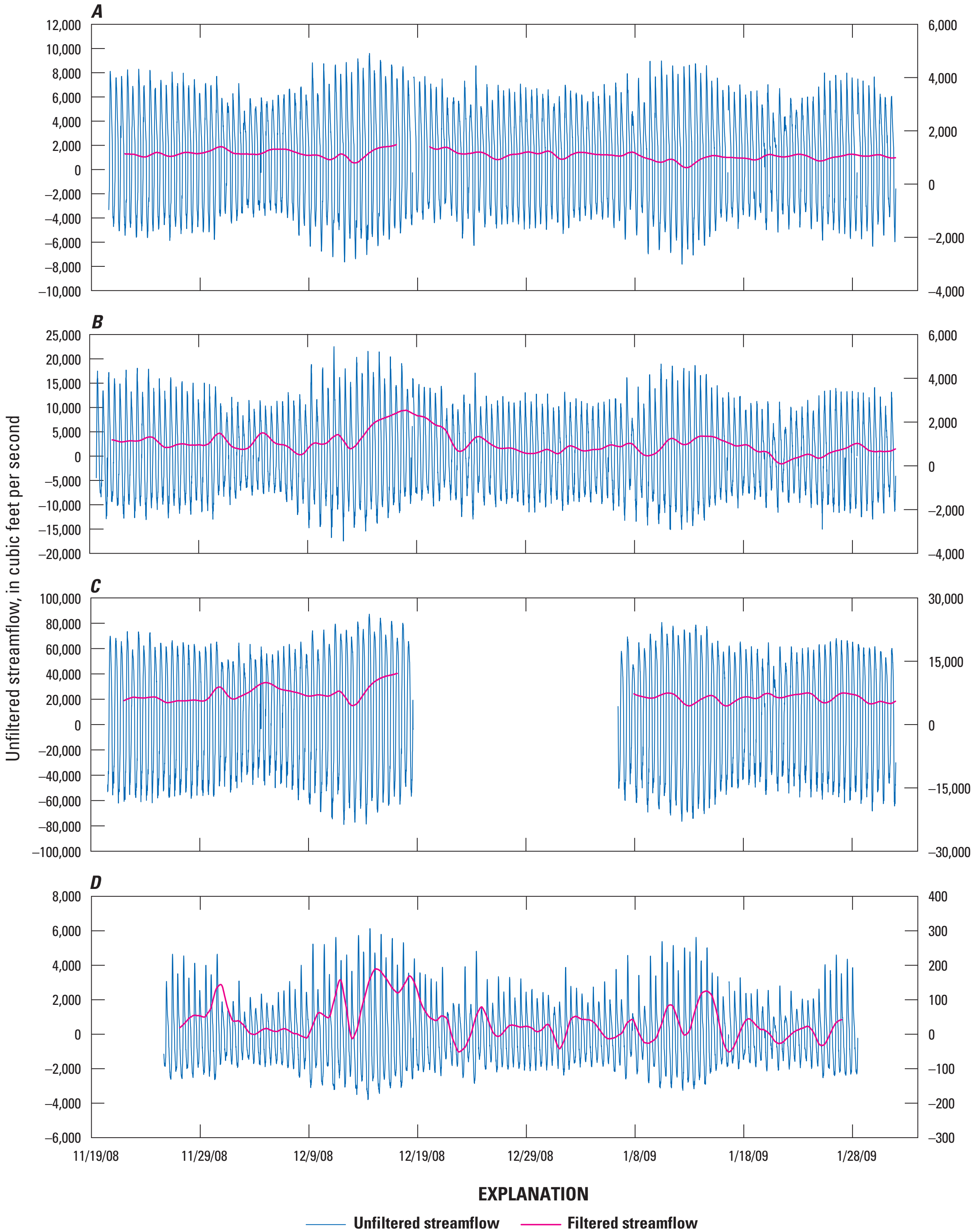

Figure 23. Hydrographs of unfiltered and filtered streamflow for the index-velocity stations on *(A)* Little Back River, *(B)* Middle River, *(C)* Front River, and *(D)* Union Creek, Lower Savannah River estuary, coastal South Carolina and Georgia, November 20, 2008, to January 30, 2009.

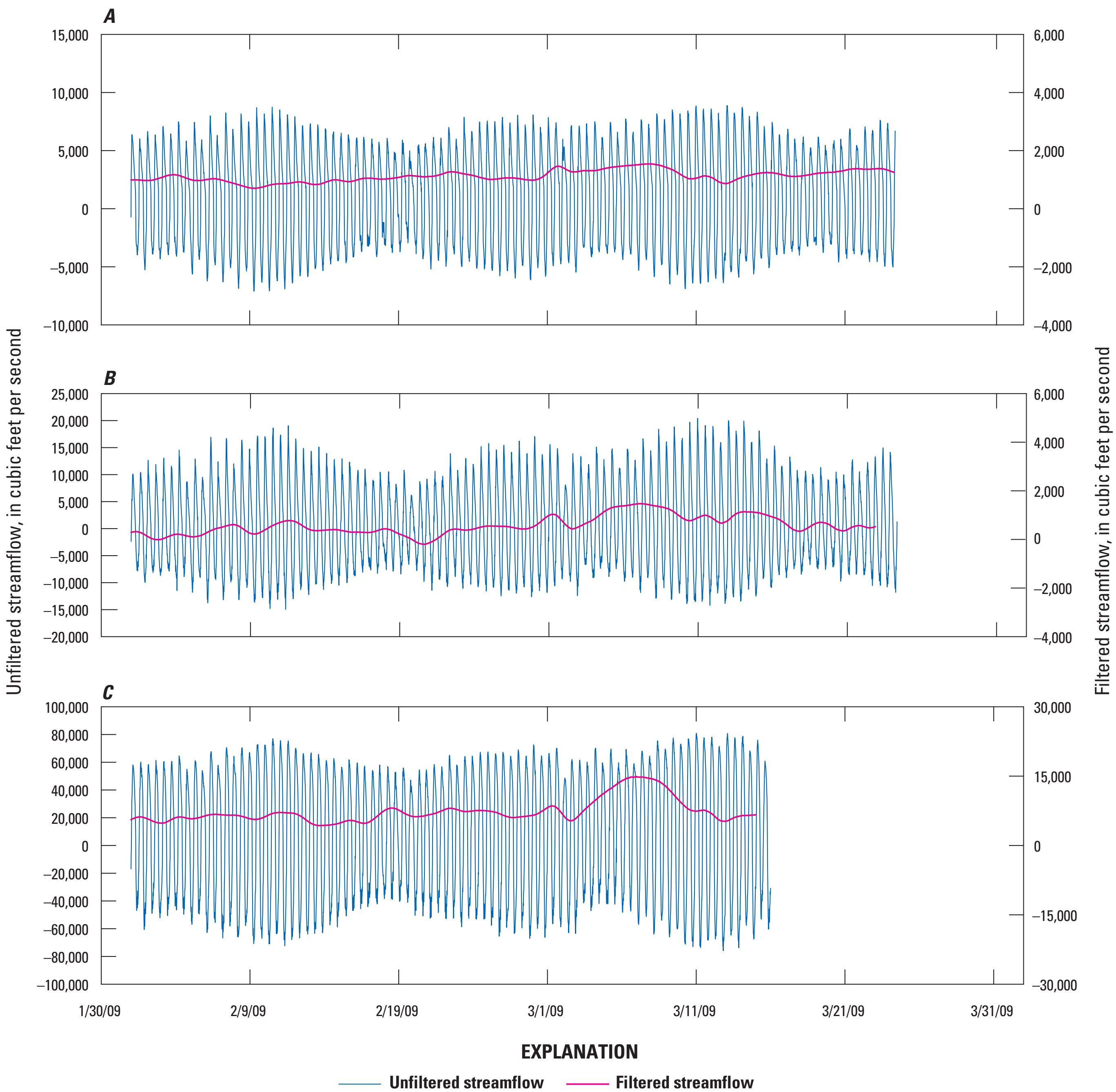

Figure 24. Hydrographs of unfiltered and filtered streamflow for the index-velocity stations on *(A)* Little Back River, *(B)* Middle River, and *(C)* Front River, Lower Savannah River estuary, coastal South Carolina and Georgia, February 1 to March 24, 2009.

The distribution of the streamflow in Little Back River, Middle River, and Front River with respect to the upstream flow entering the system can be seen in the hydrographs of daily streamflow for the Savannah River at Clyo and the daily tidally filtered data for Little Back River, Middle River, and Front River for the study period (fig. 25). The travel time between Clyo and Savannah is approximately 1–2 days. The downstream response to pulses of high flows in December and March can be seen in the filtered downstream hydrographs at Front, Middle, and Little Back Rivers. The Front River responds with a rise in streamflow of a similar magnitude as occurs at Clyo. Flows in Middle River and Little Back River were below 2,000 ft^3/s during the indexing period, with Little Back River having higher flows most of the time. Middle River shows a larger response than Little Back River to higher flows from the Savannah River, as seen on December 19, 2008, and March 9, 2009. The peak flows on March 9, 2009, showed average flows increased over 100 percent at Savannah River at Clyo and at Front and Middle Rivers, whereas the daily flows in Little Back River only increased by 35 percent. Overall, tidal flows in Middle River are higher than those on Little Back River (figs. 23*A*, *B*, 24*A*, *B*). However, the tidally filtered flows, which represent the net downstream flow on Middle River, are less than those on the Little Back River except during pulses of high flow on the Savannah River. This seems to indicate that Middle River is more tidally dominated than Little Back River.

A comparison of the continuous specific conductance data on Little Back River and Middle River shows similar behavior (figs. 9, 10). Specific conductance values for Little Back River during flood tides are always less than those for Middle River, which indicates more freshwater mixing in Little Back River than in Middle River, and that Middle River is more tidally dominated than Little Back River.

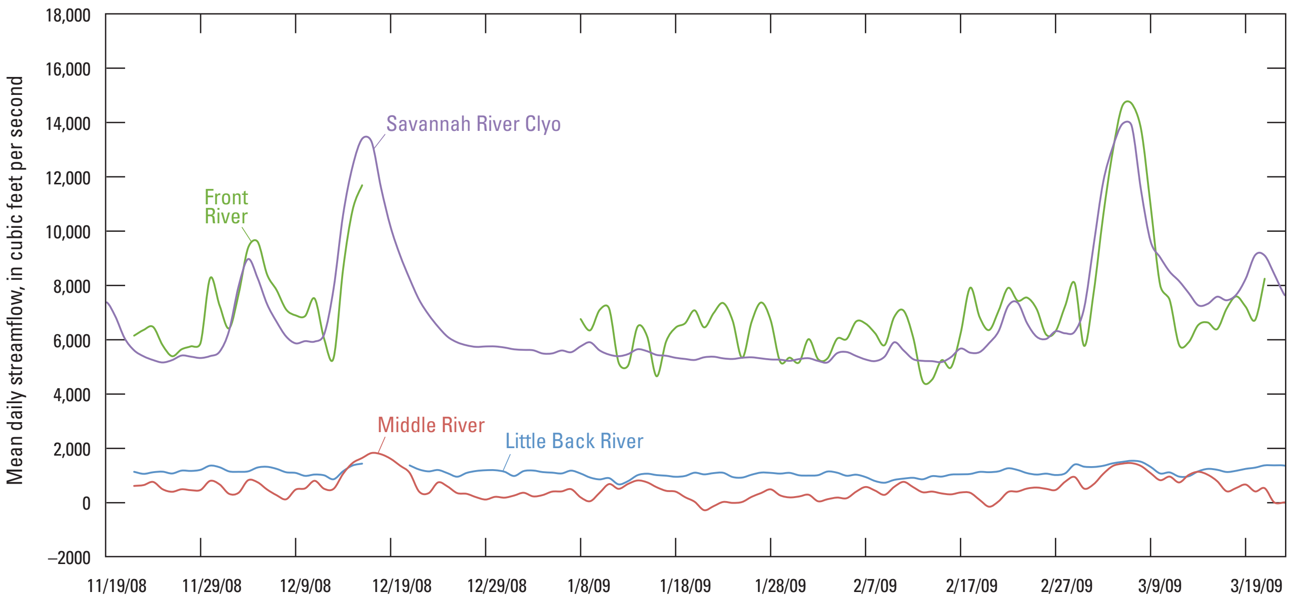

Figure 25. Daily streamflow for Savannah River near Clyo, GA, and daily tidally filtered streamflow for the Little Back River, Middle River, and Front River at Port Wentworth, GA, November 20, 2008, to March 24, 2009.

Summary

The Savannah River estuary, as with many major estuarine systems, meets many local and regional water-resource needs. The tidal parts of the Savannah River provide water supply for coastal South Carolina and Georgia, an extensive freshwater marsh habitat, assimilative capacity for municipal and industrial dischargers, and navigational access for a major shipping terminal on the east coast. Increasing industrial and residential development in Georgia and South Carolina is accompanied by competing and often conflicting interests in the water resources of the Savannah River.

In the Water Resource Development Act of 1999, the U.S. Congress authorized the deepening of the Savannah Harbor. Additional studies were then identified by the Georgia Ports Authority and other local and regional stakeholders to determine and fully describe the potential environmental effects of deepening the channel.

One need that was identified was the validation of the three-dimensional model used to evaluate mitigation scenarios for the harbor deepening and its effects on the Savannah River estuary. The streamflow in the estuary is very complex due to reversing tidal flows, interconnections of streams and tidal creeks, and daily flooding and draining of the marshes. When the three-dimensional model was originally developed, it was calibrated with limited streamflow data.

To determine the distribution of streamflow in Little Back River, Middle River, Front River, and Union Creek, four index-velocity meters were deployed for a minimum of 60 days. In addition, water level and specific conductance meters were deployed at sites on Union Creek and Middle and Little Back Rivers. Water level and specific conductance data for the Front River site were collected at U.S. Geological Survey streamgaging station 02198920 (Savannah River at GA 25, at Port Wentworth, GA). These data were used to verify the three-dimensional model and serve as background data on the streamflow dynamics prior to the deepening of the harbor.

Two tidal-cycle streamflow measurements were made during a 10- to 11-hour period at the four index stations during the deployment. The maximum flood and ebb tides measured on Little Back River for the two measurement days were –4,570 and 7,990 cubic feet per second (ft^3/s), respectively, and tidal streamflows for the instrument deployment ranged from –7,820 ft^3/s for the flood tide to 9,600 ft^3/s for the ebb tide. On Middle River, the maximum flood tide and ebb tide measured were –9,630 and 13,600 ft^3/s, respectively, and tidal streamflows for the instrument deployment ranged from –17,500 ft^3/s for the flood tide to 22,500 ft^3/s for the ebb tide. On Front River, the maximum flood tide and ebb tide measured were –34,500 and 43,700 ft^3/s, respectively, and tidal streamflows for the instrument deployment ranged from –78,900 ft^3/s for the flood tide to 87,200 ft^3/s for the ebb tide. On Union Creek, the maximum flood tide and ebb tide measurements were –2,390 and 4,610 ft^3/s, respectively, and tidal streamflows for the instrument deployment ranged from –3,850 ft^3/s for the flood tide to 6,130 ft^3/s for the ebb tide.

Acknowledgments

The authors thank the staff from the other agencies who supported and advised this velocity indexing study in the Savannah River estuary: Wade Cantrell and Larry Turner of the South Carolina Department of Health and Environmental Control; Elizabeth Booth of the Georgia Environmental Protection Division; Bud Badr and Steve deKoslowski of the South Carolina Department of Natural Resources; and Jim Greenfield of the U.S. Environmental Protection Agency Region 4.

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Manuscript approved for publication, June 21, 2010

Edited by Rebecca J. Deckard

Layout by Caryl J. Wipperfurth

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Lanier and Conrads—**Continuous Tidal Data for Union Creek and the Little Back, Middle, and Front Rivers, Savannah River Estuary**—Open-File Report 2010–1169