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SURFACE-WATER HYDROLOGY OF THE GULF INTRACOASTAL WATERWAY IN SOUTH-CENTRAL LOUISIANA, 1996-99

U.S. GEOLOGICAL SURVEY PROFESSIONAL PAPER 1672

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Cover photographs

Clockwise from top left: Bayou Penchant south of Morgan City showing water from the Avoca Island Cutoff Channel; water draining from the Gulf Intracoastal Waterway into adjacent western Terrebonne marshes; healthy freshwater marshes dominated *by Panicum hemitomon*, degraded western Terrebonne marshes.

Background: Gulf Intracoastal Waterway near Bay Wallace east of Morgan City.
(*Photographs by author*)

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By Christopher M. Swarzenski

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CONVERSION FACTORS, DATUMS, AND ABBREVIATED WATER-QUALITY UNITS

Multiply	By	To obtain
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
tons per day (tons/d)	0.9072	megagram per day (Mg/d)

Horizontal coordinate information in this report is referenced to the North American Datum of 1927.

Vertical coordinate information in this report is referenced to the North American Vertical Datum of 1988 (NAVD88) and the National Geodetic Vertical Datum of 1929 (NGVD29)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Abbreviated water-quality units:

milligrams per liter (mg/L)

parts per thousand (ppt)

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ABSTRACT

The flow of freshwater and suspended sediment from the Lower Atchafalaya River (LAR) and Wax Lake Outlet (WLO) into and along the Gulf Intracoastal Waterway (GIWW) and selected adjacent surface-water bodies between Cypremort and Larose in south-central Louisiana, from October 1996 to December 1999, was characterized using instantaneous and computed continuous discharge measurements and measurements of suspended-sediment concentrations. The GIWW parallels the entire Louisiana coast near the wetland/upland interface. Following natural hydraulic gradients, the GIWW captures water and sediment from the southward flowing LAR and the WLO where it crosses those waterways, and distributes this freshwater and sediment to points east and west.

East of Morgan City, La., an average of 12,200 ft^3/s (cubic feet per second) of water flowed from the LAR into the Avoca Island Cutoff Channel. The LAR was the primary source of water to the GIWW east of Morgan City. Drainage from the Verret Subbasin through Bayou Boeuf contributed an average of 1,000 ft^3/s to the eastward flow in the GIWW. Eastward flow in the GIWW near Bay Wallace east of Morgan City and to the west of the Houma Navigation Canal (HNC) at Houma, La., averaged about 5,700 ft^3/s. Average flow in the GIWW east of the HNC at Houma was 2,610 ft^3/s to the east, and 2,200 ft^3/s east of Bayou Lafourche at Larose, also to the east.

Measured discharge in the GIWW was always to the west between the LAR and WLO. Water entered this stretch of the GIWW from the LAR. The WLO was the primary source of water to the GIWW west of WLO. Discharge in the GIWW averaged 9,460 ft^3/s west of WLO south of Calumet and 8,230 ft^3/s east of Jaws Bay west of Franklin. Average discharge in the GIWW west of Jaws Bay near Cypremort was 3,310 ft^3/s and at Cypremort was 1,350 ft^3/s. Average discharge was to the west at all four locations, but discharge as high as 2,830 ft^3/s was measured flowing eastward toward Jaws Bay in the GIWW at Cypremort.

In bayous and canals in most of coastal Louisiana, including the GIWW, stage narrowly fluctuates around the Gulf of Mexico level. Where the GIWW crosses the LAR and WLO, stage can reach 3 ft (feet) or more above the North American Vertical Datum of 1988 (NAVD88). Flow in the GIWW results from these differences in stage. When the LAR at Morgan City reached 3 to 4 ft above NAVD88, flow in the GIWW became more predictable. Discharge at most sites between the HNC and Jaws Bay increased in varying amounts as stage of the LAR at Morgan City increased beyond 3 ft above NAVD88. At sites in the GIWW east of HNC, discharge did not increase predictably. For all measurements made when the LAR at Morgan City was 3 ft or more above NAVD88, average discharge was about 3,100 ft^3/s in the GIWW east of HNC at Houma and 2,880 ft^3/s east of Bayou Lafourche at Larose. The LAR at Morgan City is 3 ft or more above NAVD88 for about 7 months in a normal year.

When the LAR at Morgan City was less than 3 ft above NAVD88, water in the GIWW flowed along the prevailing water-level gradients, to the east between Bay Wallace and the HNC and to the west between WLO and Jaws Bay. However, local runoff and drainage from areas adjacent to the GIWW became more significant in maintaining flow at low LAR stage. Discharge was consistently higher in the GIWW west of the HNC at Houma than farther west near Bay Wallace east of Morgan City, when the LAR at Morgan City was

less than 3 ft above NAVD88. Westward flow in the GIWW between Houma and Morgan City was observed near Bay Wallace east of Morgan City but was never observed west of the HNC at Houma. Discharge in the GIWW east of Jaws Bay west of Franklin, La., frequently was higher than in the GIWW west of WLO south of Calumet, La., at low LAR stage.

East of the LAR, suspended-sediment concentrations averaged about 162 mg/L (milligrams per liter) at the two sites closest to the LAR, Avoca Island Cutoff Channel and Bayou Penchant south of Morgan City. Suspended-sediment concentrations averaged 91 mg/L in the water entering the GIWW through Bayou Boeuf at railroad bridge at Amelia. The water in the GIWW near Bay Wallace east of Morgan City to the HNC was intermediate in suspended-sediment concentrations (108-114 mg/L), reflecting the mixture of the two water types. Suspended-sediment concentrations in the GIWW near Bay Wallace east of Morgan City and east and west of the HNC were comparable, but in the GIWW east of Larose, they increased by about 45 percent. To the west of WLO, suspended-sediment concentrations averaged between 167 and 191 mg/L.

Freshwater flow directly affected salinity patterns in the GIWW and adjacent surface-water bodies. Monthly-average salinity at many sites, both in and adjacent to the GIWW, was related to monthly-average stage of the LAR at Morgan City.

When the LAR at Morgan City is 3 or more ft above NAVD88, the GIWW effectively distributes freshwater and sediment from the LAR and WLO to points in coastal Louisiana 30 to 50 miles east and west of Morgan City. The freshwater and sediment, some of which originate indirectly from the Mississippi River, are valuable resources for building wetlands and could be incorporated into ongoing efforts to restore coastal Louisiana.

INTRODUCTION

Regional and local modifications to surface-water hydrology in coastal Louisiana have disrupted the natural inflow of freshwater and sediment to wetlands for many years (Mendelssohn and others, 1984; Turner and Cahoon, 1988). The modifications have played a major role in the rapid conversion of land to open water that has characterized much of coastal Louisiana for the past 50 or more years (Gagliano and others, 1981; Turner and Cahoon, 1988; Boesch and others, 1994; Reed, 1995). The two largest modifications to the flow of freshwater and sediment into and through coastal Louisiana wetlands have been the leveeing of the Mississippi River and the construction of the Gulf Intracoastal Waterway (GIWW) in the early part of the 20th century. The confinement of the Mississippi River between levees in much of southeastern Louisiana has reduced and in places eliminated the frequent over-bank flooding that historically brought freshwater and sediment to coastal wetlands. The GIWW has modified surface-water hydrology in coastal Louisiana in ways that presently are not well understood.

The GIWW is the largest continuous ship channel in coastal Louisiana, traversing the entire Louisiana coast along the wetland/upland interface (fig. 1). Following natural hydraulic gradients, the GIWW captures water from the Lower Atchafalaya River (LAR) and the Wax Lake Outlet (WLO) and distributes it to parts of Louisiana's coastal wetlands during the annual spring flood (Paille, 1997). This flow potentially could support coastal restoration efforts with a minimum of cost (R.F. Paille, U.S. Fish and Wildlife Service, oral commun., 1999). Distinct from its potential for ecological benefits, the GIWW also provides an exit point for flood waters carried through the Atchafalaya River Basin. However, the flow of freshwater and transport of suspended sediment in the GIWW and the relation of these activities to stage of the LAR are not well understood.

In 1997, the U.S. Geological Survey (USGS) began to operate a network of data-collection sites that monitor velocity, stage, and salinity in the GIWW and several connecting waterways. This effort was initiated in cooperation with Federal agencies concerned with flood control and environmental quality, principally the U.S. Army Corps of Engineers (USACE), but also including the U.S. Fish and Wildlife Service (USFWS), Natural Resources Conservation Service, the U.S. Environmental Protection Agency, and the Coastal Wetlands Protection, Planning, and Restoration Act task force. From 1997-99 the primary data-collec-

Figure 1. Coastal Louisiana showing the Mississippi River, Atchafalaya River, and the Gulf Intracoastal Waterway.

tion effort focused on the GIWW between Cypremort, La., to the west, and Larose, La., to the east (pl. 1). Occasionally, measurements east of Larose were made in Bayou Perot and in the GIWW just west of Bayou Perot. In 1998, the USGS, in cooperation with the USACE, began a study to evaluate the collected data and describe hydrologic conditions in the GIWW in south-central Louisiana.

Purpose and Scope

This report characterizes the flow of water and suspended sediment from the LAR and WLO into and along the GIWW and in selected adjacent surface-water bodies between Cypremort and Larose from October 1996 to December 1999 (pl. 1). The relative importance of the two primary sources of water sustaining flow along the GIWW, the Atchafalaya River (LAR and WLO) and local precipitation and runoff, are evaluated. The distribution of stage and water-level gradients in the study area are discussed to evaluate flow characteristics. Suspended-sediment concentrations and discharge are discussed. The present-day salinity patterns are discussed in relation to flow and local runoff as are changes to historical salinity patterns affected by flow in selected areas along the coast.

Quantifying the amount of water flowing in the GIWW and how this relates to sediment transport and salinity conditions in coastal Louisiana may help State and Federal agencies in designing coastal wetland restoration projects and implementing flood-control measures.

Description of Study Area

The GIWW is part of the Intracoastal Waterway, a continuous system of navigation channels connecting the Atlantic and Gulf Coast States. The channels permit extensive ship-borne commerce between the states. The USACE maintains a channel depth of at least 20 ft and a width of at least 200 ft for the GIWW in the study area. The part of the GIWW in the study area is in south-central Louisiana and extends from Cypremort on the west to the intersection of the GIWW and Bayou Perot on the east. The Verret Subbasin of Terrebonne Basin (hereain referred to as the Verret Subbasin), to the north and east of Morgan City, La., drains into the GIWW and is included in the study area (pl. 1). Plate 1 also shows the Teche-Vermilion, Terrebonne, Timbalier, and Barataria interdistributary Basins, which are linked by the GIWW in the study area. Houma, La., and Morgan City are regional population centers.

The Gulf Intracoastal Waterway

East of Morgan City, surface flow in the LAR is hydraulically disconnected from the GIWW by the Bayou Boeuf locks at Morgan City and the Avoca Island levee. The levee was completed around 1952 (N.J. Powell, USACE, oral commun., 2001). Water in the LAR is prevented from flowing eastward between the Bayou Boeuf locks and the levee's termination at the Avoca Island Cutoff Channel, about 10 mi south of Morgan City (pl. 1). The Avoca Island Cutoff Channel connects the LAR to the GIWW. Because of prevailing hydraulic gradients, the Avoca Island Cutoff Channel conveys a portion of LAR water in a northeasterly direction toward the GIWW. The Avoca Island Cutoff Channel becomes Bayou Chene where it joins with Bayou Penchant, prior to reaching the GIWW. Bayou Boeuf connects to the GIWW between the Bayou Boeuf locks at Morgan City and the confluence of the GIWW and Bayou Chene. Bayou Boeuf is the primary hydrologic connection between the GIWW and the Verret Subbasin. The GIWW extends eastward to Houma, across the Houma Navigation Canal (HNC) and Bayou Lafourche toward Bayou Perot and New Orleans, Louisiana. West of Morgan City, the GIWW connects to the LAR just below the city and extends westward past Jaws Bay and Cypremort to Weeks Bay.

Much of the GIWW between Cypremort and Bayou Perot can be categorized as one of two hydrologically distinct types of segments. There are longer segments (1) where lateral flow, that is flow parallel to the coast, predominates. The GIWW might lose or gain water along such segments. A different type of segment (2) occurs where the GIWW crosses a waterway, such as a canal or bayou. Substantial amounts of water can enter or leave the GIWW in a very short distance. Jaws Bay, on the west side of Morgan City, and the HNC are major examples of the second type of segment along the GIWW in the study area. West of WLO, Jaws Bay separates two segments that convey water. This arrangement of conveyance, opening, and conveyance is mirrored on the east side of the LAR starting east of the confluence of Bayou Chene and the GIWW. The lateral flow of water in the GIWW between Bay Wallace and Bayou Lafourche is split into two segments at Houma by the HNC.

Physiography of Coastal Louisiana

The study area lies mostly within the coastal zone. The Louisiana Gulf Coast contains about 5,800 mi^2 of wetlands (Chabreck, 1972), most of which occur in the Mississippi River Delta Plain (fig. 1). The wetlands form a continuum from inland swamps and fresh marsh to salt marsh, based on tolerances of the emergent vegetation to flooding and the local open-water salinity (Gosselink, 1984). Local salinity depends on the mixing of marine waters from the Gulf of Mexico and freshwater runoff from river flow and precipitation. The coastal wetlands were formed by active deposition of mineral sediment carried by the Mississippi River during the last 6,000 to 8,000 years, after sea level stabilized to approximate current levels (Kolb and Van Lopik, 1958; Frazier, 1967), and more recently in freshwater areas, through accumulations of organic matter almost exclusively derived locally (Swarzenski and others, 1991). The Mississippi River Delta Plain is comprised of six to seven overlapping lobate deltas (Frazier, 1967). The delta lobes formed as the Mississippi River switched channels to follow a more hydraulically efficient path to the Gulf of Mexico. The switching of channels and loci of delta building occurred about every 1,000 years, and has created a physiography of large areas of low-elevation wetlands, termed inter-distributary basins, separated by natural levees which decrease in elevation toward the Gulf of Mexico (pl. 1). The natural levees act as hydrologic barriers to the cross-basin flow of water. Cross-basin flow is generally restricted to man-made canals that traverse these levees, such as the GIWW. In the study area, the GIWW hydrologically links the Teche-Vermilion, Terrebonne, Timbalier, and Barataria inter-distributary Basins (pl. 1).

Major Rivers

The Mississippi River and the Atchafalaya River are major sources of freshwater to the Louisiana coast in general, and in varying amounts to the study area. Because of the extensive levee system, the Mississippi River mostly flows into the Gulf of Mexico, and enters coastal Louisiana wetlands only indirectly as Gulf of Mexico waters work their way into the estuaries of the various bays. The Atchafalaya River has a higher hydraulic gradient and shorter path to the Gulf of Mexico than the Mississippi River but is prevented from capturing the entire flow of the Mississippi River by the Old River Control Structure (fig. 1). Since completion of the structure in the 1950's, about 30 percent of Mississippi River volume is diverted into the Atchafalaya River (Wells and Demas, 1977, p. 6). This water comprises most of the flow of the Atchafalaya River, and flow from the Red River provides some additional water (fig. 1). The water flows through the Atchafalaya Basin and enters the Gulf of Mexico through WLO and the LAR.

Approach and Methods

Synoptic measurements of discharge and suspended sediment were made along the GIWW in the study area during different times of the year. The synoptic data were supplemented by continuous data collected at three sites from which hourly discharge was computed. Water-level gradients in the study area were established by comparing stage at sites along and adjacent to the GIWW. Salinity fluctuations at coastal sites were used to track freshwater inflow from the GIWW. Table 1 lists all sites used for this report and the type of data presented. Site locations are shown on plate 1.

Discharge and Suspended Sediment

Instantaneous discharge measurements and computed continuous discharge, derived from relations between instantaneous discharge and hourly recording point-velocity and stage measurements at the same location, were used to describe flow at selected sites along the GIWW (table 1, pl. 1). Between April 1997 and December 1999, 13 to 19 measurements were made at these sites at varying stages of the LAR. Measurements were made along the entire length of the GIWW from Cypremort to Bayou Perot on synoptic trips of 2 to 4 days. The measurements were made with a 600-kilohertz boat-mounted acoustic Doppler current profiler (ADCP) (Simpson and Oltmann, 1993). In the GIWW at Cypremort, at Bayou Penchant south of Morgan City, and at Bayou Boeuf at railroad bridge at Amelia, La., stage and point-velocity were recorded hourly (continuously) by onsite data-recording equipment. A relation between these variables and the instantaneous discharge measurements across the entire channel cross-section was developed to compute continuous discharge (Morlock, 2001). The data from these sites were tabulated as hourly discharge values. While instantaneous discharge measurements were being made in the GIWW, suspended sediment usually was sampled at points in the center, left, and right of the channel cross section with a depth-integrating sampler (Edwards, 1999). There are not corresponding suspended-sediment measurements for every discharge measurement.

Flow direction can vary at and between sites in the low-gradient coastal area so a sign convention was used to label flow direction at the sites. Flow away from Morgan City and toward the Gulf of Mexico was labeled positive. To the east of Morgan City, positive flow is to the east and south with the exception of the Avoca Island Cutoff Channel. Here, positive flow is to the northeast, away from the LAR (pl. 1). West of Morgan City, positive flow is to the west; negative flow indicates flow toward Morgan City.

Monthly-average discharge for the study period was determined at four synoptic sites along the GIWW--west of HNC at Houma, near Bay Wallace east of Morgan City, west of WLO south of Calumet, and east of Jaws Bay west of Franklin--for the difference in discharge between the GIWW east and west of Jaws Bay (across Jaws Bay) and for the three recording sites at Bayou Boeuf at railroad bridge at Amelia, Bayou Penchant south of Morgan City, and the GIWW at Cypremort. At the continuously recording sites, discharge data were averaged by month. At the other site, relations

Table 1. Data-collection sites and type of data collected along the Gulf Intracoastal Waterway (GIWW) and adjacent surface-water bodies, south-central Louisiana

[USGS, U.S. Geological Survey; DWF, Louisiana Department of Wildlife and Fisheries; NAVD88, North American Vertical Datum of 1988; GPS, Global Positioning System; USACE, U.S. Army Corps of Engineers; DNR, Louisiana Department of Natural Resources; DEQ, Louisiana Department of Environmental Quality; USFWS, U.S. Fish and Wildlife Service; --, not applicable; NGVD29, National Geodetic Vertical Datum of 1929]

Map number (pl. 1)	Site name	Operator/ owner	Continuous data				Instantaneous data		Datum: survey agency (method)[1]
			Discharge	Velocity	Stage	Salinity	Discharge	Suspended sediment	
1	Vermilion Bay near Cypremort Point	USGS/DWF	--	--	X	X	--	--	NAVD88: USGS (GPS)
2	GIWW at Cypremort	USGS/USACE	X	X	X	--	X	X	NAVD88: USGS (GPS)
3	GIWW west of Jaws Bay near Cypremort	USGS/USACE	--	--	--	--	X	X	--
4	GIWW east of Jaws Bay west of Franklin	USGS/USACE	--	--	X	--	X	X	NAVD88: USGS (GPS)
5	GIWW west of Wax Lake Outlet south of Calumet	USGS/USACE	--	--	X	--	X	X	NAVD88: USACE
6	Wax Lake Outlet at Calumet	USGS/USACE	--	--	X	--	X	--	NAVD88: USGS (GPS)
7	GIWW east of Wax Lake Outlet near Calumet	USGS/USACE	--	--	--	--	X	X	--
8	GIWW at Lower Atchafalaya River south of Morgan City	USGS/USACE	--	--	--	--	X	X	--
9	Lower Atchafalaya River at Morgan City	USGS/USACE	--	--	X	--	X	--	NAVD88: USGS (GPS)
10	Avoca Island Cutoff Channel south of Morgan City	USGS/USACE	--	--	X	--	X	X	NAVD88: USGS (GPS)
11	Bayou Penchant south of Morgan City	USGS/USACE	X	X	X	--	X	X	NAVD88: USGS (GPS)
12	Bayou Boeuf at railroad bridge at Amelia	USGS/USACE	X	X	X	--	X	X	NAVD88: USGS (GPS)
13	GIWW near Bay Wallace east of Morgan City	USGS/USACE	--	--	X	--	X	X	NAVD88: USGS (GPS)
14	Bayou Penchant at Brady Canal	DNR	--	--	--	X	--	--	--
15	Bayou du Large at Theriot	USGS/DEQ	--	--	--	X	--	--	--
16	GIWW west of Houma Navigation Canal at Houma	USGS/USACE	--	--	--	--	X	X	--
17	GIWW east of Houma Navigation Canal at Houma	USGS/USACE	--	--	X	X	X	X	NAVD88: USGS (GPS)
18	Company Canal at Highway 1 at Lockport	USGS/USACE	--	--	X	--	--	--	NAVD88: USGS (GPS)
19	Bayou L'Eau Bleu	USGS/USFWS	--	X	--	X	--	--	--
20	GIWW west of Bayou Lafourche at Larose	USGS/USACE	--	--	--	--	X	X	--
21	GIWW east of Bayou Lafourche at Larose	USGS/USACE	--	--	--	--	X	X	--
22	GIWW east of Larose	DNR	--	--	X	X	--	--	NAVD88: DNR (GPS)
23	GIWW west of Bayou Perot	USGS	--	--	--	--	X	--	--
24	Intersection of GIWW and Bayou Perot	DNR	--	--	X	X	--	--	NAVD88: DNR (GPS)
25	Bayou Perot south of the GIWW	USGS	--	--	--	--	X	--	--
26	Grand Bayou tributary west of Galliano	USGS/DNR	--	--	--	X	--	--	--
27	Bayou Jean Lacroix near Montegut	USGS/DNR	--	--	--	X	--	--	--
28	Bayou Terrebonne at Bush Canal, south of Chauvin	USGS/DNR	--	--	--	X	--	--	--
29	Houma Navigation Canal at Dulac	USGS/USACE	--	X	X	X	X	--	NGVD29 (conventional levels)
30	Caillou Lake (Sister Lake) southwest of Dulac	USGS/DWF	--	--	--	X	--	--	--
31	Côte Blanche 4	DNR	--	--	--	X	--	--	NAVD88: DNR (GPS)
32	Little Lake near Cut Off	USGS/DNR	--	--	--	X	--	--	--

[1]Elevation surveys were accomplished using GPS and conventional leveling; USGS survey was done as part of this study, using a single first order benchmark at Patterson, Louisiana.

between instantaneous discharge measurements and same-day average stage of the LAR at Morgan City were used to develop regression equations. The difference in same-day discharge across Jaws Bay was used in the regression from this location. Only measurements made when the LAR at Morgan City was 2 ft or more above NAVD88 were used in developing the regression equations. Discharge measurements in the GIWW after the high rainfall event in 1998 also were eliminated from the regressions because of the explainable departure from expected values. Monthly-average discharge was computed for those months when the LAR at Morgan City averaged 3 ft or more above NAVD88. The appendix contains the equations used at the respective stations. Stage of the LAR at Morgan City was 3 ft or more above NAVD88 for the first 7 months of 1997, 1998, and 1999.

Data from the individual synoptic trips were used to determine if and under what conditions wetlands or waterways adjacent to a specific segment of the GIWW were storing water from or releasing water to that particular segment. Discharge measured at the downstream end of a particular segment was subtracted from that entering the same segment for each synoptic trip. This difference was plotted against either the discharge entering the GIWW from the respective river source or the prior 21-day average discharge at Bayou Boeuf at railroad bridge at Amelia. The 21-day discharge at Bayou Boeuf at railroad bridge at Amelia was used to approximate runoff generated from local rainfall entering the GIWW and coastal Louisiana. Negative values indicate water from the surrounding wetlands is draining into the GIWW and leaving the segment. Positive values indicate less water is flowing out of the segment than entering; water is being stored in the segment.

Stage and Water-Level Gradients

Gages measuring stage are distributed at sites throughout the study area (table 1). Data from these sites were used to compare stage and establish water-level gradients in the GIWW and selected adjacent bayous and canals. All gages used in this study were surveyed to NAVD88, with a Global Positioning System (GPS) using a first order benchmark at Patterson, La., as part of this study except where noted (table 1). The gage in the HNC at Dulac was not part of the USGS GPS survey, but was surveyed by the USGS from a nearby benchmark to the NGVD29. Two sites were surveyed by Louisiana Department of Natural Resources (DNR) to NAVD88 datum. The importance of reliable elevation data in establishing gradients increases with distance from the LAR, as the gradient becomes smaller. Small differences in gradient may be attributed to differences in surveys rather than actual differences in measured stage.

Monthly-average values for stage were used in this comparison to determine water-level gradients across the study area. To the east of Morgan City, stage data from LAR at Morgan City and HNC at Dulac were used as the upstream and downstream points. To the west of WLO, stage data from WLO at Calumet and Vermilion Bay near Cypremort Point were used as the upstream and downstream points.

Acknowledgments

The author extends his thanks to Troy Constance and Nancy J. Powell of the U.S. Army Corps of Engineers and Ronald F. Paille of the U.S. Fish and Wildlife Service for their support with this project. Paille was among the first to recognize the potential value of the flow of freshwater and sediments in the GIWW to restoration of coastal Louisiana wetlands. The field work and data collection were carried out by C. Kevin Labbe and Andrew Tarver of the USGS office in Baton Rouge.

HYDROLOGIC CONDITIONS DURING STUDY

Stage and discharge measured in LAR at Morgan City and discharge measured at WLO at Calumet from October 1996 to December 1999 have similar hydrographs (fig. 2). Stage of LAR at Morgan City reached almost 8 ft above NAVD88 for a brief time in April. The spring rise started in late February 1997 and continued through mid-July. After July, stage and discharge remained low until early January 1998. The spring flood in 1998 started earlier and, although not reaching the levels of 1997, remained high until late July. Stage during the low water season (August through December) in 1998 was slightly higher than in 1997. In

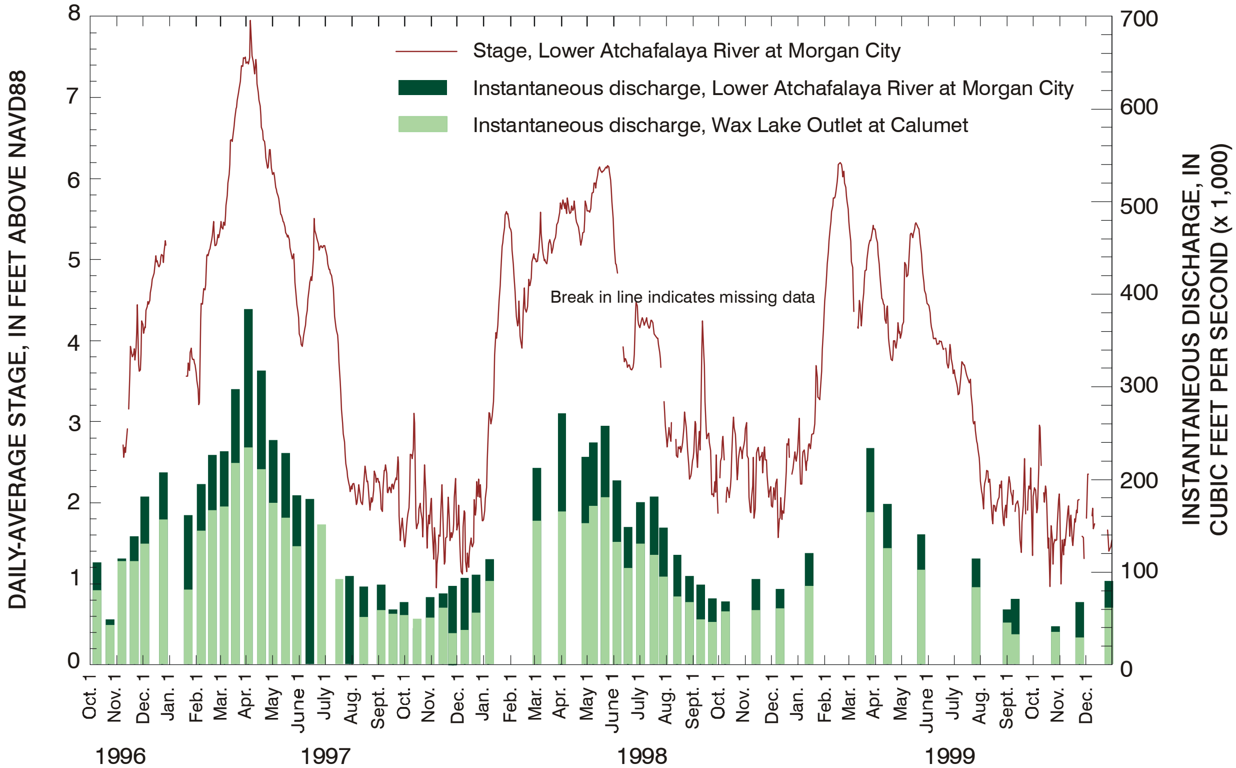


Figure 2. Instantaneous discharge of the Lower Atchafalaya River at Morgan City and Wax Lake Outlet at Calumet, and daily-average stage of the Lower Atchafalaya River at Morgan City, Louisiana, October 1996 to December 1999.

1999, the spring flood also developed later than in 1997 and had a smaller volume. During the low water season, the stage of LAR at Morgan City was at least 3 ft above NAVD88 only in 1996. In November and December 1999, stage of LAR at Morgan City frequently was less than 1.5 ft above NAVD88.

Peak measured instantaneous discharge for the period of study was about 380,000 ft^3/s for LAR at Morgan City and 220,000 ft^3/s for WLO at Calumet for a combined discharge of about 600,000 ft^3/s. The LAR at Morgan City received from 43 to 75 percent of the combined discharge, with most of the variability occurring when LAR at Morgan City was 3 ft or less above NAVD88. For all measurements, an average of 59 percent ± 5 percent of the combined discharge entered the LAR at Morgan City. The average percentage of Atchafalaya River flow entering LAR at Morgan City determined by measurements during this study is similar to the division of discharge determined by measurements made between 1980 and 1982 (Arcement, 1988).

Precipitation also affects flow in the GIWW. Monthly precipitation data are shown for weather stations at Morgan City and Houma (fig. 3). Data for the Palmer Hydrological Drought Index (PHDI) for the South-Central Division, which extends west from Morgan City halfway to the Texas border, and for the Southeast Division, which extends east of Morgan City across the Mississippi River to the border with Mississippi, also are presented (National Oceanic and Atmospheric Administration National Climatic Data Center, 2000). The PHDI is an index that assesses regional long-term moisture supply. October and November of 1996 had below average rainfall. From January to June 1997, rainfall was near or above the long-term average for both stations. From August through October, precipitation was below the long-term average. The PHDI indicated an incipient to mild drought from September through December 1997. About 10 to 12 inches more rain than average was measured at the two stations during January 1998. Rainfall was near normal through April 1998, but then was below average until the storms of September 1998. Very little rain fell in May 1998.

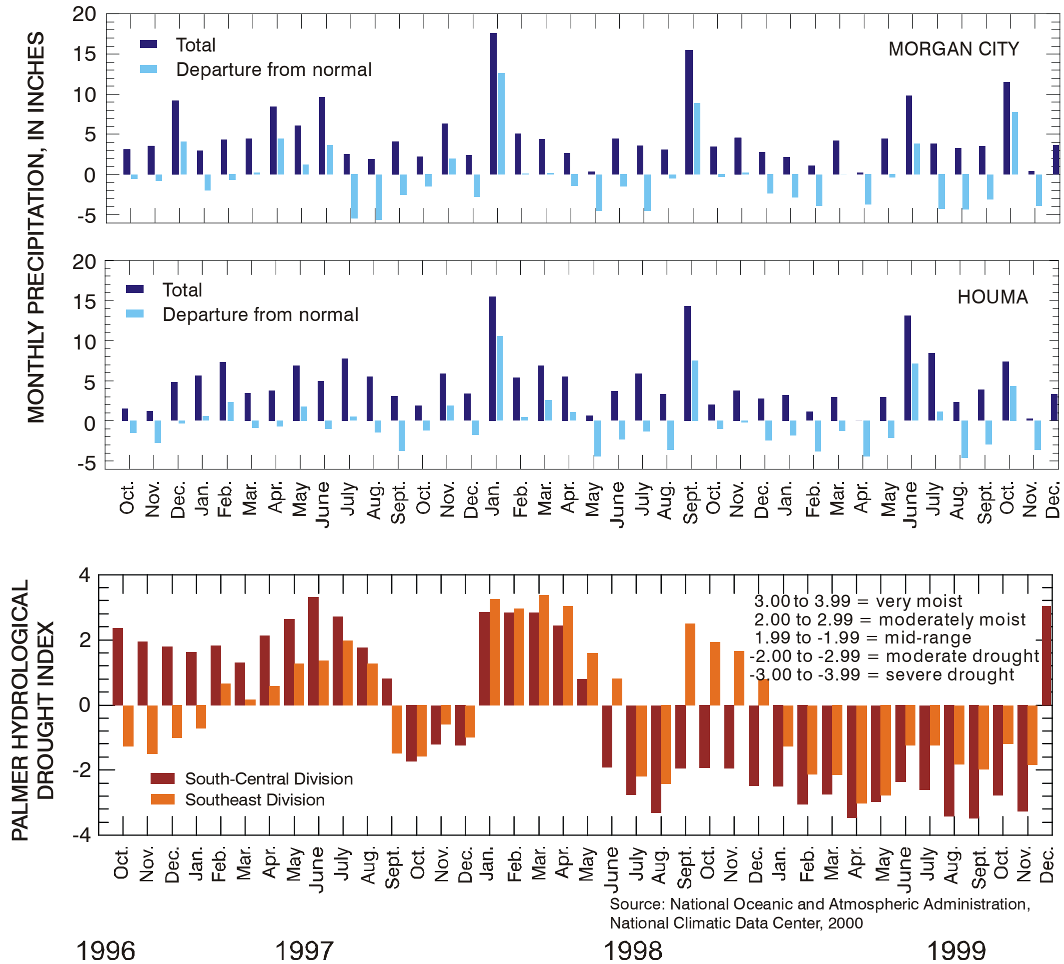


Figure 3. Monthly total precipitation and departure from normal at Morgan City and Houma, Louisiana, and Palmer Hydrological Drought Index for the Southeast and South-Central Climatological Divisions in Louisiana, October 1996 to December 1999.

Even with the high rainfall in September, the South-Central Division was in a mild to moderate drought from May through the end of the year. The Southeast Division was in a moderate drought in July and August 1998. From October 1998 through May 1999, rainfall was below average. Both divisions were in a moderate drought for most months during 1999.

Two events during the fall low-water season raised LAR at Morgan City stage for prolonged periods (fig. 4). During the last week of September and the first 2 weeks of October 1997, a period of strong south winds raised the stage along the coast and in the LAR at Morgan City. In early and mid-September of 1998, Hurricane Earle (August 30-September 1) and Tropical Storms Frances (September 10-12) and Hermine (September 19-20) were major storms that produced substantial precipitation and raised the stage along the coast and in the LAR at Morgan City. In contrast, the high LAR stage in September 1997 occurred without a major storm or substantial precipitation.

SURFACE-WATER HYDROLOGY

In this section, flow characteristics in the GIWW are discussed. Distribution and differences in discharge, stage, and water-level gradients, and suspended-sediment and salinity concentrations are described.

Flow Characteristics

Discharge in the GIWW was highest where it crossed the LAR and at WLO south of Calumet,

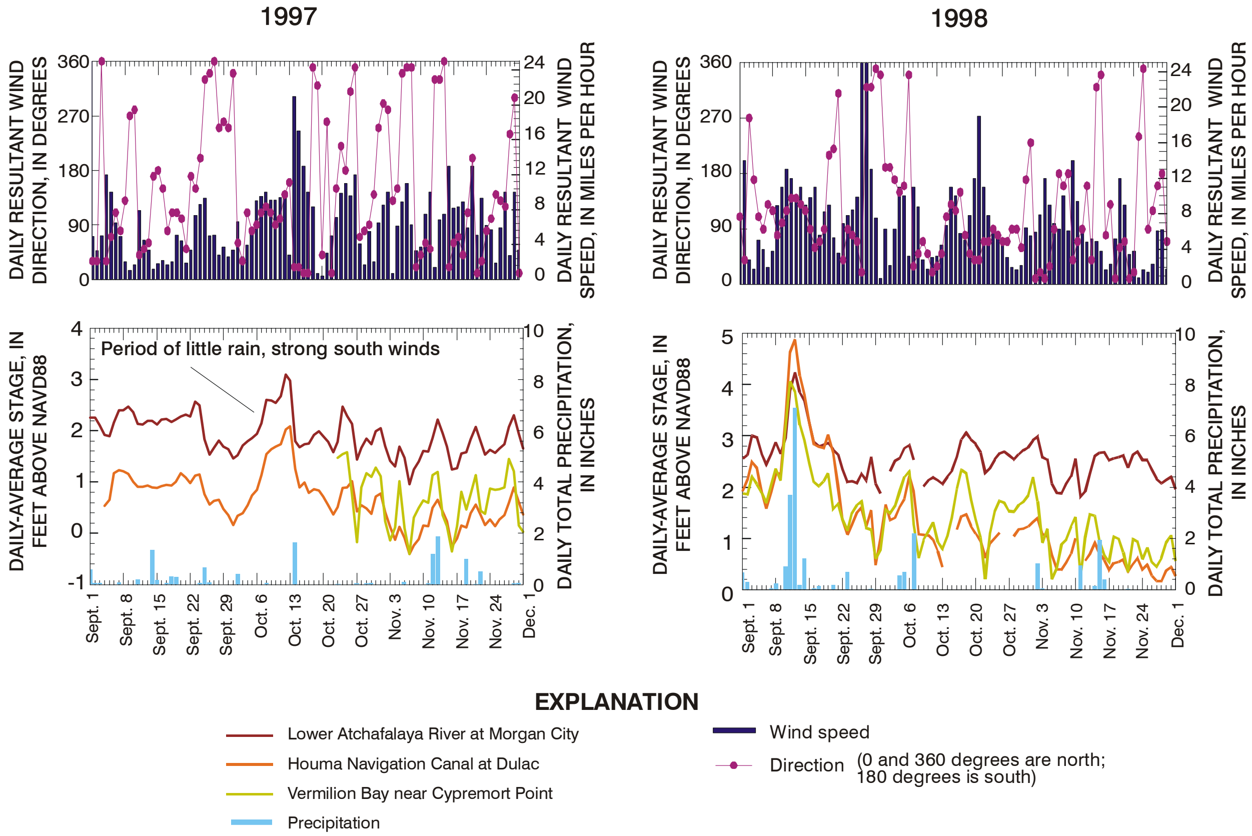


Figure 4. Daily resultant wind speed and direction at New Orleans, Louisiana, daily-average stage at selected sites in coastal Louisiana, and daily total precipitation at Morgan City, Louisiana, from September 1 to November 30, 1997 and 1998.

and decreased with increasing distance east and west (table 2). At the Avoca Island Cutoff Channel, discharge ranged from 267 to 31,100 ft^3/s; the average discharge was 12,200 ft^3/s. At Bayou Penchant south of Morgan City, flow was usually to the southeast, away from the Avoca Island Cutoff Channel. The average discharge was 3,250 ft^3/s. Measured discharge at Bayou Boeuf at railroad bridge at Amelia ranged from 9,110 ft^3/s flowing north into the Verret Subbasin to 15,300 ft^3/s flowing south from the basin toward the GIWW. The average discharge was 1,000 ft^3/s entering the GIWW from the Verret Subbasin. Discharge was usually to the east and averaged about 5,700 ft^3/s in the GIWW near Bay Wallace east of Morgan City and the GIWW west of HNC at Houma. Discharge of 922 ft^3/s to the west was measured at the former site. Discharge always was to the east in the GIWW west of HNC at Houma.

Discharge measured in the GIWW east of HNC at Houma averaged 2,610 ft^3/s and ranged from 1,100 ft^3/s, flowing westward toward the HNC, to 4,640 ft^3/s flowing eastward toward Bayou Lafourche. Discharge in the GIWW west and east of Bayou Lafourche at Larose was similar in magnitude and direction and averaged about 2,200 ft^3/s to the east. Eastward discharge of as much as 5,320 ft^3/s toward Bayou Perot was measured. Flow westward toward Houma was observed on two occasions in the GIWW, with a maximum discharge of 1,860 ft^3/s east of Bayou Lafourche at Larose.

In Barataria Basin, to the east of Larose, instantaneous discharge was measured in the GIWW west of the intersection with Bayou Perot, and in Bayou Perot just south of the intersection on several occasions. The measurements were made

Table 2. Summary of instantaneous discharge measurements made at selected sites along or near the Gulf Intracoastal Waterway (GIWW) in south-central Louisiana, 1997-99

[Discharge measurements are in cubic feet per second. Negative discharge indicates flow toward Morgan City or northward flow.]

Map number (pl. 1)	Site name	Instantaneous discharge				
		Number of measure-ments	Mean (±standard deviation)	Median	Range	
					Minimum	Maximum
		East of Lower Atchafalaya River				
	Between Lower Atchafalaya River and Houma Navigation Canal					
10	Avoca Island Cutoff Channel south of Morgan City	18	12,200 ± 9,790	9,400	267	31,100
11	Bayou Penchant south of Morgan City	18	3,250 ± 2,370	2,620	260	7,570
12	Bayou Boeuf at railroad bridge at Amelia	17	1,000 ± 6,720	768	-9,110	15,300
13	GIWW near Bay Wallace east of Morgan City	18	5,600 ± 3,940	5,630	-922	10,600
16	GIWW west of Houma Navigation Canal at Houma	19	5,770 ± 3,190	4,980	845	11,800
	East of Houma Navigation Canal					
17	GIWW east of Houma Navigation Canal at Houma	19	2,610 ± 1,740	2,200	-1,100	4,640
20	GIWW west of Bayou Lafourche at Larose	19	2,220 ± 1,760	2,510	-1,580	5,320
21	GIWW east of Bayou Lafourche at Larose	19	2,190 ± 1,830	2,670	-1,860	4,930
		West of Lower Atchafalaya River				
	Between Lower Atchafalaya River and Wax Lake Outlet					
8	GIWW at Lower Atchafalaya River south of Morgan City	13	13,400 ± 9,380	12,200	3,910	35,200
7	GIWW east of Wax Lake Outlet near Calumet	18	9,230 ± 3,350	8,890	4,430	16,200
	West of Wax Lake Outlet					
5	GIWW west of Wax Lake Outlet south of Calumet	16	9,460 ± 5,610	10,300	2,050	20,300
4	GIWW east of Jaws Bay west of Franklin	18	8,230 ± 4,110	6,600	3,560	17,000
3	GIWW west of Jaws Bay near Cypremort	18	3,310 ± 2,160	2,850	1,000	10,200
2	GIWW at Cypremort	17	1,350 ± 2,550	2,090	- 2,830	4,830

in conjunction with synoptic surveys of discharge along the GIWW, but were not made as frequently (table 3). In the GIWW west of Bayou Perot, discharge was to the east and ranged from 126 ft^3/s to more than 3,450 ft^3/s. In Bayou Perot, discharge was much higher than in the GIWW and was measured at 29,300 ft^3/s flowing south and 12,000 ft^3/s flowing north into Lake Salvador.

Instantaneous discharge was measured at two sites between the LAR and WLO at Calumet (pl. 1, table 2): GIWW at LAR south of Morgan City and the GIWW east of WLO at Calumet. Measured discharge always indicated flow from east to west in this short stretch of the GIWW. At the GIWW at LAR south of Morgan City, average discharge (13,400 ft^3/s) and maximum discharge (35,200 ft^3/s) were the highest of all 14 sites.

West of the WLO, discharge in the GIWW decreased toward the west (table 2). In the GIWW west of WLO south of Calumet, measurements ranged from 2,050 to 20,300 ft^3/s, with an average of 9,460 ft^3/s. In the GIWW east of Jaws Bay west of Franklin, average measured discharge was 8,230 ft^3/s, and reached a maximum of 17,000 ft^3/s. In the GIWW west of Jaws Bay near Cypremort, the average discharge was 3,310 ft^3/s, and flow was always to the west. In the GIWW at Cypremort, average discharge was 1,350 ft^3/s. Maximum westward discharge was 4,830 ft^3/s, but eastward discharge as high as 2,830 ft^3/s toward Jaws Bay was measured.

Daily-average stage and discharge in Bayou Penchant south of Morgan City, Bayou Boeuf at railroad bridge at Amelia, and GIWW at Cypremort are presented (fig. 5). The gages did not start operating at the same time. At Bayou Penchant south of Morgan City, computed discharge tracked stage fluctuations, with fall discharge about half that during the spring (fig. 5). Flow was almost always to the southeast, with isolated days when there was a net flow of water northwest toward the Avoca Island Cutoff Channel. Water flowed both into (north) and out of (south) the Verret Subbasin

Table 3. Supplemental instantaneous discharge measurements made at the Gulf Intracoastal Waterway (GIWW) west of Bayou Perot, in Bayou Perot south of the Gulf Intracoastal Waterway, and in the Houma Navigation Canal at Dulac, south-central Louisiana, 1997-99

[Positive discharge is to the east or south. --, no data; NAVD88, North American Vertical Datum of 1988]

Date	Stage, Lower Atchafalaya River at Morgan City (site 9) (feet above NAVD88)	Instantaneous discharge (cubic feet per second)		
		GIWW west of Bayou Perot (site 23)	Bayou Perot south of GIWW (site 25)	Houma Navigation Canal at Dulac (site 29)
4-15-97	6.97	3,450	17,500	4.200
7-22-97	5.25	1,900	17,400	--
9-23-97	2.57	126	800	--
9-24-97	2.50	--	--	4,690
11-19-97	1.50	--	--	4,240
1-28-98	5.56	--	--	13,700
6- 3-98	4.95	--	--	5,980
6-15-98	3.70	--	--	4,670
4-21-99	3.83	1,440	18,000	--
6- 1-99	4.44	1,050	18,400	--
7-14-99	3.64	1,300	-12,000	--
8-26-99	1.98	709	10,100	--
10- 7-99	2.43	1,220	29,300	--
11- 4-99	1.55	1,340	5,990	--

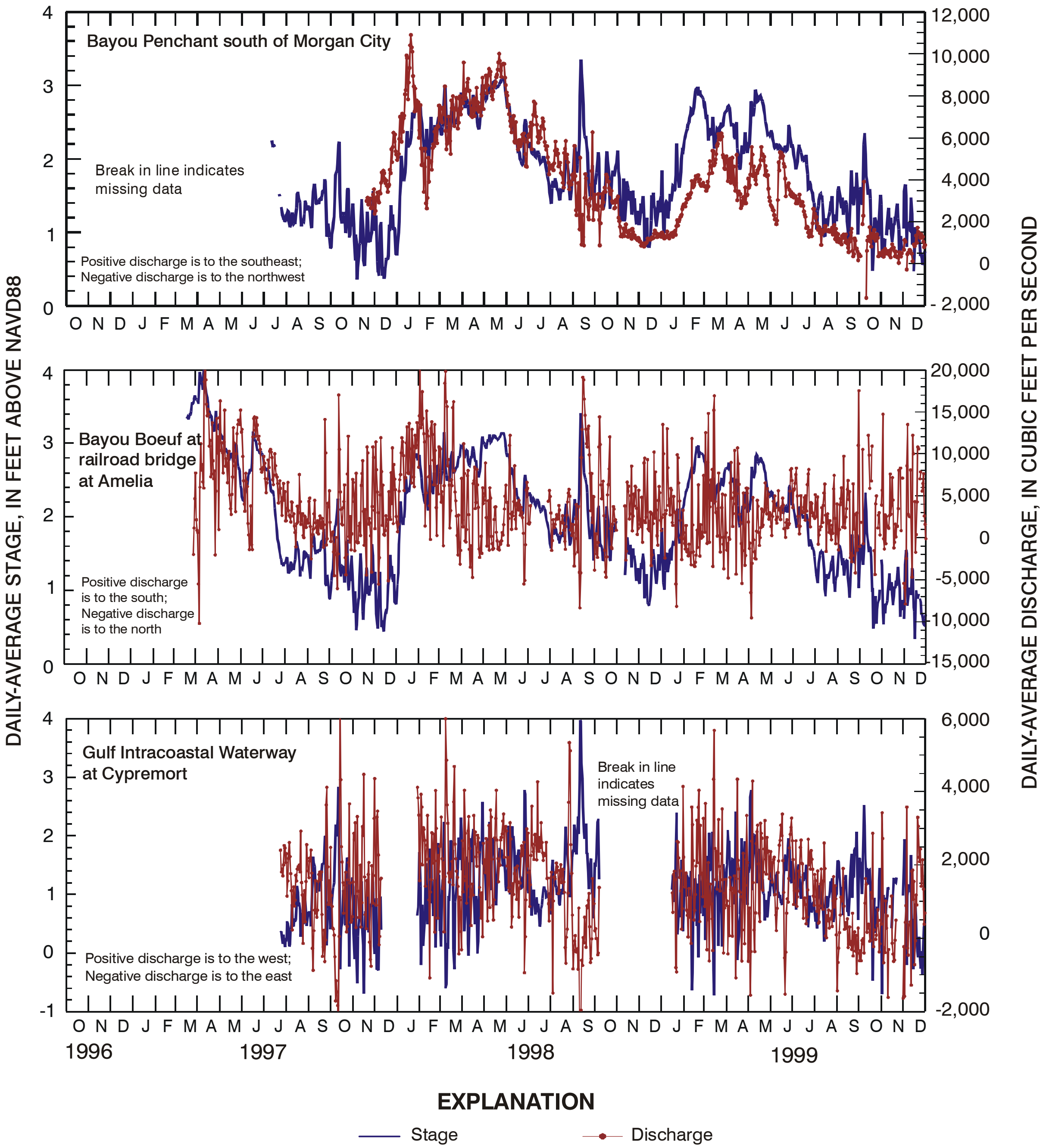


Figure 5. Daily-average discharge and stage at Bayou Penchant south of Morgan City, Bayou Boeuf at railroad bridge at Amelia, and Gulf Intracoastal Waterway at Cypremort, Louisiana, October 1996 to December 1999.

through Bayou Boeuf (fig. 5). Flow was mostly to the south to the confluence of Bayou Boeuf and the GIWW. Discharge was not simply related to stage of the LAR at Morgan City. For example, April through July 1997 and January, February, and September 1998 were months when relatively more Verret Subbasin water was entering the GIWW and mixing with LAR water (fig. 5). In February and May 1999, discharge was small and often entered rather than drained the Verret Subbasin.

Hourly point-velocity was measured at Bayou L'Eau Bleu from May to December 1996 as part of a separate study. Although continuous discharge was not computed for this site, velocity data indicate flow mostly was to the south, away from the GIWW (fig. 6). This was true even in the fall months, when flow direction frequently reversed due to strong south winds. Available instantaneous discharge measurements have indicated between 200 and 400 ft^3/s of water flowing to the south (USGS miscellaneous measurements).

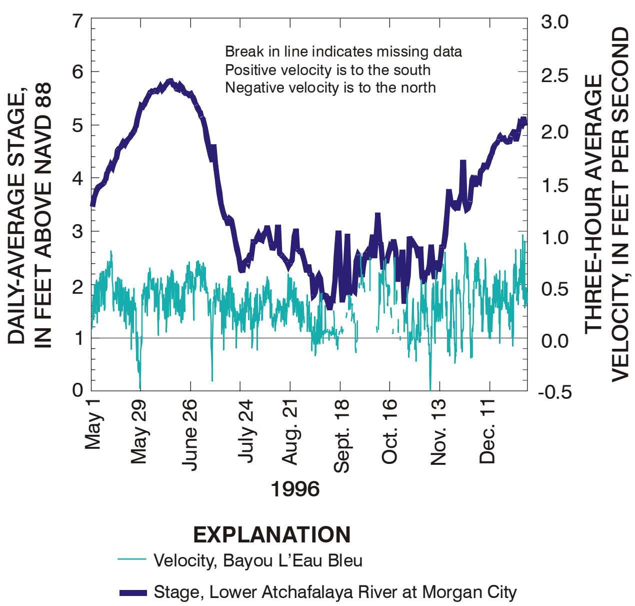


Figure 6. Daily-average stage of the Lower Atchafalaya River at Morgan City and three-hour average velocity of Bayou L'Eau Bleu, Louisiana, May to December 1996.

In the GIWW at Cypremort, daily-average discharge was usually to the west, toward Vermilion Bay. The exception was September 1998 (fig. 5), when discharge was eastward toward Jaws Bay. On average, fall discharge was smaller than earlier in the year. In the fall of 1999, discharge was much smaller than in the fall of 1997, and flow more frequently was to the east.

Discharge in Relation to Stage of the Lower Atchafalaya River and Precipitation

To evaluate how stage of LAR at Morgan City affects flow in the GIWW, the instantaneous discharge measurements made at all points along the GIWW were plotted against same-day average stage of the LAR at Morgan City (pl. 1). Measurements made after periods of heavy precipitation or little prior precipitation are highlighted to show the influence of precipitation on flow in the GIWW.

Between Lower Atchafalaya River and Houma Navigation Canal

Water draining the Verret Subbasin through Bayou Boeuf at railroad bridge at Amelia and LAR water entering through the Avoca Island Cutoff Channel maintain eastward flow in the GIWW east of Morgan City. The amount of water flowing into Avoca Island Cutoff Channel from the LAR generally increased as stage of the LAR at Morgan City rose, but this relation was affected by how much water was leaving Bayou Boeuf at railroad bridge at Amelia (pl. 1). During periods of high southward flow in Bayou Boeuf at railroad bridge at Amelia, water entering the GIWW through Avoca Island Cutoff Channel was less than could be expected based solely on stage of the LAR at Morgan City. Thus, peak discharge of 25,000 to 35,000 ft^3/s in Avoca Island Cutoff Channel was measured when there was little water exiting the Verret Subbasin through Bayou Boeuf and stage of LAR at Morgan City was 4 to 5 ft above NAVD88. When stage of the LAR at Morgan City was 5.5 to 7 ft above NAVD88, discharge in the Avoca Island Cutoff Channel was only 17,000 to 22,000 ft^3/s. In January 1998, more water was flowing south through Bayou Boeuf at railroad bridge at Amelia due to the unusually heavy precipitation. Inflow through the Avoca Island Cutoff Channel was close to zero even though the LAR at Morgan City was 5.5 ft above NAVD88. Discharge in the Avoca Island Cutoff Channel during periods with little prior precipitation seemed to maintain the same relation with stage of the LAR at Morgan City as during other times (pl. 1).

The amount of water flowing south through Bayou Boeuf at railroad bridge at Amelia increased with precipitation (fig. 7). In 1997, total monthly rainfall was high for April, May, and June. Flow in Bayou Boeuf at railroad bridge at Amelia was to the south, and monthly-average discharge was between 8,000 and 10,000 ft^3/s. In April, May, and June 1998, precipitation was low and monthly-average discharge was only 2,700 ft^3/s to the south. In February 1999, there was very little rain, and monthly-average discharge in Bayou Boeuf was close to zero. LAR stage was still increasing during this time. In April 1999, there was even less rain than in February 1999, but discharge in Bayou Boeuf was slightly higher, possibly due to the fall-

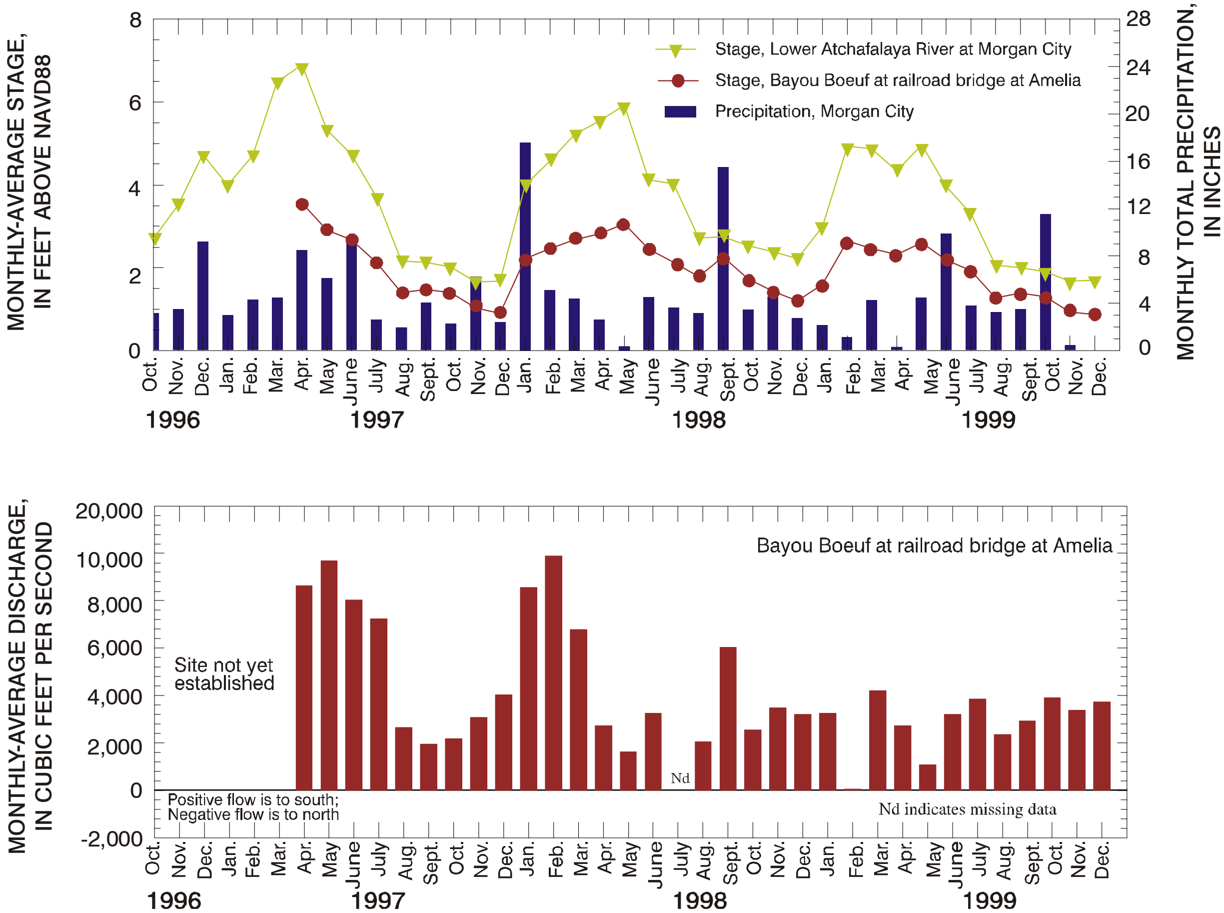


Figure 7. Monthly-average stage of the Lower Atchafalaya River at Morgan City and Bayou Boeuf at railroad bridge at Amelia, monthly total precipitation at Morgan City, and monthly-average discharge at Bayou Boeuf at railroad bridge at Amelia, Louisiana, October 1996 to December 1999.

ing stage of the LAR at Morgan City. An unknown portion of the Verret Subbasin flow is generated by the Atchafalaya River through locks far upstream of Morgan City (Wells and Demas, 1977).

Bayou Penchant intersects the Avoca Island Cutoff Channel at the confluence with Bayou Chene (pl. 1). Bayou Penchant captures water from the Avoca Island Cutoff Channel that would otherwise be available for eastward flow in the GIWW and is one of two main conduits of water flowing into the interior of the western Terrebonne Basin (between Lower Atchafalaya River and Houma Navigational Canal) wetlands. Monthly-average discharge at Bayou Penchant south of Morgan City was always to the southeast (fig. 8), removing water from the Avoca Island Cutoff Channel. Monthly-average discharge at Bayou Penchant south of Morgan City had a positive relation with stage of the LAR at Morgan City. High discharge occurred even when there was little precipitation, for example in April and May 1998 and April 1999. High precipitation may have contributed to the high average discharge in January 1998, but an increase in precipitation did not appear to increase discharge at Bayou Penchant south of Morgan City in October 1999. The lower discharge measured in 1999 compared to 1998 appeared to result from deployment of new instrumentation and a new stage and point-velocity flow relation rather than natural phenomena such as less rainfall, although it rained less in 1999 than in 1998. The disconnect between stage and discharge from September to October 1998 is shown by the continuous data plotted in figure 5. The data prior to October 1998 probably overestimate actual discharge. The new stage-discharge relation has been in use since September 1998.

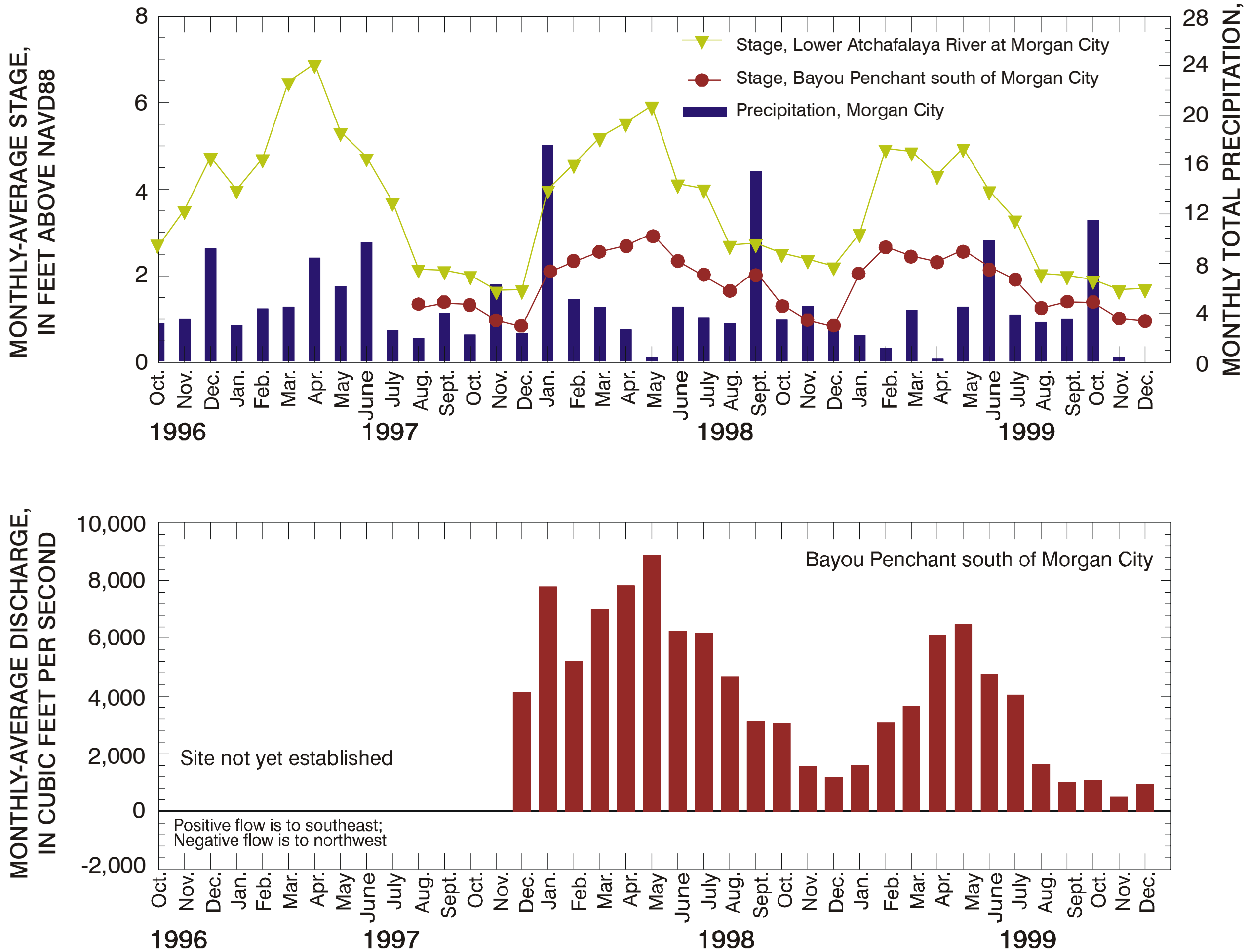


Figure 8. Monthly-average stage of the Lower Atchafalaya River at Morgan City and Bayou Penchant south of Morgan City, monthly total precipitation at Morgan City, and monthly-average discharge of Bayou Penchant south of Morgan City, Louisiana, October 1996 to December 1999.

The GIWW near Bay Wallace east of Morgan City is the other main conduit of water from the LAR at Morgan City and the Verret Subbasin. Here, water usually moved eastward toward the HNC. Discharge in both Bayou Penchant south of Morgan City and in the GIWW near Bay Wallace east of Morgan City increased predictably with increases in the stage of the LAR at Morgan City (pl. 1). Discharge in the GIWW near Bay Wallace east of Morgan City and west of the HNC at Houma was similar in magnitude and responded in similar fashion to changes in stage of the LAR at Morgan City. At stages between 2.5 and 4 ft above NAVD88, discharge increased rapidly to about 8,000 ft^3/s and, then, continued to increase more gradually to maximums of about 10,000 to 12,000 ft^3/s. Discharge measured after the heavy rainfall in January 1998 was within the range of measurements made at other times. Extended periods with little rain did not alter the relation between stage and discharge substantially. The GIWW between Bay Wallace and Houma has few sections with well-defined levees. Rather than being restricted to the GIWW, water easily can leave the GIWW at the many breaks in the levees. When the LAR at Morgan City was 3 ft or less above NAVD88, measured discharge in the GIWW near Bay Wallace east of Morgan City frequently was less than that measured west of the HNC at Houma. Discharge at the latter site generally remained above 4,000 ft^3/s. Flow reversals (flow toward the LAR) were observed several times in the GIWW near Bay Wallace east of Morgan City during low stage of the LAR at Morgan City, but were never observed west of the HNC at Houma.

Water leaves the GIWW and flows into the western Terrebonne Basin wetlands through Bayou Penchant south of Morgan City, as previously discussed, and through Bayou Copasaw and Minor's Canal farther east. The latter two waterways capture a percentage of the flow in the GIWW during high stage of the LAR at Morgan City and convey water southward (fig. 9). Combined discharge in Bayou Copasaw and Minor's Canal was about 10 to 30 percent of the discharge in the GIWW.

Stage of the LAR at Morgan City was a good predictor of how much water was flowing into the GIWW, but conditions of little or heavy prior precipitation determined the proportions and routing of the main sources of the water. In general, unless there was a severe drought, water in the GIWW east of the confluence with Bayou Chene contained at least some Bayou Boeuf water. During periods of heavy precipitation, some of the water from Bayou Boeuf moved southward through Bayou Chene and combined with LAR water flowing into Bayou Penchant south of Morgan City from the Avoca Island Cutoff Channel south of Morgan City (author's personal observations during 1997-99). Periods of heavy precipitation and low LAR stage increased the proportion of water from the Verret Subbasin flowing south along this route.

East of Houma Navigation Canal

Discharge in the GIWW at sites between Houma and Larose increased to about 4,000 ft^3/s as the stage of the LAR increased from 2.5 to 4 ft above NAVD88 (pl. 1). If discharge in the GIWW east of the HNC predictably increases as stage of the LAR at Morgan City increases to 4 ft or more above NAVD88, it was not readily apparent from the measurements made during the present study. Discharge in the GIWW east of the HNC at Houma and east and west of Bayou Lafourche at Larose was similar. An estimate of the volume of water flowing east was made by averaging all discharge measurements when stage of the LAR at Morgan City was 3 ft above NAVD88. In the GIWW east of the HNC at Houma, average discharge was about 3,100 ft^3/s. In the GIWW east and west of Bayou Lafourche at Larose, the discharge was about 2,880 ft^3/s. Bayou Lafourche typically carries about 200 to 250 ft^3/s of water southward to the GIWW at Larose (Garrison and others, 1996). A small amount of water may leave the GIWW to the south through Bayou Lafourche.

Heavy precipitation during January 1998 reduced flow in the GIWW east of the HNC at Houma (pl. 1). This could be due to runoff causing increased stage in the Barataria Basin. Increased stage in the Barataria Basin would impede eastward flow in the GIWW and route more water southward through available outlets such as Bayou L'Eau Bleu and the HNC. This effect would be magnified by the extra water Bayou Lafourche would be carrying following heavy precipitation. Periods with little prior precipitation did not appear to affect the relation between discharge and stage of the LAR at Morgan City. During low river stage, eastward flow in the GIWW past the HNC varied from near zero to 2,000 ft^3/s. Flow occasionally was reversed (westward flow) in the GIWW east of the HNC at Houma, and west and east of Bayou Lafourche at Larose.

Between Lower Atchafalaya River and Wax Lake Outlet

Discharge in the GIWW at LAR south of Morgan City increased rapidly with increased stage in a linear manner, reaching a peak of about 35,000 ft^3/s when stage of the LAR at Morgan City was 7 ft above NAVD88 (pl. 1). At that stage, about 380,000 ft^3/s was flowing south in the LAR at Morgan City. At stages higher than 5 ft above NAVD88, discharge in the GIWW east of WLO at Calumet ranged from 5,000 to about 10,000 ft^3/s, but did not show a direct relation to stage. As the LAR at Morgan City increased from 5 to 7 ft above NAVD88, much of the additional water flowing into the GIWW south of Morgan City drained south through the connecting bayous, rather than continuing on to WLO. The heavy rains of January 1998 seemed to increase the amount of water flowing in this segment of the GIWW, but discharge was not clearly lower during periods of little prior precipitation. When the LAR at Morgan City was less than 3 ft above NAVD88, discharge in the GIWW east of WLO near Calumet and in the LAR south of Morgan City usually was similar in magnitude, but varied more or less independently of stage of the LAR at Morgan City.

West of the Wax Lake Outlet

Discharge in the GIWW west of WLO south of Calumet increased linearly with increases in stage of the LAR at Morgan City when stage was

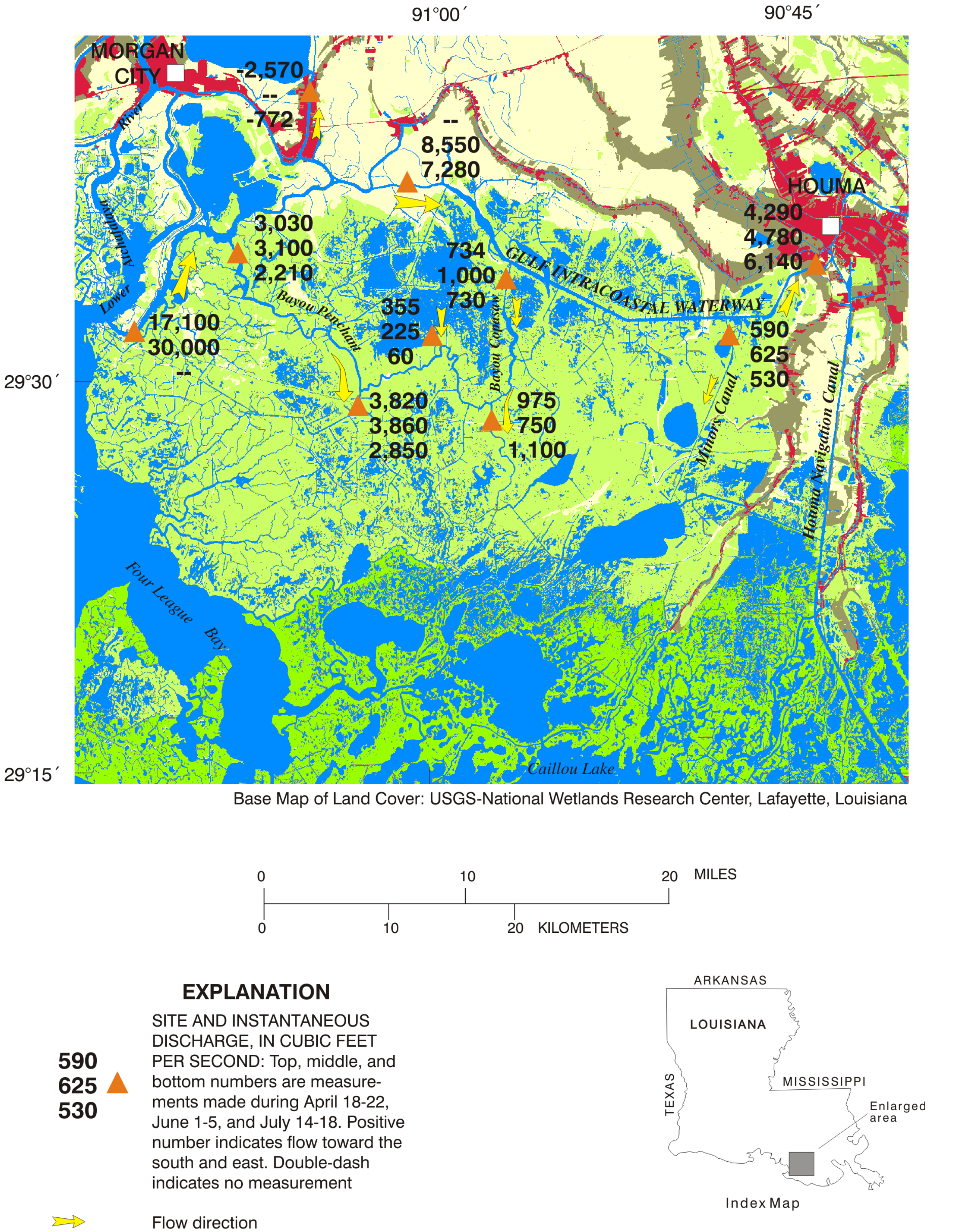


Figure 9. Instantaneous discharge at sites between the Lower Atchafalaya River and Houma Navigation Canal, Louisiana, April, June, and July 1999.

2.5 ft or more above NAVD88 (pl. 1). When LAR at Morgan City was 7 ft above NAVD88, about 20,000 ft^3/s flowed westward from the WLO into the GIWW. This was about 10 percent of the approximately 200,000 ft^3/s flowing south in WLO at Calumet. When the LAR at Morgan City reached 5 ft or more above NAVD88, discharge in GIWW east of Jaws Bay west of Franklin decreased relative to discharge west of WLO south of Calumet, indicating the intervening stretch of the GIWW accumulated some of the inflowing water. When the LAR at Morgan City was less than 2 ft above NAVD88, the opposite generally was true; discharge in the GIWW east of Jaws Bay west of Franklin was between 5,000 and 8,000 ft^3/s, but west of WLO south of Calumet was less than 5,000 ft^3/s. When the LAR at Morgan City was at low stage, the segment of the GIWW between west of WLO south of Calumet and east of Jaws Bay west of Franklin contributed water flowing toward Jaws Bay that did not originate from WLO. Flow at both sites was to the west.

Discharge in the GIWW east and west of Jaws Bay after heavy precipitation was higher than expected from relations between other discharge measurements and LAR stage (pl. 1). Heavy antecedent precipitation likely caused this anomaly. Flow did not appear depressed after periods of little prior precipitation. The Charenton Canal intersects the GIWW at the opening to Jaws Bay and could influence the amount of water entering the GIWW and West Côte Blanche Bay. The canal may play an important role in maintaining flow in the GIWW during periods of low stage of the LAR at Morgan City or in adding large amounts of runoff to the GIWW when there is heavy precipitation. The USGS began monitoring discharge in this canal with a continuous velocity and stage gage in the summer of 1999; however, results were not included in this study.

Discharge in the GIWW was substantially less on the west side of Jaws Bay compared with discharge measured to the east of Jaws Bay (table 2). Discharge measured west of Jaws Bay near Cypremort was about 3,000 to 5,000 ft^3/s whenever stage of the LAR at Morgan City increased to 5 ft or more above NAVD88. Discharge here and 15 mi farther west in the GIWW at Cypremort usually was similar in magnitude and flow was always to the west, except during periods when the LAR at Morgan City was less than 2.5 ft above NAVD88. At such times, flow reversals at the latter site were frequent. The computed hourly discharge at the continuously recording gage in the GIWW at Cypremort was averaged by month and compared to total monthly precipitation at Morgan City, stage of the LAR at Morgan City, and stage in GIWW at Cypremort. Monthly-average discharge in the GIWW at Cypremort correlated positively with stage of the LAR at Morgan City. Lower discharge occurred in the fall; higher discharge occurred during the spring flood (fig. 10). Neither little nor heavy prior precipitation affected discharge during high LAR stage, remaining steady at about 2,000 ft^3/s for much of the peak discharge. High Gulf of Mexico levels affected flow along this stretch of the GIWW. For example, in September 1998, the average monthly discharge was toward the east. Gulf of Mexico level was unusually high during this month because of the tropical storms (fig. 4), and appeared to disrupt the westerly flow in the GIWW between Jaws Bay and Cypremort.

Discharge along the GIWW was highest where it crossed the LAR and WLO. Water flowed east and west in the GIWW, in decreasing volumes with increasing distance from the source. Discharge tended to increase as same-day average stage of the LAR at Morgan City increased beyond 3 ft above NAVD88 at most of the sites between HNC and Jaws Bay. When the LAR at Morgan City reached 3 to 4 ft above NAVD88, discharge in the GIWW became more predictable. The flow of freshwater along most of the GIWW studied was enhanced not so much by absolute high stage of the LAR at Morgan City as by the total time the LAR at Morgan City was 3 ft or more above NAVD88. The LAR at Morgan City is 3 ft or more above NAVD88 for about 7 months in an average year.

Discharge in the Gulf Intracoastal Waterway from 1997-99

To the east of the LAR, monthly-average discharge from the Verret Subbasin through Bayou Boeuf at railroad bridge at Amelia varied from month to month and year to year, independently from stage of the LAR at Morgan City (table 4). For example, from April through June 1999, the volume of water flowing south through Bayou Boeuf and into the GIWW was about a third as

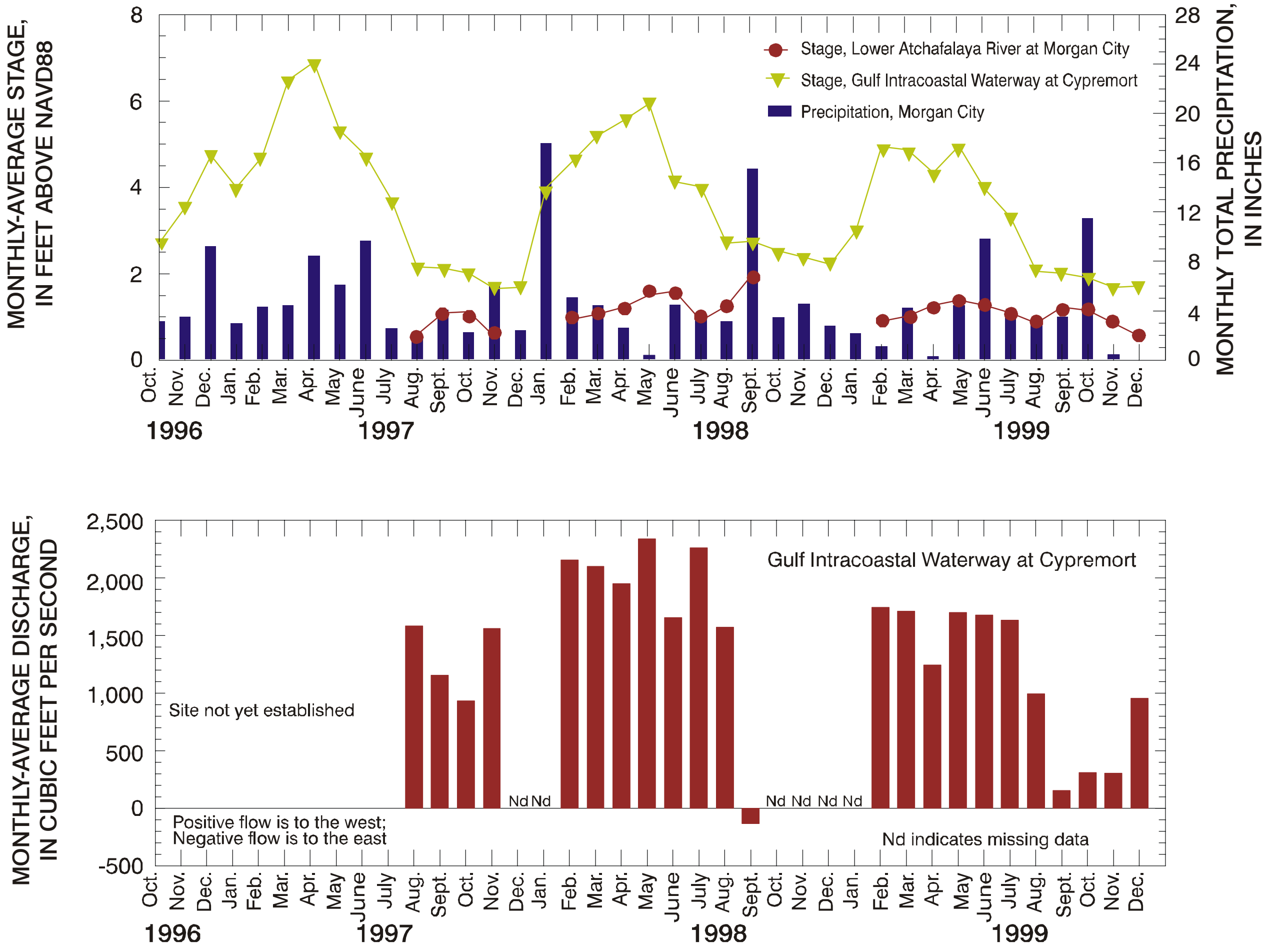


Figure 10. Monthly-average stage of the Lower Atchafalaya River at Morgan City and the Gulf Intracoastal Waterway at Cypremort, monthly total precipitation at Morgan City, and monthly-average discharge in the Gulf Intracoastal Waterway at Cypremort, Louisiana, October 1996 to December 1999.

much as in 1997 during the same months. The volume of eastward flow in the GIWW near Bay Wallace east of Morgan City did not decrease during these months between 1997 and 1999 by the same amount as in Bayou Boeuf. To compensate for the loss of inflowing water from Bayou Boeuf, proportionately more LAR water presumably was flowing into the GIWW through the Avoca Island Cutoff Channel in 1999 than in 1997, even though the spring flood of the LAR was greater in 1997. In 1997, relatively more water from the LAR was routed southeasterly through Bayou Penchant south of Morgan City rather than flowing north and east toward Bay Wallace. The water flowing eastward in the GIWW past Bay Wallace at times consisted primarily of the Bayou Boeuf flow, and at other times substantially less.

Discharge past Houma, across Bayou Lafourche, and into Barataria Basin did not increase predictably with increasing stage of the LAR at Morgan City. Flow was always eastward whenever stage of the LAR at Morgan City was 3 ft or more above NAVD88 (pl. 1). When stage of the LAR at Morgan City was 3 ft above NAVD88, average discharge in the GIWW east of the HNC at Houma was about 3,100 ft^3/s, and in the GIWW east and west of Bayou Lafourche at Larose, the discharge was about 2,880 ft^3/s. As little as 30 percent to more than 50 percent of the water reaching the HNC continued flowing east in the GIWW rather than flowing south in the HNC. As flow reaching the HNC increased, proportionately more water flowed south in the HNC rather than continued east in the GIWW.

Table 4. Monthly-average discharge calculated from regression equations and from stage-discharge relations for sites along or near the Gulf Intracoastal Waterway (GIWW) east of the Lower Atchafalaya River, 1997-99

[Stage is in feet above North American Vertical Datum of 1988. Discharge is in cubic feet per second. nd, missing data; --, not applicable]

Month	1997					1998					1999				
	Stage, Lower Atchafalaya River at Morgan City	Discharge				Stage, Lower Atchafalaya River at Morgan City	Discharge				Stage, Lower Atchafalaya River at Morgan City	Discharge			
		Bayou Penchant south of Morgan City[1]	Bayou Boeuf at railroad bridge at Amelia[1]	GIWW near Bay Wallace east of Morgan City[2]	GIWW west of the Houma Navigation Canal at Houma[2]		Bayou Penchant south of Morgan City[1]	Bayou Boeuf at railroad bridge at Amelia[1]	GIWW near Bay Wallace east of Morgan City[2]	GIWW west of the Houma Navigation Canal at Houma[2]		Bayou Penchant south of Morgan City[1]	Bayou Boeuf at railroad bridge at Amelia[1]	GIWW near Bay Wallace east of Morgan City[2]	GIWW west of the Houma Navigation Canal at Houma[2]
Jan.	3.99	nd	nd	8,060	6,990	4.00	nd	8,560	8,080	7,000	2.99	1,590	3,260	6,290	5,420
Feb.	4.71	nd	nd	9,080	8,120	4.59	nd	9,890	8,920	7,930	4.94	3,080	60	9,370	8,480
Mar.	6.49	nd	nd	11,000	10,900	5.20	nd	6,780	9,680	8,890	4.87	3,650	4,240	9,280	8,370
Apr.	6.90	nd	8,640	11,400	11,600	5.54	nd	2,720	10,100	9,430	4.33	6,120	2,730	8,560	7,530
May	5.32	nd	9,680	9,820	9,080	5.93	nd	1,630	10,500	10,000	4.96	6,490	1,080	9,390	8,520
June	4.74	nd	8,030	9,110	8,170	4.13	nd	3,260	8,270	7,210	3.97	4,740	3,190	8,030	6,960
July	3.71	nd	7,240	7,620	6,550	4.02	nd	nd	8,100	7,040	3.31	4,050	3,850	6,920	5,930
Aug.	2.16	nd	2,660	--	--	2.71	nd	2,060	--	--	2.06	1,640	2,360	--	--
Sept.	2.13	nd	1,950	--	--	2.75	nd	6,040	--	--	2.01	1,000	2,940	--	--
Oct.	2.01	nd	2,180	--	--	2.53	3,049	250	--	--	1.91	1,070	3,910	--	--
Nov.	1.66	nd	3,090	--	--	2.93	1,576	3,480	--	--	1.68	500	3,380	--	--
Dec.	1.68	nd	4,030	--	--	2.22	1,171	3,210	--	--	1.71	940	3,730	--	--
Average (Jan.-July)		nd	nd	9,440	8,770		nd	nd	9,090	8,220		4,240	2,630	8,260	7,320
Average (Aug.-Dec.)		nd	2,780	--	--		nd	3,000	--	--		1,030	3,260	--	--

[1]From stage-discharge relations.

[2]From regression equation (see appendix, fig. A1).

Table 5. Monthly-average discharge calculated from regression equations and from stage-discharge relations for sites along the Gulf Intracoastal Waterway (GIWW) west of the Lower Atchafalaya River, 1997-99

[Stage is in feet above the North American Vertical Datum of 1988. Discharge is in cubic feet per second. Positive discharge indicates flow to west. Negative discharge indicates flow to east. nd, missing data; --, not applicable]

Month	1997					1998					1999				
	Stage, Lower Atchafalaya River at Morgan City	Discharge				Stage, Lower Atchafalaya River at Morgan City	Discharge				Stage, Lower Atchafalaya River at Morgan City	Discharge			
		GIWW west of Wax Lake Outlet south of Calumet[1]	GIWW east of Jaws Bay west of Franklin[1]	Across Jaws Bay[1]	GIWW at Cypremort[2]		GIWW west of Wax Lake Outlet south of Calumet[1]	GIWW east of Jaws Bay west of Franklin[1]	Across Jaws Bay[1]	GIWW at Cypremort[2]		GIWW west of Wax Lake Outlet south of Calumet[1]	GIWW east of Jaws Bay west of Franklin[1]	Across Jaws Bay[1]	GIWW at Cypremort[2]
Jan.	3.99	10,700	9,630	6,570	nd	4.00	10,700	9,660	6,590	nd	2.99	7,140	7,080	4,690	nd
Feb.	4.71	13,200	11,100	7,650	nd	4.59	12,800	10,900	7,480	2,160	4.94	14,000	11,500	7,960	1,740
Mar.	6.49	19,500	13,900	9,740	nd	5.20	15,000	12,000	8,300	2,100	4.87	13,800	11,400	7,870	1,720
Apr.	6.90	21,000	14,500	10,100	nd	5.54	16,200	12,500	8,710	1,950	4.33	11,900	10,400	7,100	1,250
May	5.32	15,400	12,200	8,450	nd	5.93	17,500	13,100	9,150	2,340	4.96	14,100	11,600	7,990	1,700
June	4.74	13,300	11,200	7,700	nd	4.13	11,200	9,940	6,800	1,650	3.97	10,600	9,600	6,500	1,680
July	3.71	9,700	8,990	6,100	nd	4.02	10,800	9,700	6,620	2,260	3.31	8,300	7,970	5,350	1,630
Aug.	2.16	--	--	--	1,580	2.71	--	--	--	1,570	2.06	--	--	--	1,000
Sept.	2.13	--	--	--	1,150	2.75	--	--	--	-130	2.01	--	--	--	160
Oct.	2.01	--	--	--	930	2.53	--	--	--	nd	1.91	--	--	--	310
Nov.	1.66	--	--	--	1,560	2.93	--	--	--	nd	1.68	--	--	--	310
Dec.	1.68	--	--	--	nd	2.22	--	--	--	nd	1.71	--	--	--	950
Average (Jan.-July)		14,700	11,600	8,040	nd		13,500	11,100	7,660	nd		11,400	9,930	6,780	nd
Average (Aug.-Dec.)		--	--	--	nd		--	--	--	nd		--	--	--	540

[1]From regression equation (see appendix, fig. A2).

[2]From stage-discharge relations.

Monthly-average discharge decreased westward from Morgan City, with a sharp decrease across Jaws Bay at the opening to West Côte Blanche Bay (table 5). From January to August, about 60 percent of the volume of water entering the GIWW west of WLO near Calumet left the GIWW at Jaws Bay. More than 10 percent of the original volume reached the GIWW at Cypremort, but the source of the westward flowing water was not necessarily all derived from WLO.

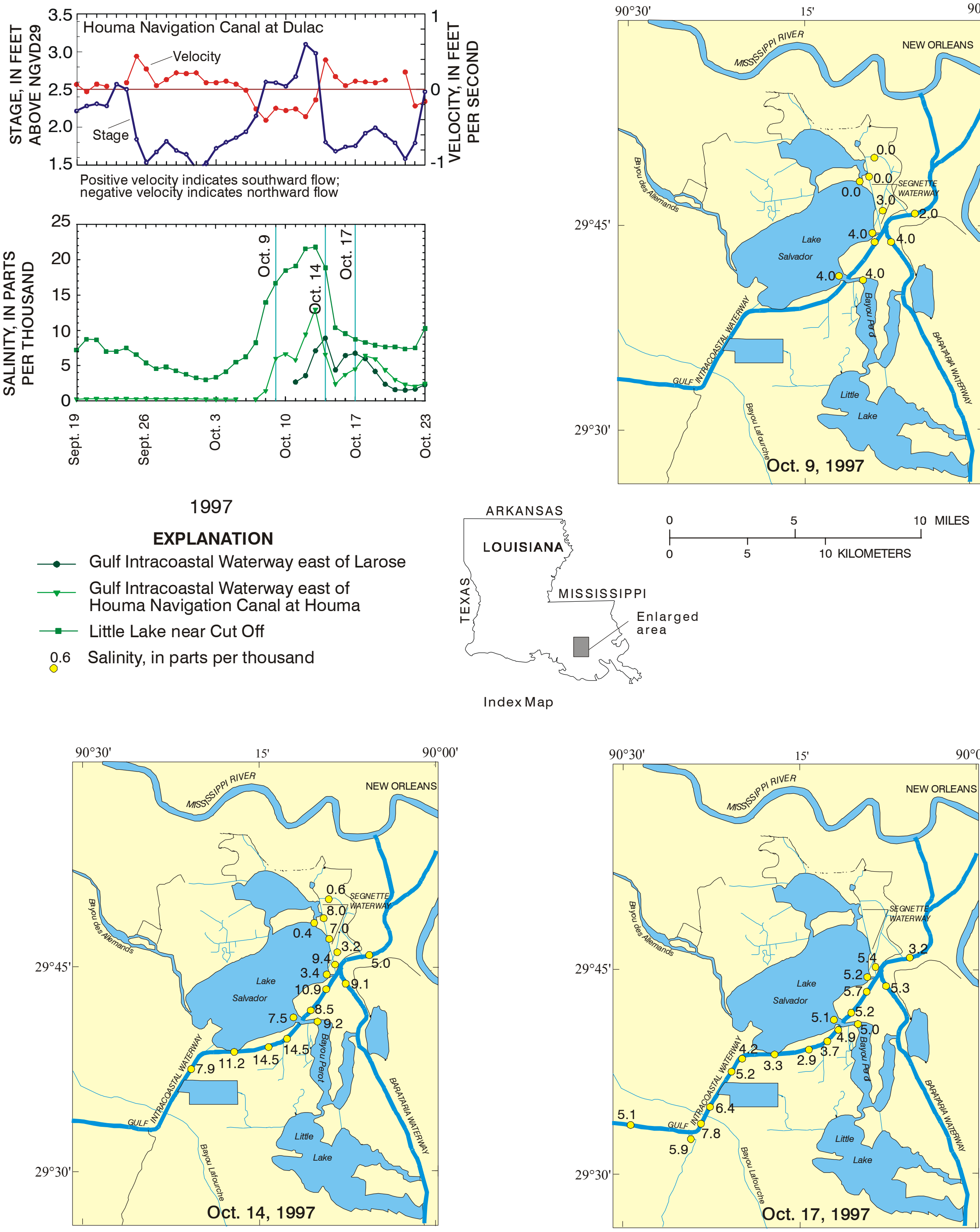
Measuring discharge directly with a gage continuously recording velocity and stage is preferable to using estimates derived from regression equations. Indirect estimates using the stage of the LAR at Morgan City and instantaneous discharge measurements are subject to increased error. The regression equations used to indirectly estimate discharge have a relatively high correlation coefficient and meet the needs of this study. There is value to the numbers generated by the regressions to evaluate in general terms what contributes to the flow of a particular segment in the GIWW. When the LAR at Morgan City is 3 ft or more above NAVD88, the GIWW effectively distributes freshwater and sediments from the LAR and WLO to points in coastal Louisiana 30 to 50 mi east and west of Morgan City.

Flow Reversals

Events that push Gulf of Mexico water in an inland direction can result in short periods of flow reversal in the GIWW and periods when the GIWW can move saltwater laterally. These can be driven by elevated stage associated with tropical storms and/or winds. Under these conditions, the north-south trending HNC and Bayou Perot can convey saltwater in an inland direction into the GIWW. From there, the water can then move laterally in the GIWW following the normal gradients.

Elevated stage in the Gulf of Mexico can cause flow reversals in the GIWW, canals, and bayous, and push salinity in an inland direction. For example, in the last week of September and for the first 2 weeks of October 1997, strong offshore winds pushed more saline water toward the fresher parts of coastal Louisiana (fig. 5). At the HNC at Dulac, daily average discharge was in an inland direction from October 7-13. Salinity at Little Lake near Cut Off increased markedly during the same time, indicating northward flow of more saline waters from the Gulf of Mexico (fig. 11). Three synoptic surveys of surface-water salinity in the GIWW between Larose and Lafitte, La., were done during this time (fig. 11). Data collected during the surveys indicate that some of the saltier water moving north flowed east and west into the GIWW where it crossed Bayou Perot. Salinities greater than 14 ppt were measured in the GIWW west of Bayou Perot just after passage of a weather front from October 13-14. Salinity reached 8 ppt in Segnette Waterway. The water intruded through the canal, and not through Lake Salvador. Under these conditions of rapidly inflowing water from the south, flow was temporarily westward in the GIWW from Bayou Perot toward Bayou

Aerial view looking south beyond the intersection of the Gulf Intracoastal Waterway and Bayou Perot toward Little Lake, Louisiana.



Louisiana Oil Spill Coordinator, Office of the Governor, Louisiana GIS CD: A Digital Map of the State, Version 2.0

Figure 11. Daily-average salinity in the Gulf Intracoastal Waterway east of Houma Navigation Canal at Houma, east of Larose, and in Little Lake near Cut Off, and daily-average velocity and stage of the Houma Navigation Canal at Dulac in September and October 1997; synoptic surveys of salinity in the Gulf Intracoastal Waterway and associated surface waters in Louisiana, October 9, 14, and 17, 1997.

Lafourche, and flow was eastward in the GIWW from the HNC toward Bayou Lafourche. After passage of the weather front, eastward flow along the entire stretch of the GIWW between the HNC and Bayou Perot resumed.

Net Gain or Loss of Water Along Major Segments

To better understand the surface-water hydrology of the GIWW and its implications for regional freshwater availability, it is helpful to consider (1) whether individual segments of the GIWW contribute water to the surrounding wetlands or drain water from them, and (2) whether this characteristic changes depending on inflowing river water or antecedent precipitation. Three segments of the GIWW east of Morgan City between Bay Wallace and Bayou Lafourche and three segments of the GIWW west of Morgan City between the WLO and Cypremort were characterized. Net inflow or outflow can occur in any of these segments. Net inflow occurs when more water enters than leaves from one or both ends of a segment and flows into the surrounding wetlands. In this instance, the GIWW functions as a freshwater diversion, contributing to the water budget of the wetlands. Net outflow occurs when more water leaves than enters a segment through one or both ends. In this case, the GIWW drains some water from the wetlands. Water from the surrounding wetlands contributes flow to the GIWW.

For the three segments east of Morgan City (segments A, B, C; fig. 12), the difference in instantaneous discharge between segment start and segment end was plotted with the instantaneous discharge at GIWW near Bay Wallace east of Morgan City. The complex interactions of flow from Bayou Boeuf, Bayou Chene, and the Avoca Island Cutoff Channel were the reason the analysis started at GIWW near Bay Wallace east of Morgan City and not closer to the LAR. For the three segments west of Morgan City (segments D, E, F; fig. 13), the difference in instantaneous discharge at the start and end of each segment was plotted with instantaneous discharge in the GIWW west of WLO near Calumet. For all six segments the difference in instantaneous discharge at the start and end of each segment also was plotted with the 21-day average discharge at Bayou Boeuf at railroad bridge at Amelia preceding each set of measurements. The 21-day average discharge at Bayou Boeuf at railroad bridge at Amelia was assumed to indicate influence of local runoff on flow in the GIWW.

During slightly more than half the synoptic trips, instantaneous discharge was greater in the GIWW west of the HNC at Houma than near Bay Wallace (segment A, fig. 12). Adjacent wetlands contributed water to the GIWW along this segment during high and low stage of the LAR at Morgan City. On two occasions, water flowed both west toward Morgan City and east toward the HNC. When the 21-day average discharge was less than 4,500 ft^3/s at Bayou Boeuf at railroad bridge at Amelia, this segment acted both as a source and sink of water (fig. 12). The segment tended to store inflowing water when the LAR at Morgan City was 3 ft or more above NAVD88. When the LAR at Morgan City was less than 3 ft above NAVD88, more water tended to flow out of this segment than entered. When the 21-day average discharge of water from Bayou Boeuf was greater than 6,000 ft^3/s, there was a net outflow of water to adjacent wetlands from the segment of the GIWW between Bay Wallace and west of the HNC.

The GIWW was a source of water to the HNC in segment B (fig. 12) during almost all the synoptic trips. The volume of water entering the HNC generally increased as eastward flow in the GIWW near Bay Wallace east of Morgan City increased, but the relation between LAR stage and discharge from the GIWW to the HNC was variable. For example, when the LAR at Morgan City was 4 ft or more above NAVD88, discharge from the GIWW to the HNC ranged from near zero to greater than 8,000 ft^3/s. The relation between local runoff and the amount of water that left the GIWW at the HNC was more direct. As the 21-day average discharge at Bayou Boeuf at railroad bridge at Amelia increased, the amount of water leaving the GIWW through the HNC increased steadily, regardless of whether stage of the LAR at Morgan City was high or low. Local runoff appears to contribute to the flow of water in the GIWW near the HNC.

The wetlands adjacent to the GIWW between the HNC and Bayou Lafourche stored and

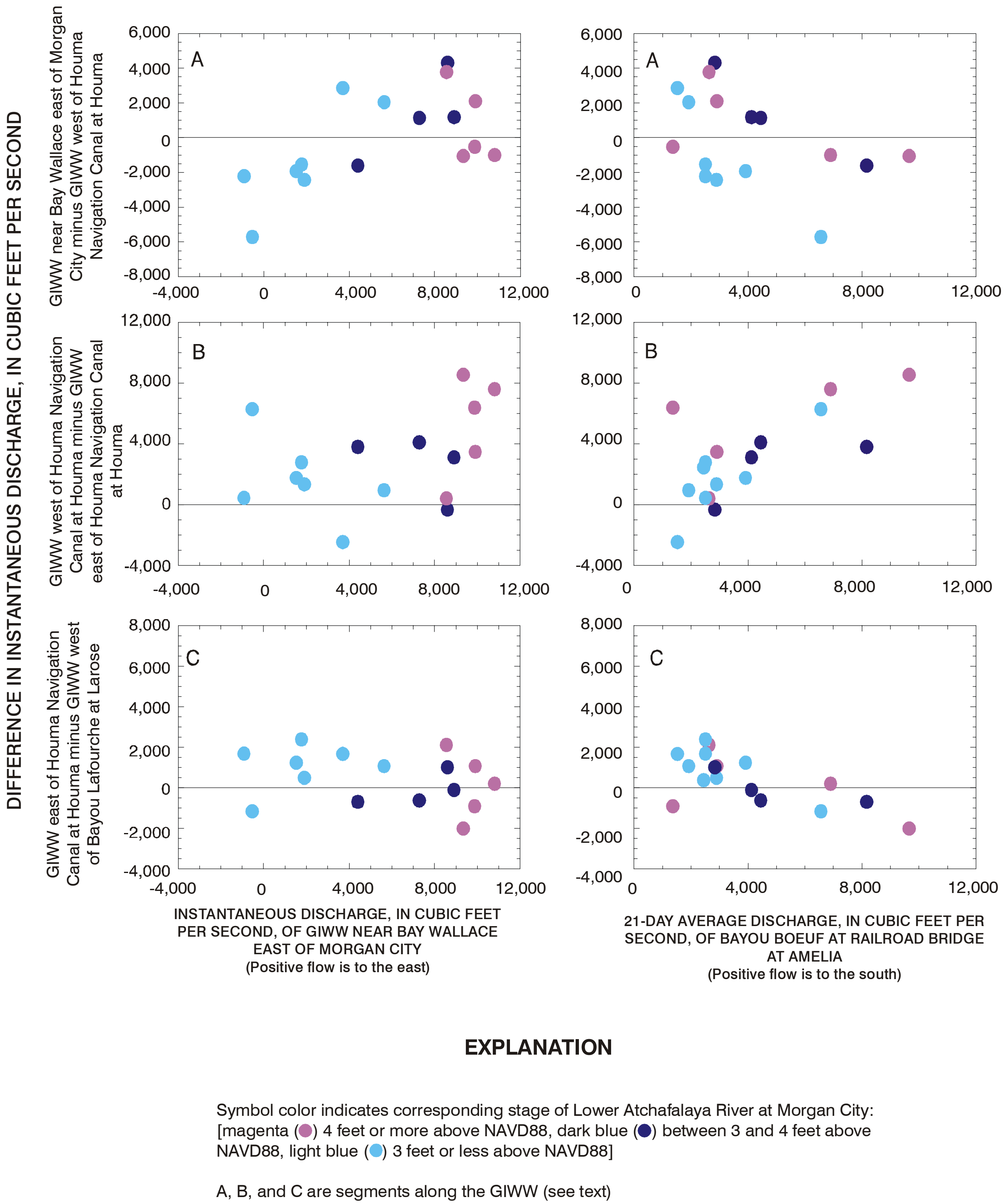
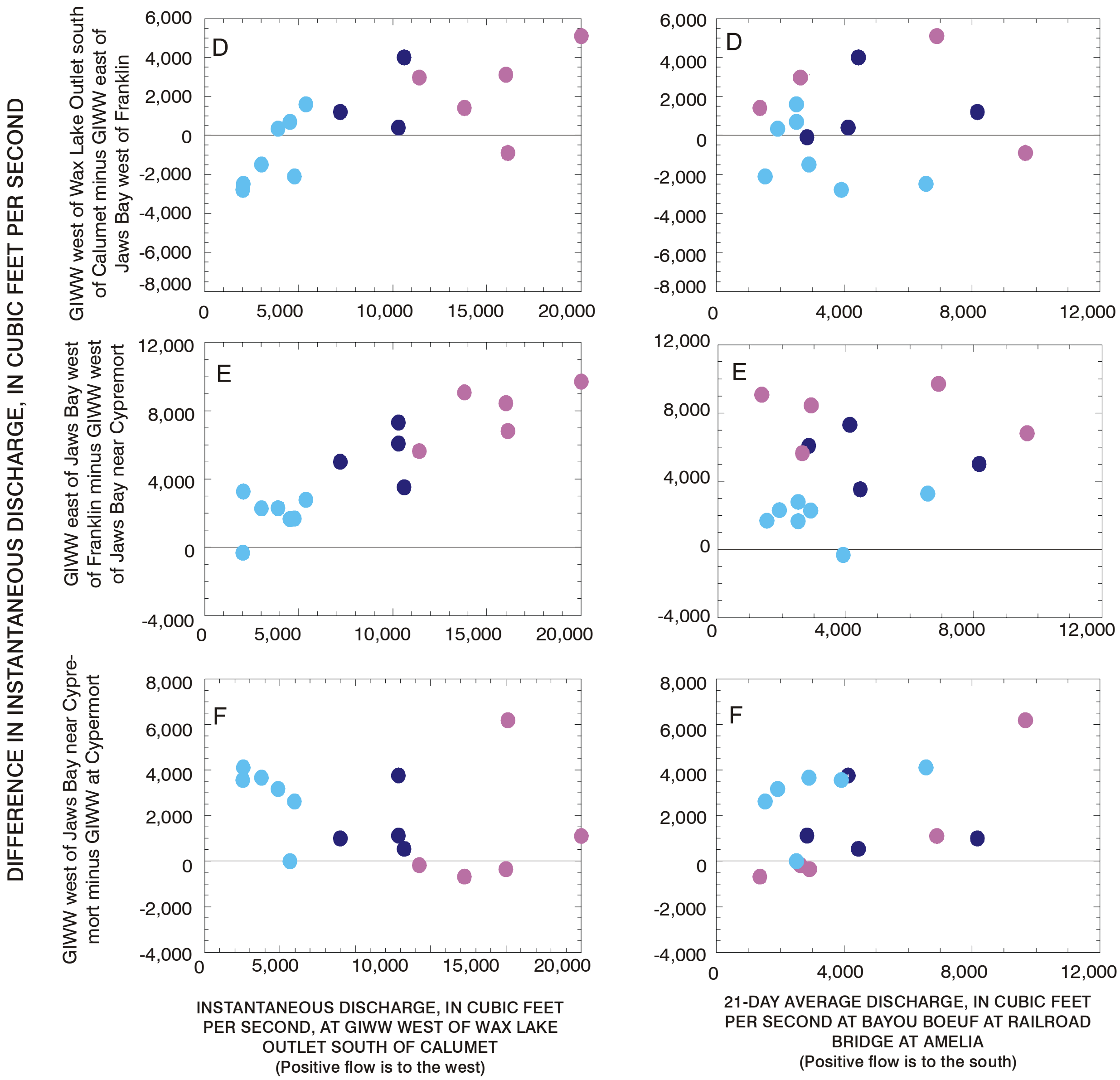


Figure 12. Relation between net inflow (positive) or outflow (negative) of water in three segments of the Gulf Intracoastal Waterway (GIWW) east of Morgan City and instantaneous discharge in the GIWW near Bay Wallace east of Morgan City and the 21-day average discharge at Bayou Boeuf at railroad bridge at Amelia, Louisiana, 1997-99.



EXPLANATION

Symbol color indicates corresponding stage of Lower Atchafalaya River at Morgan City: [magenta (●) 4 feet or more above NAVD88, dark blue (●) between 3 and 4 feet above NAVD88, light blue (●) 3 feet or less above NAVD88]

D, E, and F are segments along the GIWW (see text)

Figure 13. Relation between net inflow (positive) or outflow (negative) of water in three segments of the Gulf Intracoastal Waterway (GIWW) west of the Wax Lake Outlet and instantaneous discharge in the GIWW west of Wax Lake Outlet south of Calumet and the 21-day average discharge at Bayou Boeuf at railroad bridge at Amelia, Louisiana, 1997-99.

drained water (segment C, fig. 12). Typically, when the LAR at Morgan City was less than 3 ft above NAVD88, water was stored in this segment. The volume stored did not increase or decrease depending on the initial amount of water flowing eastward at GIWW near Bay Wallace east of Morgan City. Less frequently, this segment of the GIWW released water to the adjacent parts of the GIWW. When local runoff was low as indicated by the 21-day average discharge in Bayou Boeuf at railroad bridge at Amelia, the GIWW between the HNC and Bayou Lafourche and adjacent wetlands appeared to store the inflowing water. As local runoff increased, more water appeared to leave this segment by flowing eastward. The data suggest that as local runoff increases, this segment is a source of water to adjacent parts of the GIWW. The relation is reasonably direct for the available data.

The GIWW between WLO and Jaws Bay shifted from draining water to Jaws Bay to storing water as instantaneous discharge in the GIWW west of WLO south of Calumet increased in segment D (fig. 13). During low discharge, more water left the GIWW at Jaws Bay than entered the GIWW from the WLO. Water from the Charenton Drainage Canal and adjacent wetlands contributed to flow in the GIWW. Local runoff did not appear to influence whether more or less water was stored along this segment (fig. 13).

With one exception, water flowed from the GIWW to Jaws Bay in segment E during all synoptic trips (fig. 13). About 2,000 to 3,000 ft^3/s or more water was leaving the GIWW east of Jaws Bay west of Franklin than was entering west of WLO south of Calumet when the LAR at Morgan City was 3 ft or less above NAVD88. The volume of water leaving increased steadily as flow entering the GIWW west of WLO south of Calumet increased. When the LAR at Morgan City was 4 ft or less above NAVD88, the volume of water leaving the GIWW at Jaws Bay appeared to increase as local runoff increased. When the LAR at Morgan City was 4 ft or more above NAVD88, a relation between local inflow and instantaneous discharge across Jaws Bay was not evident.

Water entered from the west and was stored in segment F between Jaws Bay and Cypremort, when the LAR at Morgan City was 3 ft or less above NAVD88, but the volume progressively decreased as flow into the GIWW from WLO increased (fig. 13). When the LAR at Morgan City was 4 ft or more above NAVD88, the volume of water entering this segment at Jaws Bay generally was similar to the volume leaving at Cypremort indicating throughflow conditions. The exception occurred during the high precipitation in January 1998, when almost 6,000 ft^3/s of water was stored along the segment of the GIWW between Jaws Bay and Cypremort. As the 21-day average discharge at Bayou Boeuf at railroad bridge at Amelia increased from 2,000 ft^3/s to more than 8,000 ft^3/s, the rate at which water was stored in the GIWW between the Jaws and Cypremort increased by about 1,000 to 2,000 ft^3/s. Two linear curves with the same slope show this trend. The data indicate that local runoff also accumulates in and contributes to flow along this segment of the GIWW.

The segments of the GIWW east of Morgan City and west of WLO differ hydrologically in whether they contribute water to, or drain water from adjacent wetlands. In the segments closest to the source (segments A and D), water entering the GIWW west of WLO south of Calumet was stored in increasing volumes in the area between WLO and Jaws Bay as inflow increased. To the east of Morgan City in segment A, the wetlands between the GIWW near Bay Wallace east of Morgan City and west of the HNC at Houma more frequently contributed water to the GIWW than stored water from the GIWW. Water left the GIWW both at Jaws Bay and at the HNC. The volume of water leaving the GIWW at Jaws Bay in segment E increased as the volume of river water entering the GIWW west of WLO south of Calumet increased. The volume of water leaving the GIWW through the HNC in segment B increased as discharge at Bayou Boeuf at railroad bridge at Amelia increased. The increase in flow into the HNC was influenced less by the volume of water entering the GIWW near Bay Wallace east of Morgan City (fig. 12). The GIWW between Jaws Bay and Cypremort (segment F) rapidly changed from contributing water to the wetlands to mainly net throughflow as the inflow into the GIWW west of WLO near Calumet increased from low to high. At low inflow, water entering this segment was from west of Cypremort and west of Jaws Bay. East of Morgan City, the volume of water flowing eastward near Bay Wallace east of Morgan City did not influence storage or release of water in the GIWW in segment C between the HNC and Bayou Lafourche. Local runoff appeared to change storage characteristics of the two segments farthest from WLO and the LAR but in opposite ways. West of WLO, the volume of water stored in segment F increased as runoff increased. Increasing local runoff appeared to increase the net volume of water leaving segment C of the GIWW between Houma and Larose.

Magnitude, Duration, and Timing of Flow

The difference in elevation between the stage of the LAR or WLO and surrounding waters controls the magnitude, duration, and timing of the flow in the GIWW east and west of Morgan City. In an earlier section of the report, it was demonstrated that discharge in the GIWW becomes more predictable whenever the stage of the LAR at Morgan City is 3 to 4 ft or more above NAVD88. The period when this condition is met varies considerably from year to year. An examination of the stage record of the LAR allows inferences to be drawn on flow characteristics of the GIWW. Figure 14 shows stages of the LAR at Morgan City averaged from 1989-99, for years when the spring flood of the Atchafalaya River was exceptionally high or low, and for a period of sustained moderate flow.

Under average conditions, stage of the LAR at Morgan City remains 3 ft or more above NAVD88 from about January to mid-July, and 4 ft or more above NAVD88 for about 6 weeks less. In 2000, annual discharges of the Mississippi River and Atchafalaya River were among the 10 lowest on record. Stage of the LAR at Morgan City exceeded 4 ft or more above NAVD88 only briefly and was 3 ft or more above NAVD88 from April to mid-May and for about 2 weeks in July. During 1997, which was a record flood year, stage of the LAR at Morgan City reached 8 ft above NAVD88. For a brief period flow along the GIWW would have been exceptionally high, but because LAR stage was below the long-term average from July through December 1997, the total volume of river water moving laterally in the GIWW was not much different from an average year. To sustain flow and maximize the volume of freshwater delivered to coastal Louisiana marshes, stage of the LAR at Morgan City should remain 3 ft or more above NAVD88 for prolonged periods. This occurred in

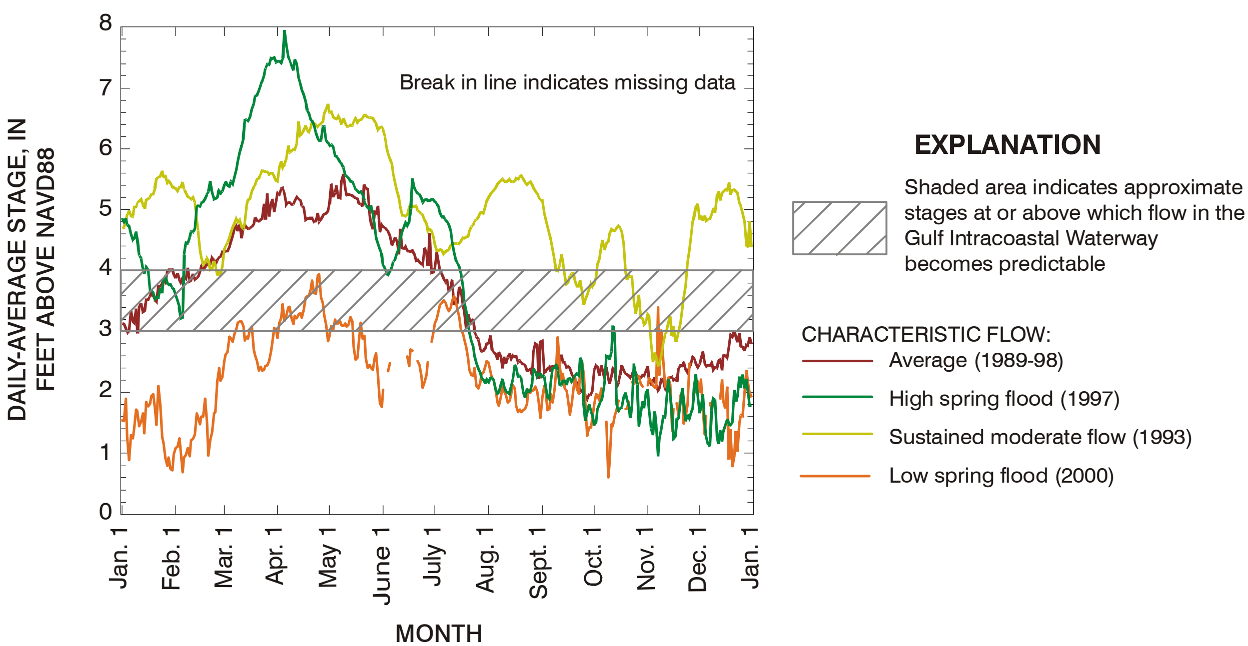


Figure 14. Daily-average stage of the Lower Atchafalaya River at Morgan City, Louisiana, for characteristic flows of the Lower Atchafalaya River.

1993, when the LAR at Morgan City was 4 ft or more above NAVD88 for almost 11 months in 1993 and was below 3 ft above NAVD88 for less than 2 weeks.

The percent of time in a year that stage of the LAR at Morgan City was between 3 ft above NAVD88 and the maximum elevation for that time period was tabulated in ½-ft increments for the four characteristic flows described above (fig. 15). The regression equations relating discharge at selected sites along the GIWW with stage of the LAR at Morgan City (see appendix) were then applied to estimate the discharge at selected sites along the GIWW. The percent of time in the year a discharge equaled or exceeded indicated levels in the GIWW near Bay Wallace east of Morgan City, west of HNC at Houma, east of Jaws Bay west of Franklin, and across Jaws Bay was calculated for characteristic flows in the LAR when stage in the LAR was 3 ft or more above NAVD88. The relations in figure 15 suggest the time during a year at characteristic flows indicated discharge is expected to occur at the selected sites. The amount of freshwater flowing in the GIWW influences sediment transport and salinity in coastal Louisiana (discussed in later sections of this report) and has implications for wetland restoration.

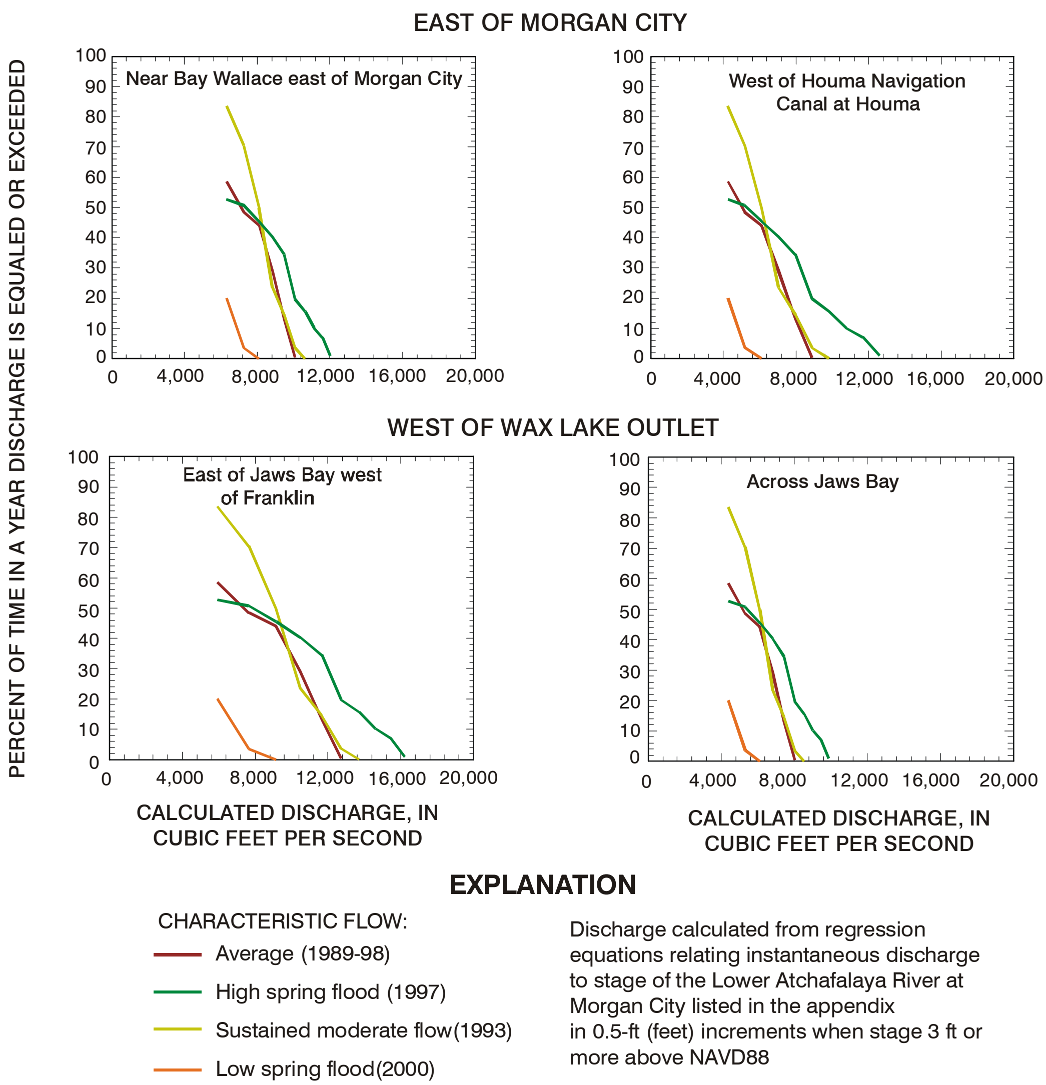


Figure 15. Percent of time in a year discharge at selected sites is equaled or exceeded for characteristic flows of the Lower Atchafalaya River, Louisiana.

In 2000, stage of the LAR was 3 ft or less above NAVD88 about 80 percent of the time; discharge was predictable for less than 20 percent of the time. Peak discharge was 25 to 60 percent lower than in the other three time periods. For the time periods 1989-98 and 1997, discharge was predictable 55 to 60 percent of the time. In 1997, when the Atchafalaya River experienced a large spring flood, calculated discharge was greater than for the three other time periods about 45 percent of the time. In 1993, discharge was predictable for more than 80 percent of the time. For average conditions (1989-98) and in 1993, discharge in the GIWW near Bay Wallace east of Morgan City was between 9,000 and 11,000 ft^3/s for at least 40 percent of the time; peak discharge for the two time periods was about 70 percent of that reached in 1997. For average conditions and in 1993, about 6,000 to 8,000 ft^3/s of water discharged across the Jaws Bay opening at least 40 percent of the time (fig. 15). In 1997, between 12,000 and 16,000 ft^3/s of water flowed across the Jaws Bay opening at least 40 percent of the time. In 2000, at most 4,000 to 6,000 ft^3/s of water flowed across Jaws Bay, and this maximum flow occurred less than 20 percent of the time.

Stage in the LAR has increased steadily since the 1950's and in 1999 was about 2 to 2.5 ft higher (Harley Winer, USACE, oral commun., 1999). The downstream emergence of the Atchafalaya Delta in the late 1970's and the aggradation of the river bed are the principal reasons for this increase. As the time when the stage of the LAR is 3 to 4 ft or more above NAVD88 increases, and the duration of stage differences between the LAR and canals and bayous in adjacent waterbodies increases, the volume of water moving laterally in the GIWW also will increase. The percent of time when the stage of the LAR is greater than 3 ft above NAVD88 could increase in the future with further aggradation of the river bed.

Discharge in the GIWW at Bay Wallace measured during 1997-99 is higher relative to a given stage of the LAR at Morgan City than in a series of measurements made in 1983 and 1984 by the USACE (Donnel and Lederer, 1992) (fig. 16). The increase is substantial. Some of the increase may be attributed to widening and deepening of the Avoca Island Cutoff Channel in the early 1980's (N.J. Powell, USACE, oral commun., 1999).

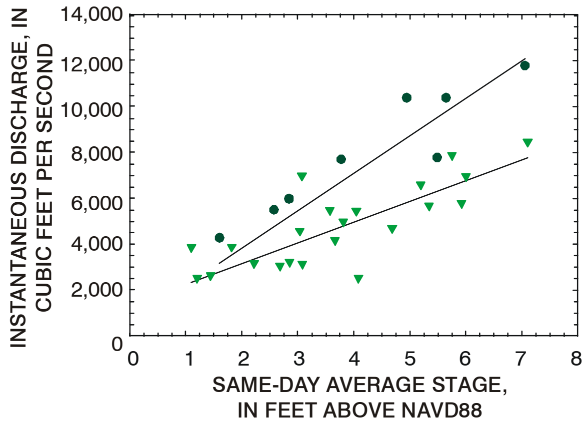


Figure 16. Relation between instantaneous discharge in the Gulf Intracoastal Waterway west of Houma Navigation Canal at Houma and same-day average stage of the Lower Atchafalaya River at Morgan City, Louisiana, 1983-84 and 1997-98.

The distance from the GIWW that coastal wetlands have been affected by freshwater entering from the GIWW has increased since the 1970's. Vegetation surveys of coastal Louisiana marshes made at regular intervals indicate less salt-tolerant species have expanded in a southeasterly direction in western Terrebonne Basin wetlands (Visser and others, 1999). Average monthly salinity measured during 6 consecutive years in the 1970's, and again from 1995-99, at Caillou Lake (Sister Lake) southwest of Dulac, shows a freshening in the spring months for the more recent time period (fig. 17).

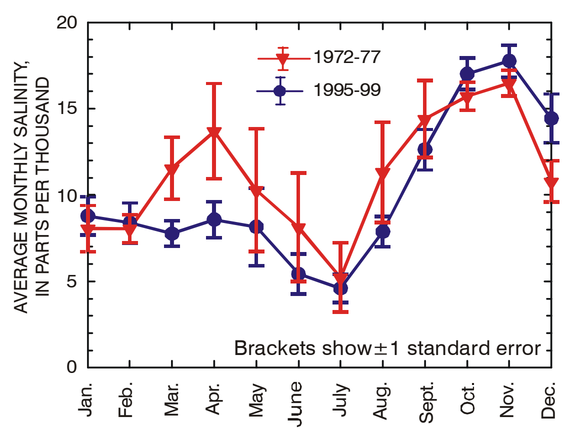


Figure 17. Average monthly salinity at Caillou Lake (Sister Lake) southwest of Dulac, Louisiana, from 1972-77 and from 1995-99.

In the GIWW at the intersection with the HNC and in Larose, salinity in the spring averaged about 0.2 ppt from 1957-60, prior to the construction of the HNC, and again more recently, from 1983-88 (fig. 18). From 1972-77, salinity was higher in the spring, almost reaching 1 ppt. The flow of freshwater in the GIWW presumably lowered the salinity in the spring months during 1983-88. In the fall, this freshwater flow was not available, and average monthly salinity was greater than 1 ppt.

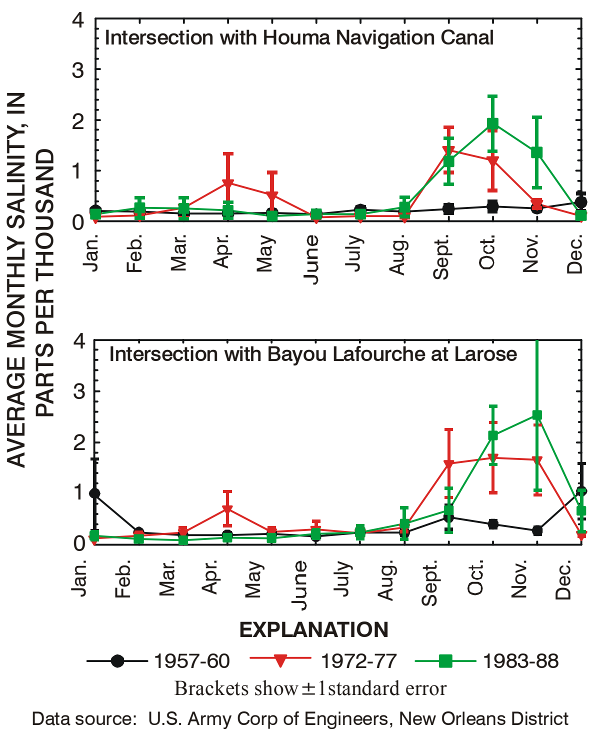


Figure 18. Average monthly salinity in the Gulf Intracoastal Waterway at the intersections with Houma Navigation Canal and Bayou Lafourche at Larose, Louisiana, from 1957-60, 1972-77, and 1983-88.

Stage and Water-Level Gradients

Flow in the GIWW is influenced by the differences in stage between the LAR or WLO and the interconnecting network of canals, bayous, and other surface-water bodies along and near the GIWW. Differences in stage and water-level gradients in the GIWW and adjacent waterways are vital to understanding flow in the GIWW.

Stage at all the sites along the GIWW tracked the stage of the LAR at Morgan City (figs. 19-22). The spring flood on the LAR was recorded at all sites. Water-level gradients were steepest closest to the LAR and WLO and decreased rapidly with increasing distance from the two sources. Water-level gradients along the GIWW were most pronounced during the spring flood and were attenuated in the fall months. The September storms in 1998 raised stage along the entire study reach. Elevated Gulf of Mexico levels contributed to the high stage in the GIWW, by direct influence and by impeding flow of accumulated runoff from the heavy precipitation.

East of Morgan City, more stage data were available from which to infer water-level gradients in the GIWW and adjacent water bodies. Monthly-average stage at the Avoca Island Cutoff Channel, Bayou Boeuf at railroad bridge at Amelia, and Bayou Penchant south of Morgan City were very similar and tracked stage of the LAR at Morgan City (fig. 19). Differences in stage between the LAR at Morgan City and these three sites were greater than 3 ft during the spring flooding, but decreased to less than 1 ft in the fall low-water season. The limited data available for the GIWW near Bay Wallace east of Morgan City during the spring floods for 1998-99 indicate stage is about 0.3-0.5 ft lower compared to the three sites farther west when the LAR at Morgan City was at flood stage. The difference in stage was greater in 1998, when the spring flood was greater, than in 1999. Along this segment of the GIWW, stage is lowest east of the HNC at Houma. There was a steeper rise in stage in the GIWW near Bay Wallace east of Morgan City in response to rising stage of the LAR than east of the HNC at Houma when the LAR at Morgan City was 4 ft or more above NAVD88. The water-level gradient between the two sites became steeper as the stage of the LAR at Morgan City increased. From August to December, water-level gradients among the sites in the western Terrebonne Basin were at their lowest.

Monthly-average stage at sites along the GIWW between Morgan City and Houma responded to those of the LAR at Morgan City when the LAR at Morgan City was about 2.75 to 3 ft or more above NAVD88 (fig. 20). In the GIWW east of HNC at Houma, the response was small, with an average increase of about 0.3 to 0.5 ft as the LAR at Morgan City increased from 3 to 7 ft above NAVD88. In contrast to the sites

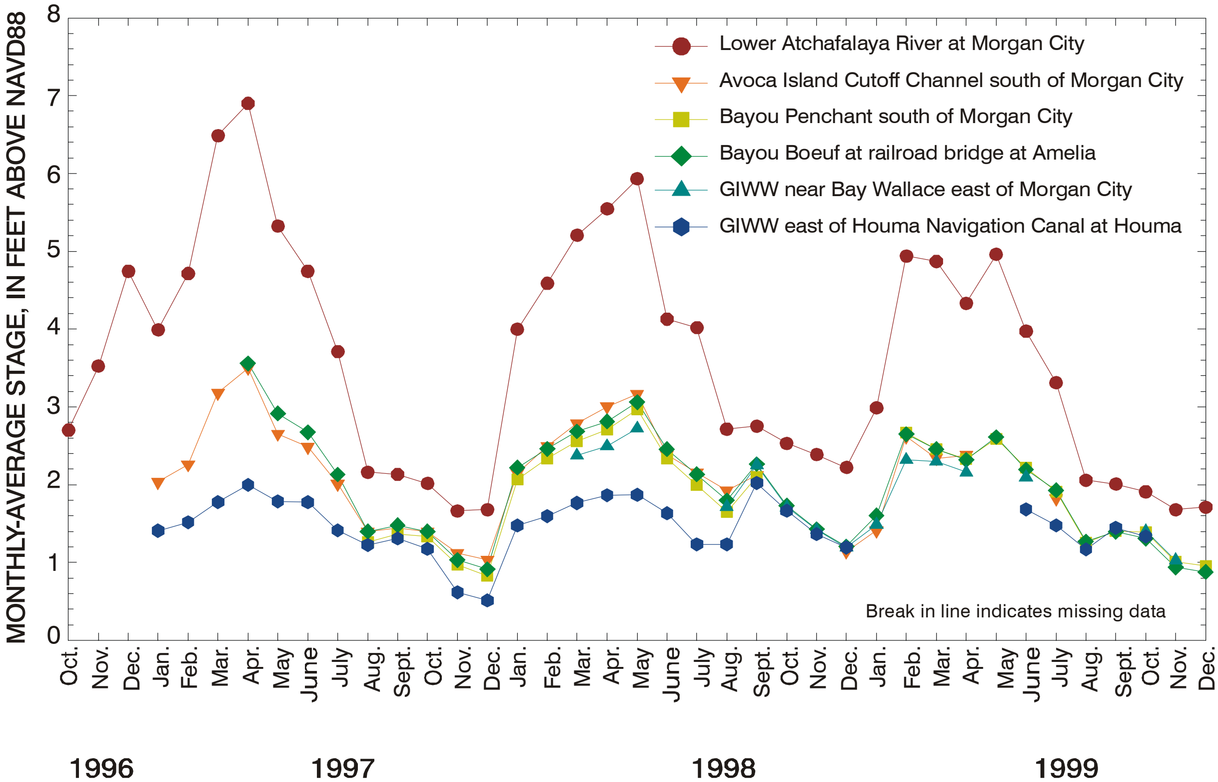


Figure 19. Monthly-average stage for the Lower Atchafalaya River at Morgan City, Avoca Island Cutoff Channel south of Morgan City, Bayou Penchant south of Morgan City, Bayou Boeuf at railroad bridge at Amelia, and in the Gulf Intracoastal Waterway (GIWW) near Bay Wallace east of Morgan City and east of Houma Navigation Canal at Houma, Louisiana, October 1996 to December 1999.

closer to the LAR, the response of stage in the GIWW east of the HNC in Houma was more variable, especially when the LAR at Morgan City was less than 5 ft above NAVD88. Stage in the GIWW east of HNC at Houma responded in a similar manner as stage in the HNC at Dulac. There appeared to be two relations between stage in the Avoca Island Cutoff Channel, Bayou Penchant south of Morgan City, Bayou Boeuf at railroad bridge at Amelia, and GIWW east of HNC at Houma, depending on whether the LAR was in flood or not.

East of Houma, stage decreased toward Bayou Lafourche, both in Company Canal, and in the GIWW east of Bayou Lafourche (fig. 21). The site at Company Canal is located about a tenth of a mile from Bayou Lafourche and is about 7 mi upstream of the GIWW-Bayou Lafourche intersection. Stage in Company Canal was higher than in the GIWW at Bayou Lafourche.

Stage also decreased southward from Houma along the HNC. The gradient in stage in the GIWW from Bayou Lafourche to Bayou Perot was very low. During spring peak flow of the LAR, the gradient was highest. High stage in September 1998 was characteristic of all sites in this part of coastal Louisiana. At sites near Morgan City, the spring peak in the LAR influenced stage more than at distant sites. When gradients are low, for example in the fall, a small error in datum rather than real differences in stage may be the cause of the observed gradient. Stage in the sites to the east of Houma appeared to track stage in the HNC at Dulac more closely than the LAR at Morgan City with the exception of the GIWW-Bayou Perot intersection (fig. 21).

Stage for sites between the WLO and Vermilion Bay near Cypremort Point are shown in figure 22. The record at all five sites is incomplete.

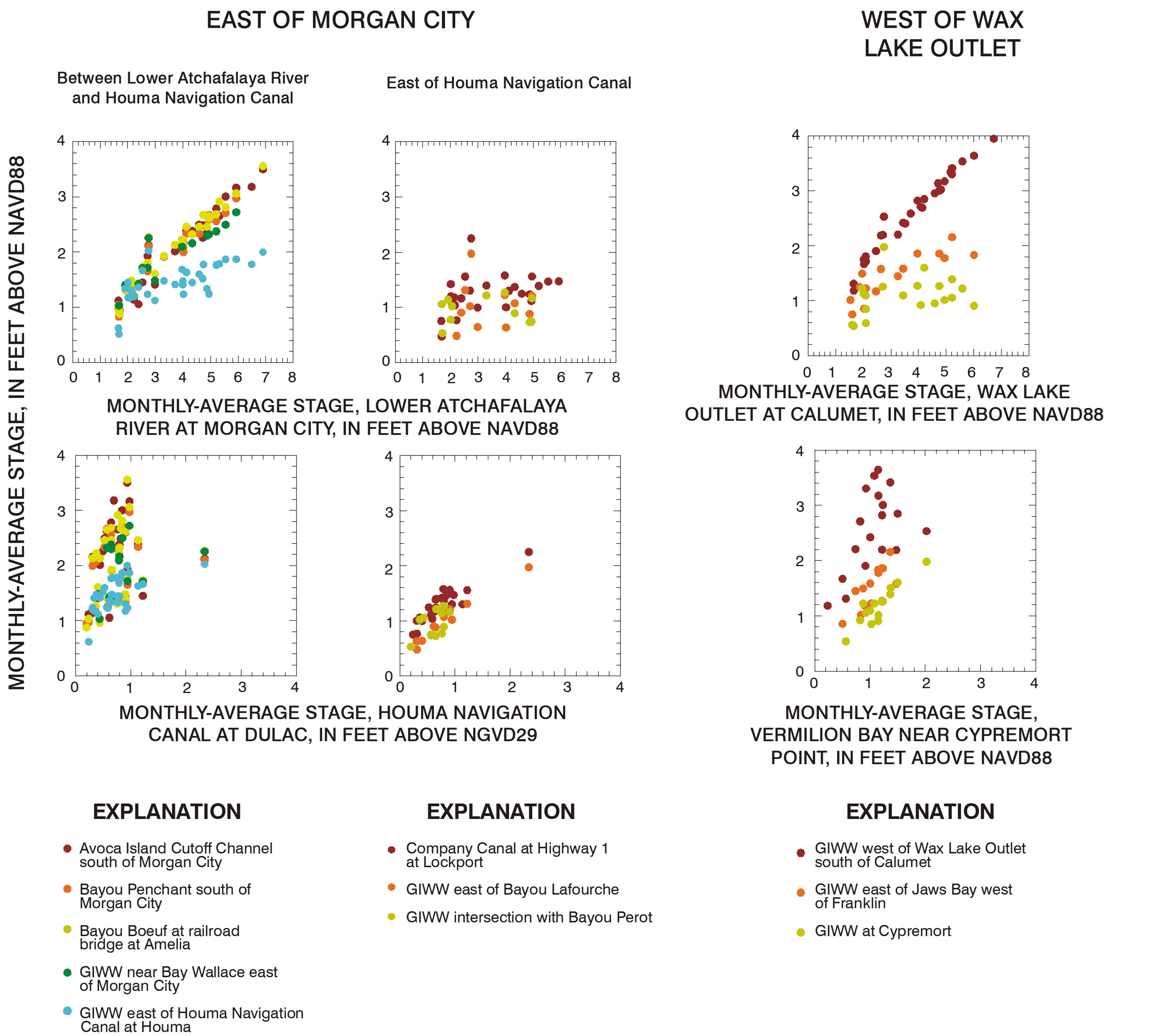


Figure 20. Relation between monthly-average stage at selected sites east of Morgan City and monthly-average stage of the Lower Atchafalaya River at Morgan City and Houma Navigation Canal at Dulac; and between monthly-average stage at selected sites on the Gulf Intracoastal Waterway west of Wax Lake Outlet and monthly-average stage of Wax Lake Outlet at Calumet and Vermilion Bay near Cypremort Point, Louisiana, October 1996 to December 1999.

Moreover, stage in the GIWW west of Wax Lake Outlet near Calumet is from a gage surveyed to NAVD88, but not by the USGS. Measured stage may deviate from the actual stage by some unknown amount. Data from Vermilion Bay near Cypremort Point indicate the Gulf of Mexico levels.

Stage in the GIWW west of WLO near Calumet was between 0.5 and 2 ft higher than east of Jaws Bay west of Franklin. In the GIWW between east of Jaws Bay west of Franklin and Cypremort, the maximum difference in stage that occurred during the annual river flood was about 1 ft. This difference did not occur in the fall and winter months during periods when the river was not in flood. Stage in the GIWW at Cypremort and in Vermilion Bay was similar.

Monthly-average stages along the GIWW are plotted with stage for WLO at Calumet and for Vermilion Bay near Cypremort Point (fig. 20).

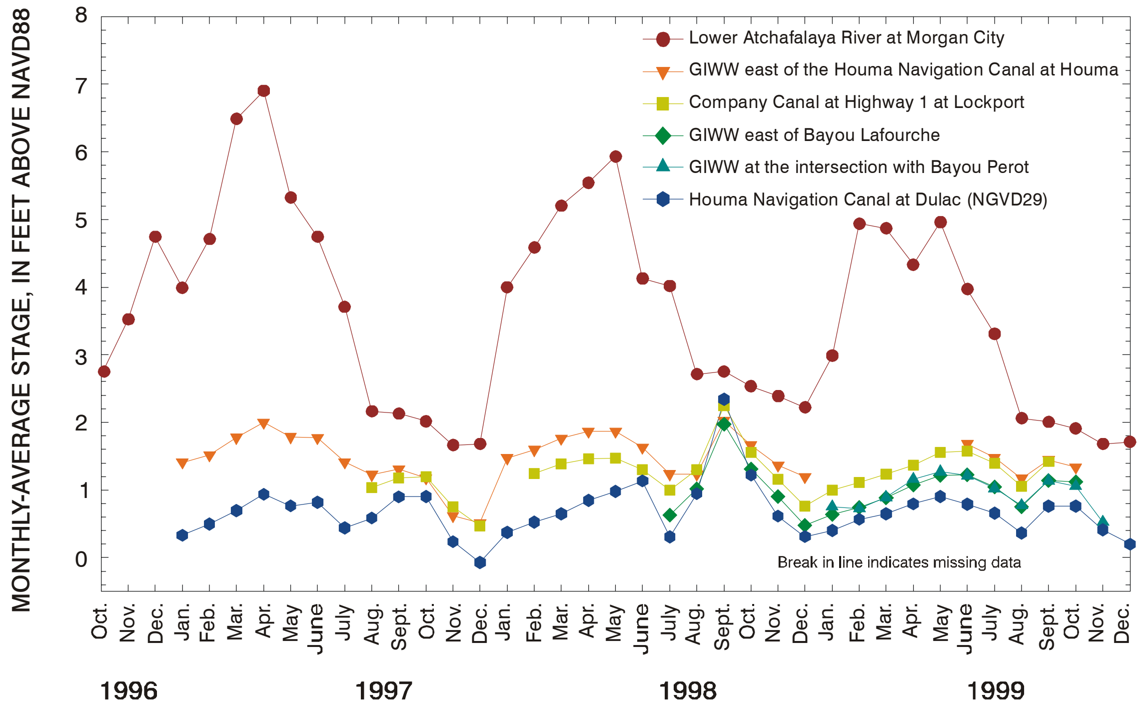


Figure 21. Monthly-average stage for the Lower Atchafalaya River at Morgan City, the Houma Navigation Canal at Dulac, Company Canal at Highway 1 at Lockport, and in the Gulf Intracoastal Waterway (GIWW) east of Houma Navigation Canal at Houma, east of Larose, and at the intersection with Bayou Perot, Louisiana, October 1996 to December 1999.

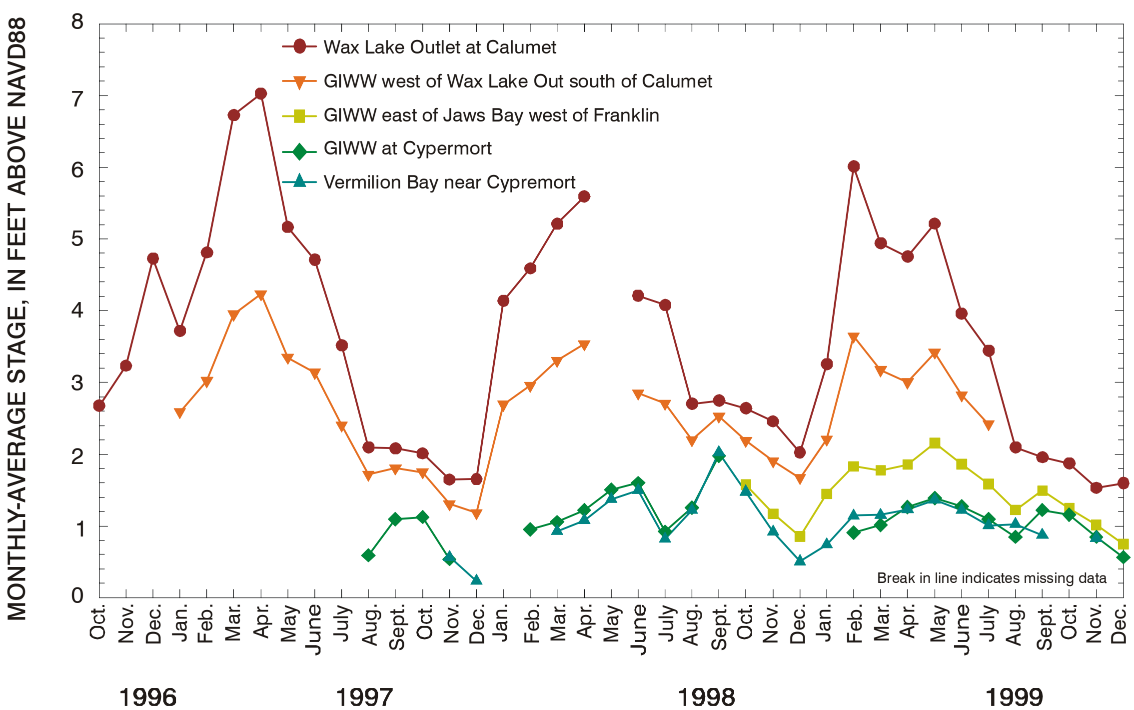


Figure 22. Monthly-average stage for the Wax Lake Outlet at Calumet, Vermilion Bay near Cypremort Point, and in the Gulf Intracoastal Waterway (GIWW) west of Wax Lake Outlet south of Calumet, east of Jaws Bay west of Franklin, and at Cypremort, Louisiana, October 1996 to December 1999.

Stage increased in the GIWW west of WLO near Calumet from 2 to over 4 ft as stage at WLO at Calumet increased from 2 to 7 ft. A similar increase was evident in the GIWW east of Jaws Bay west of Franklin, but the magnitude was smaller. As WLO at Calumet stage increased by 4 ft, stage in the GIWW east of Jaws Bay west of Franklin increased by less than 1 ft. Stage in the GIWW at Cypremort did not track WLO at Calumet stage fluctuations; it tracked stage in Vermilion Bay near Cypremort Point. The two sites on either side of Jaws Bay also responded to changes in Vermilion Bay stage. Two separate relations between stage in the GIWW east of Jaws Bay west of Franklin and stage in Vermilion Bay near Cypremort Point were offset by about 0.5 ft, presumably depending on whether the LAR was in flood or not. Stage in the GIWW west of WLO near Calumet always increased as stage at Vermilion Bay near Cypremort increased, but stage was often much higher than would have occurred if Vermilion Bay was the only factor affecting stage in the GIWW.

The differences in stage between the LAR and WLO and between the GIWW and adjacent surface-water bodies, strongly influence the local and regional surface-water hydrology of large parts of coastal Louisiana. The stage differences, and the resulting flows affect the north-south, and east-west movement of water, much of it fresh, in major bayous and canals that criss-cross the wetlands. Long-term measurements of stage and discharge in the GIWW and adjacent surface-water bodies are needed to more fully characterize the surface-water hydrology and to better incorporate the flows into the ongoing efforts relating to coastal wetland restoration. This is perhaps most easily achieved if stage and discharge measurements in the GIWW are integrated into long-term monitoring programs of coastal Louisiana waters. Studies are also needed to understand how the water flowing in the GIWW may affect the wetlands. To date, the effect of the freshwater flow and associated water-quality in the GIWW for the integrity and health of adjacent wetlands is largely unknown.

Selected Water-Quality Constituents

The water flowing in the GIWW carries sediment and generally is fresh. The freshwater moderates salinity in receiving water bodies. This effect decreases with distance from the sources, the LAR and WLO, and with increasing distance from the GIWW. In rare instances when Gulf of Mexico water intrudes inland, the GIWW can also move more saline water laterally along the coast.

Suspended Sediment

Suspended-sediment concentrations and discharge data are summarized in table 6. On the east side of the LAR, average suspended-sediment concentrations in the Avoca Island Cutoff Channel and Bayou Penchant south of Morgan City were about 50 to 70 mg/L higher than at the next four sites to the east, averaging 162 mg/L (table 6). Suspended-sediment discharge ranged from 74 to 7,440 tons/d at Bayou Penchant south of Morgan City and was as much as 22,900 tons/d at the Avoca Island Cutoff Channel. Discharge at the latter site was variable. Bayou Boeuf at railroad bridge at Amelia consistently had the lowest suspended-sediment concentrations among all sites sampled. Concentrations ranged from 47 to 175 mg/L but averaged 91 mg/L. Suspended-sediment discharge ranged from 2,990 tons/d moving into the Verret Subbasin to 4,250 tons/d moving out of the basin. In the GIWW near Bay Wallace east of Morgan City, and the GIWW west of the HNC at Houma, suspended-sediment concentrations averaged 114 and 108 mg/L, respectively. In the GIWW near Bay Wallace east of Morgan City, an average of 1,610 tons/d of suspended sediment were transported eastward, with about one-fourth of the suspended-sediment discharge entering at the Avoca Island Cutoff Channel.

In the GIWW west and east of Bayou Lafourche at Larose, suspended-sediment concentrations averaged about 134 and 161 mg/L, respectively. The higher average concentrations of suspended sediment to the east of Bayou Lafourche are likely due to the inflow and eastward movement of water from Bayou Lafourche. Average concentration is about 45 percent higher than in the GIWW near Bay Wallace east of Morgan City. Average suspended-sediment discharge was about 1,150 tons/d flowing eastward into Barataria Basin, with maximums of 2,500 to 3,240 tons/d.

Suspended-sediment concentrations at the two sites between WLO and the LAR were similar, about 172 to 183 mg/L. On average, about half the sediment discharge entering the GIWW from the LAR left the GIWW through the WLO.

Table 6. Suspended-sediment concentrations and discharge at selected sites along or near the Gulf Intracoastal Waterway (GIWW) in south-central Louisiana, 1997-99

[Negative sign indicates discharge is toward Morgan City or to the north. mg/L, milligrams per liter]

Map number (pl. 1)	Site name	Number of samples	Suspended sediment					
			Concentration (mg/L)			Discharge (tons per day)		
			Average (±standard deviation)	Range		Average (±standard deviation)	Range	
				Mini-mum	Maxi-mum		Mini-mum	Maxi-mum
	East of Lower Atchafalaya River							
	Between Lower Atchafalaya River and Houma Navigation Canal							
10	Avoca Island Cutoff Channel south of Morgan City	17	164±64	79	273	6,540±6,490	65	22,900
11	Bayou Penchant south of Morgan City	13	161±64	103	270	1,470±1,164	74	7,440
12	Bayou Boeuf at railroad bridge at Amelia	14	91±35	47	175	143±1,910	-2,990	4,250
13	GIWW near Bay Wallace east of Morgan City	15	114±33	68	180	1,610±1,050	-421	3,050
16	GIWW west of Houma Navigation Canal at Houma	15	108±30	75	182	1,760±1,120	187	4,320
	East of Houma Navigation Canal							
17	GIWW east of Houma Navigation Canal at Houma	15	117±41	68	225	994±550	-345	1,700
20	GIWW west of Bayou Lafourche at Larose	14	134±62	74	246	1,020±570	306	2,500
21	GIWW east of Bayou Lafourche at Larose	14	161±62	80	267	1,230±827	22	3,240
	West of Lower Atchafalaya River							
	Between Lower Atchafalaya River and Wax Lake Outlet							
8	GIWW at Lower Atchafalaya River south of Morgan City	13	183±69	85	286	8,690±6,650	900	19.900
7	GIWW east of Wax Lake Outlet near Calumet	15	172±42	105	248	4,550±2,320	1,840	10,900
	West of Wax Lake Outlet							
5	GIWW west of Wax Lake Outlet south of Calumet	13	179±66	87	332	5,130±3,530	1,731	11,800
4	GIWW east of Jaws Bay west of Franklin	13	172±62	106	307	4,130±3,420	1,020	14,100
3	GIWW west of Jaws Bay near Cypremort	13	167±55	110	290	1,670±1,570	572	6,390
2	GIWW at Cypremort	12	191±65	127	325	509±1,440	-2,480	2,660

Suspended-sediment concentrations averaged 179 to 172 mg/L at sites in the GIWW west of WLO south of Calumet and the GIWW east of Jaws Bay west of Franklin, respectively. Concentrations greater than 300 mg/L were measured at least once at the two sites. The average suspended-sediment discharge was about 15 percent less in the GIWW east of Jaws Bay west of Franklin compared to the GIWW west of WLO south of Calumet. In the GIWW west of Jaws Bay near Cypremort, average suspended-sediment concentrations were 167 mg/L. In the GIWW at Cypremort, average suspended-sediment concentrations were 191 mg/L. Reversed flow occurred here, with about 2,500 tons/d of suspended sediment moving east on at least one occasion.

Suspended sediment is important to the maintenance of wetlands. It provides nourishment to wetland plants and building materials for soil. The GIWW carries a substantial amount of suspended sediment to points east and west of Morgan City that may be of use in wetland restoration projects. The data collected from this study indicate that in addition to sediments from the Atchafalaya River, local sources of inflow such as Bayou Boeuf and Bayou Lafourche influence suspended-sediment concentrations in the GIWW. Resuspension of sediments presumably becomes more important farther away from the LAR and WLO, but the sustained flow in the GIWW also will help in moving the resuspended sediment.

Salinity

Sites where salinity was measured in the study area were (1) directly on the GIWW, (2) hydrologically connected and in close proximity to the GIWW, and (3) only indirectly connected to the GIWW. Data were collected at some sites during most of the study, whereas data collection was discontinued or began operation at other sites during the study. Most sites were operated by the USGS. Data from sondes installed by DNR in mid-summer of 1998 on Bayou Penchant at Brady Canal, in the GIWW at a point about 5 mi east of Larose, and at the GIWW intersection with Bayou Perot also were used in this study.

During high stage of LAR at Morgan City, salinity in the GIWW east of HNC at Houma and east of Bayou Lafourche intersection at Larose generally was about 0.2 to 0.6 ppt (pl. 1). In the fall, salinity was mostly low, but increased briefly on a frequent basis, at times to 10 ppt. In the fall of 1997 and 1999, the salinity increases were of longer duration than in the fall of 1998. Salinity in the HNC at Dulac had a similar seasonal pattern, but the brief salinity increases were higher, and more frequent. In 1996 and 1998, salinity did not decrease as much between the brief increases and the salinity was higher during the increases than in the intervening 2 years. Although less frequent, salinity increased even during periods of high stage of the LAR at Morgan City, most noticeably in April 1997, when stage of the LAR at Morgan City was near 8 ft above NAVD88.

Salinity was related to stage of the LAR at Morgan City at sites adjacent to and east of the LAR at Morgan City and distant from the GIWW (pl. 1). Salinity at Bayou du Large near Theriot decreased to about 1 ppt, when stage of the LAR at Morgan City was elevated. Salinity at Bayou Penchant at Brady Canal had brief increases of less than 5 ppt occurring in the fall, but otherwise was low. At Caillou Lake (Sister Lake) southwest of Dulac, salinity peaked at 15 to 25 ppt in the fall, when the stage of the LAR at Morgan City was low. When the LAR at Morgan City was in flood in the spring of 1997-98, salinity decreased to less than 4 ppt for extended periods.

At sites between the HNC and Bayou Lafourche, salinity was similar and responded less to changes in stage of the LAR at Morgan City than at the previously discussed sites with the exception of Bayou L'Eau Bleu (pl. 1). At this site in 1996-97, salinity was low when the LAR was in flood but increased in the fall.

Two sites, Vermilion Bay near Cypremort Point and Côte Blanche 4, provided the only available salinity data from the west side of the study area (pl. 1). Côte Blanche 4 is located in the wetlands east of Jaws Bay and south of the GIWW. Salinity was low during peak stage of the LAR at Morgan City in the spring. In 1997-98, salinity decreased to almost zero. In 1998, salinity started increasing before the river stage decreased. In mid-summer 1999 when the LAR was in flood, salinity was 2 to 3 ppt. In the fall of 1999, salinity reached the highest concentration for the study period at the two sites.

Salinity in the study area is affected by freshwater inflow from the LAR and WLO through the GIWW and by local precipitation and runoff. The freshwater from these sources mixes with saltwater from the Gulf of Mexico. The influence of river stage and precipitation on salinity was evaluated first by plotting monthly-average values of salinity at selected sites in relation to monthly-average stage of the LAR at Morgan City and WLO and monthly total precipitation. Sites were grouped depending on whether they were (1) on or near the GIWW or (2) at some distance from the GIWW. Next, pair-wise correlation coefficients between monthly-average salinity at a given site and stage of the LAR at Morgan City, monthly total precipitation at Morgan City, and the PHDI value were established (table 7). Only sites with the most complete data record were used for this analysis.

Salinity at all four sites on or near the GIWW, both east and west of the LAR, was less than 4 ppt whenever the LAR was in flood (fig. 23). Water in the GIWW east of HNC at Houma and Côte Blanche 4 remained fresh during high river stage in 1997-1999, but salinity became slightly elevated in September, October, and November. Salinity was not as high in the fall of 1998 as in the fall of 1997 or 1999. Salinity at the HNC at Dulac and at Vermilion Bay near Cypremort Point ranged from 8 to 15 ppt during the fall of 1998. Salinity at both sites did not decrease as much in 1999 as in 1998. In late fall 1999, salinity was between 12 and 14 ppt. In Vermilion Bay near Cypremort Point, the salinity pattern appeared to be low in late winter and high in September and October in response to, first, the spring peak in river flow, and then, the annual peak Gulf of Mexico level in the fall. The pattern changed in 1998 when salinity in September and October was lower than the salinity in July. The relatively low salinity at all four sites in fall 1998 compared to fall of 1997 and 1999 was most likely due to the excess precipitation that fell along Louisiana's coast during three storms in late September and early October 1998. Salinity increased for June and July, after the spring flood of the Mississippi and Atchafalaya Rivers receded. Salinity reached a maximum during the fall. Salinity increased from 2 ppt to greater than 10 ppt from July to August 1999 at Vermilion Bay near Cypremort Point; the sensitivity to lack of rain may be seen by the prolonged high salinity in the late fall months of 1999 (fig. 24). Even though precipitation in October was high, the south-central Climate Division was in a moderate to extreme drought during the entire fall (see fig. 4). Cumulative annual rainfall was substantially below average for 1996 and 1999 and above average for the first few months of 1997 and in the mid-summer of 1998 (fig. 24).

Only data from the east side of the LAR were available to evaluate response of salinity to freshwater inflows at some distance from the GIWW (fig. 23). Salinity was similar and decreased at the three sites during the first six months of 1997. In mid-summer 1997 salinity was the lowest measured during the study. In 1998-99, salinity increased from a mid-winter low to a high in May and June. In the fall of 1998 and 1999, salinity increased gradually from September to December at Bayou Terrebonne at Bush Canal, south of Chauvin and at Grand Bayou tributary west of Galliano. This was unusual. Typically, salinity follows a bell-shaped curve for the fall months, such as occurred in 1996-97 for all three sites. The high rainfall that occurred in September 1998 probably decreased salinity at these sites at this time. The lack of rain during the year likely underlay the atypical pattern of salinity seen at all sites in fall 1999. Salinity increased steadily after August and continued through December at sites distant from the GIWW (fig. 23), or increased rapidly and remained high at sites on or near the GIWW (fig. 23). Salinity during the first 5 months of 1999 was higher than during comparable times in the 2 previous years.

Caillou Lake (Sister Lake) southwest of Dulac is located between Four League Bay to the west and the HNC to the east. Salinity at this site ranged from 3 to about 20 ppt and was influenced by the stage and discharge of the LAR and seasonal variations in Gulf of Mexico levels. Typically salinity peaked in the spring and again in the fall. Annual highs occurred during the fall peak. In 1996 and 1999, the fall peak was 2 to 4 ppt higher than in the intervening 2 years. Lowest monthly-average salinity occurred during the mid-summer low in 1997, after the record flood in spring 1997. The lowest salinity in 1999 occurred in August and was more than twice the lowest salinity in 1997, which occurred in July.

Table 7. Correlation matrix for monthly-average salinity at selected sites, monthly-average stage of the Lower Atchafalaya River at Morgan City, Louisiana, monthly total precipitation at Morgan City, and Palmer Hydrological Drought Index

[Individual Pearson correlation coefficient is the top number and significance level is the bottom number. A significant difference is indicated when the significance level is less than 0.05. Bold result indicates a significant correlation with the variable in column 2. GIWW, Gulf Intracoastal Waterway; NAVD88, North American Vertical Datum of 1988; <, less than]

Map number (pl. 1)	Variable, monthly-average salinity, in parts per thousand, at indicated site	Monthly-average salinity (parts per thousand)						Monthly-average stage, Lower Atchafalaya River at Morgan City (feet above NAVD88)	Monthly total precipitation at Morgan City (inches)	Palmer Hydrological Drought Index
		GIWW east of Houma Navigation Canal at Houma	Vermilion Bay near Cypremort Point	Houma Navigation Canal at Dulac	Bayou Terrebonne at Bush Canal, south of Chauvin	Caillou Lake (Sister Lake) southwest of Dulac	Grand Bayou tributary west of Galliano			
17	GIWW east of Houma Navigation Canal at Houma		**0.65** <.001	**0.87** <.001	**0.62** <.001	**0.67** <.001	0.08 .680	**-0.49** .004	0.105 .607	-0.30 .093
1	Vermilion Bay near Cypremort Point			**.73** <.001	**.60** <.001	**.64** <.001	.22 .242	**-.79** <.001	-.03 .856	**-.61** <.001
29	Houma Navigation Canal at Dulac				**.67** <.001	**.78** <.001	.20 .251	**-.66** <.001	-.02 .92	-.34 0.037
28	Bayou Terrebonne at Bush Canal, south of Chauvin					**.91** <.001	**.78** <.001	**-.49** .002	-.13 .442	**-.51** <.001
30	Caillou Lake (Sister Lake) southwest of Dulac						**.57** <.001	**-.63** <.001	-.15 .380	**-.42** .010
26	Grand Bayou tributary west of Galliano							-.30 .079	-.05 .769	**-.53** <.001

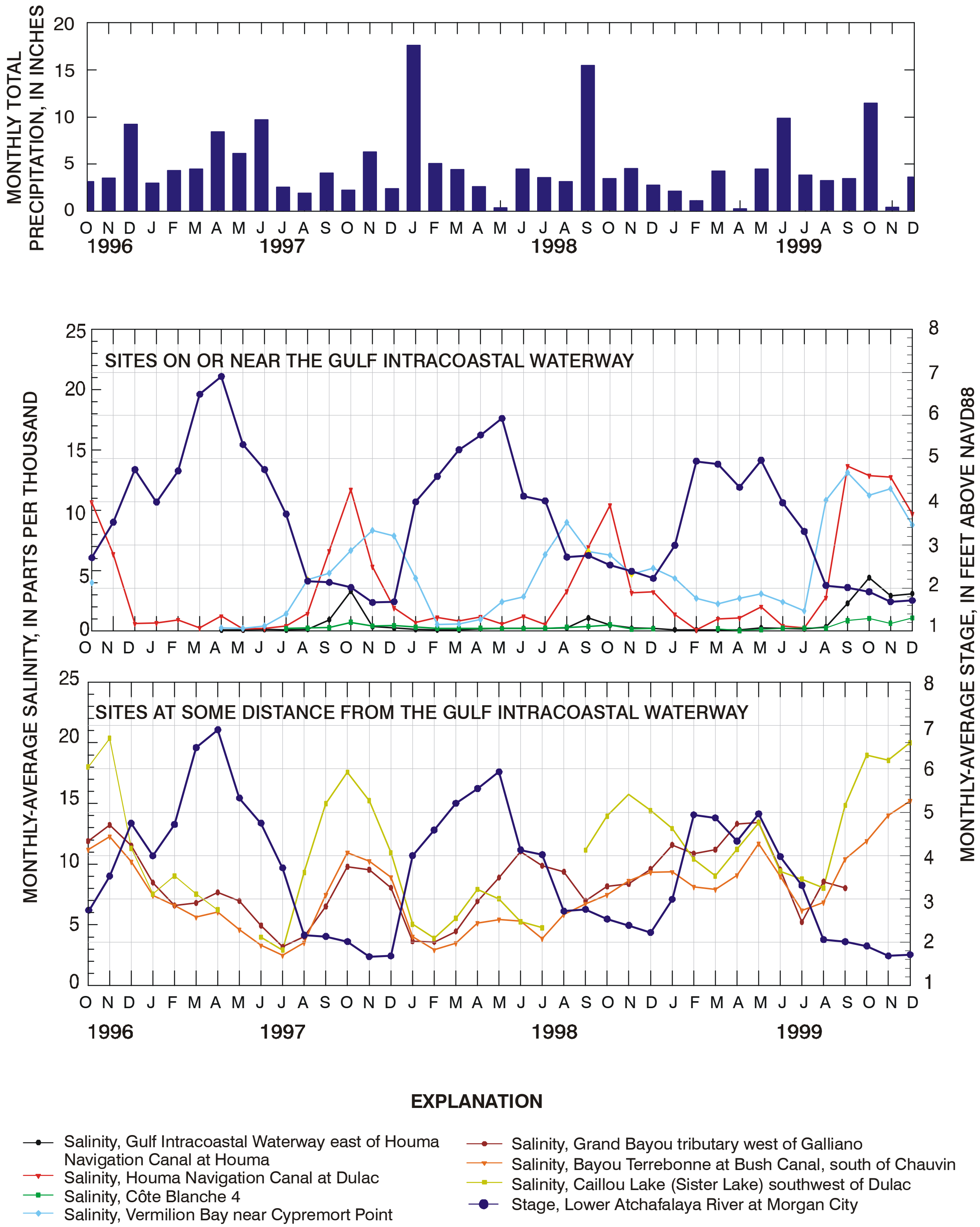


Figure 23. Relation between monthly-average salinity at selected sites in south-central Louisiana and monthly total precipitation at Morgan City and monthly-average stage of Lower Atchafalaya River at Morgan City, October 1996 to December 1999.

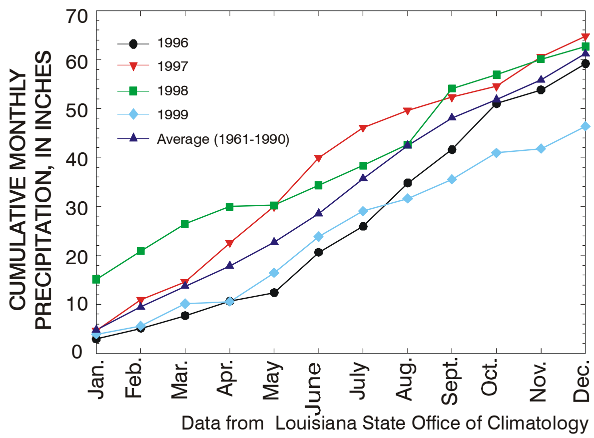


Figure 24. Cumulative monthly precipitation by year (1996-99) and average (1961-90) for the South-Central Climatological Division in Louisiana.

Bayou Terrebonne and Grand Bayou are located to the east of the HNC and to the south of the GIWW. Grand Bayou tributary west of Galliano is mostly cut off from freshwater sources except for rain and some inflow through Bayou L'Eau Bleu through the GIWW. Company Canal connects Bayou Terrebonne at Bush Canal, south of Chauvin with the GIWW at Houma. Bayou Terrebonne at Bush Canal, south of Chauvin is also connected indirectly to the HNC near Dulac and Bayou Grand Caillou by channels crossing Lake Boudreaux. In 1997, salinity at the two sites was similar. Salinity in Grand Bayou tributary west of Galliano was slightly higher during early summer; salinity in Bayou Terrebonne was higher during the fall. In May and June 1998, salinity was 2 to 5 ppt higher than the previous year at the same time. At Bayou Terrebonne at Bush Canal, south of Chauvin, salinity increased from July to December 1998. The fall peak salinity was less than the previous year, probably due to local runoff. At Grand Bayou tributary west of Galliano, salinity increased from the fall of 1998 through April and May 1999 but then decreased through June and July 1999.

Monthly-average salinity at the sites with the most complete record from both sides of the study area were plotted against monthly-average stage of the LAR at Morgan City and the HNC at Dulac (fig. 25) to determine the influence of river stage and Gulf of Mexico levels, respectively. Salinity at sites on or near the GIWW, east of the HNC at Houma, HNC at Dulac, Côte Blanche 4, and Vermilion Bay near Cypremort Point decreased with increases in stage of the LAR at Morgan City. When the LAR at Morgan City was 2 ft or more above NAVD88, monthly-average salinity in the GIWW east of HNC at Houma did not increase much above 1 ppt. With one exception, monthly-average salinity at HNC at Dulac was 2 ppt or less when the LAR at Morgan City was 3 ft or more above NAVD88. As stage of the LAR at Morgan City increased to 7 ft above NAVD88, salinity did not exceed progressively smaller values for Vermilion Bay near Cypremort Point. When the LAR at Morgan City was 5 ft or more above NAVD88, salinity was never greater than 3 ppt. However, salinity was frequently lower than a direct correlation with stage would predict, indicating that aside from LAR water, freshwater runoff and Gulf of Mexico stage also influenced salinity in Vermilion Bay near Cypremort Point.

Stage of the LAR at Morgan City affected salinity at Caillou Lake (Sister Lake) southwest of Dulac and salinity at Vermilion Bay near Cypremort Point in much the same way. As stage of the LAR at Morgan City increased, maximum salinity decreased. Salinity at the other three sites at some distance from GIWW did not respond to changing stage of the LAR at Morgan City as directly, increasing and decreasing as stage increased at most stages of the LAR at Morgan City (fig. 25). However, salinity at all three sites was consistently higher when the LAR at Morgan City was 7 ft above NAVD88 than when the LAR at Morgan City was 5 ft above NAVD88. More data could aid in verifying this relation. There may be an indirect effect of seasonally higher Gulf of Mexico levels along the coast of Louisiana. Discharges from the Mississippi River and the LAR are highest in April and May. Onshore winds last for several weeks during much of the same time and push Gulf of Mexico water into estuaries along the coast (Byrne and others, 1976). Freshwater input in the form of precipitation and variations in Gulf of Mexico level affected salinity at all four sites. At Grand Bayou tributary west of Galliano and at Bayou Terrebonne at Bush Canal, south of Chauvin, there was a relation below which salinity did not decrease as stage of the HNC at Dulac increased. Such a relation was less apparent at Bayou Jean Lacroix near Montegut, La.

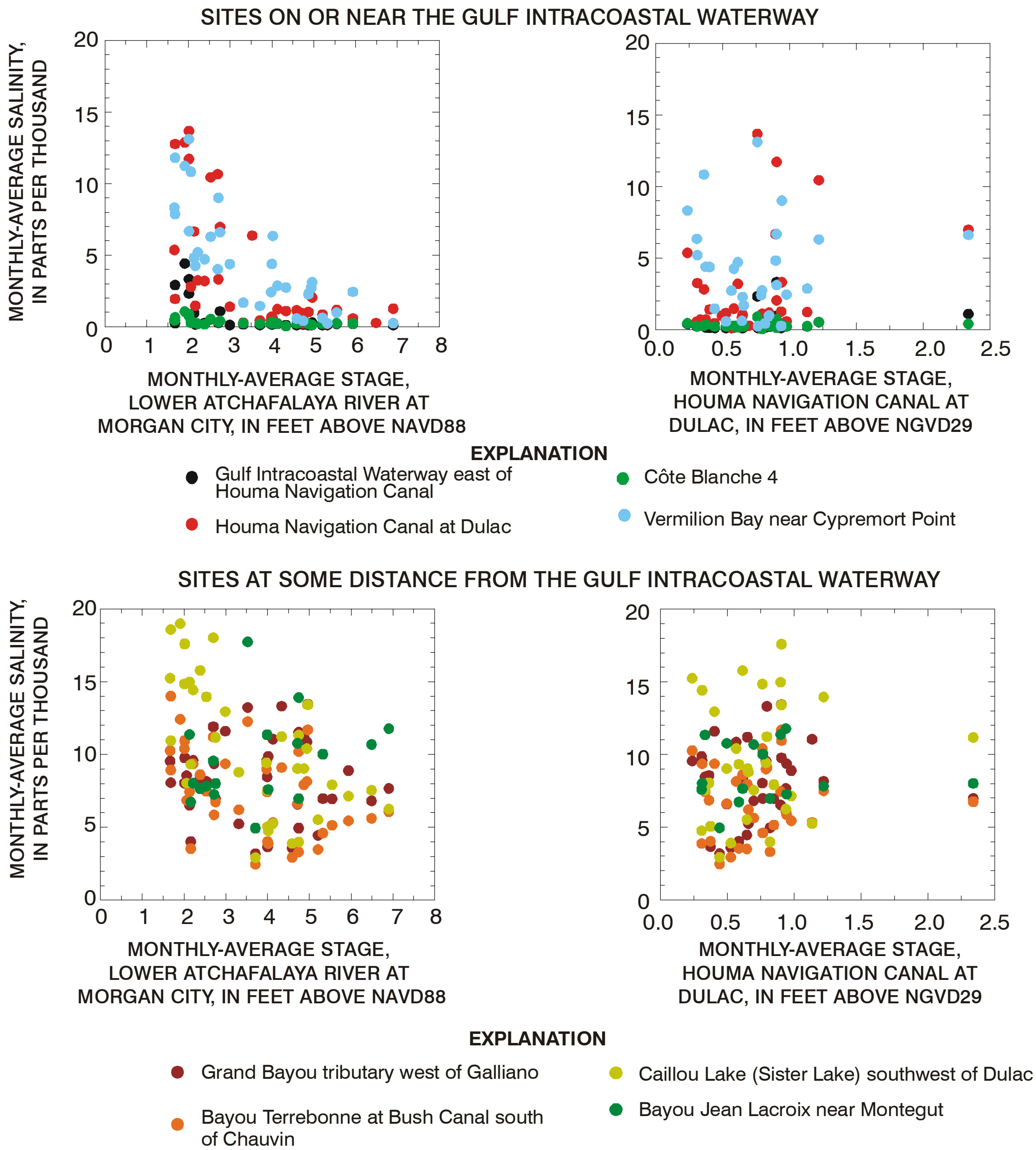


Figure 25. Relation between monthly-average salinity at eight sites in coastal Louisiana and monthly-average stage of Lower Atchafalaya River at Morgan City and Houma Navigation Canal at Dulac, Louisiana, October 1996 to December 1999.

Table 7 lists pair-wise regression coefficients for monthly-average salinity at selected sites and monthly-average stage of the LAR at Morgan City, monthly total precipitation at Morgan City, and the PHDI. Pair-wise regression coefficients also are listed for monthly-average salinity among sites. Salinity at Vermilion Bay at Cypremort Point and Caillou Lake (Sister Lake) southwest of Dulac correlated significantly with stage of the LAR at Morgan City. Vermilion Bay near Cypremort Point was sensitive to drought as well, as indicated by the significant negative correlation between monthly-average salinity and PHDI. Salinity at Grand Bayou tributary west of Galliano showed the highest correlation with the PHDI and the least with stage of the LAR at Morgan City, which indicates isolation from the GIWW freshwater and strong climatic influence on salinity. Monthly total precipitation and salinity were not significantly correlated at any stations. There were significant correlations in monthly-average salinity among all stations.

The GIWW influences salinity in a wide part of coastal Louisiana and in many instances in a predictable manner. The significant correlations between salinity at selected sites and stage of the LAR have important implications for managing and restoring coastal wetlands in Louisiana. The relations between salinity and stage of the LAR can be used with relations presented previously in this report between stage of the LAR and discharge at selected sites to better understand availability of freshwater inflow or lack of inflow at specific locations along the Louisiana coast.

SUMMARY AND CONCLUSIONS

The flow of freshwater and suspended sediments from the Lower Atchafalaya River (LAR) and Wax Lake Outlet (WLO) into and along the Gulf Intracoastal Waterway (GIWW) and selected adjacent surface-water bodies between Cypremort and Larose in south-central Louisiana from October 1996 to December 1999 was characterized using instantaneous and continuous discharge measurements, and measurements of suspended-sediment concentrations. The GIWW parallels the entire Louisiana coast near the wetland/upland interface. Following natural hydraulic gradients, the GIWW captures water from the southward flowing LAR and the WLO where it crosses those waterways, and distributes the freshwater and sediment to points east and west. Water-level gradients of surface waters in the study area were determined and the potential for flow evaluated. The influence of freshwater flow in the GIWW on current and historical salinity patterns in the GIWW and adjacent surface-waters also was evaluated.

The LAR was the primary source of water to the GIWW east of Morgan City. East of Morgan City, an average of 12,200 ft^3/s (cubic feet per second) of water flowed from the LAR directly into the Avoca Island Cutoff Channel. Measured discharge ranged from 267 to 31,100 ft^3/s entering the Avoca Island Cutoff Channel. Drainage from the Verret Subbasin through Bayou Boeuf at railroad bridge at Amelia contributed an average of 1,000 ft^3/s to flow east of Morgan City. Measured discharge ranged from 9,110 ft^3/s entering to 15,300 ft^3/s draining the Verret Subbasin. Bayou Penchant south of Morgan City, connecting to the Avoca Island Cutoff Channel south of the GIWW, drained on average 3,250 ft^3/s of varying proportions of LAR and Verret Subbasin water in a southeasterly direction. A combination of LAR and Verret Subbasin water flowed east in the GIWW near Bay Wallace east of Morgan City and west of the HNC (Houma Navigation Canal) at Houma, averaging about 5,700 ft^3/s and frequently reaching at least 8,000 ft^3/s at both sites.

Average discharge in the GIWW east of the HNC at Houma was about 2,610 ft^3/s in an eastward direction, and ranged from 1,100 ft^3/s flowing west toward the HNC to 4,640 ft^3/s flowing east toward the intersection of the GIWW. Discharge in the GIWW east of Bayou Lafourche at Larose averaged 2,220 ft^3/s, and peaked at 5,320 ft^3/s, also flowing to the east. Flow towards Houma was observed on two occasions, with a maximum discharge of 1,860 ft^3/s. At sites west of the HNC, discharge in the GIWW increased predictably with increasing LAR stage. This was not the case to the east of the HNC.

Flow was always to the west between the LAR and WLO. Average discharge was about 13,400 ft^3/s in the GIWW at LAR south of Morgan City. The highest discharge measurement of any synoptic trip was made here, at 35,200 ft^3/s. Discharge increased predictably with increasing LAR stage. In the GIWW east of WLO near Calumet, average discharge was 9,460 ft^3/s. Discharge did not appear to increase with increasing LAR stage beyond 5 ft above NAVD88, indicating increasing volumes of water flowed south toward Atchafalaya Bay when this condition was met.

Flow was always to the west in the GIWW west of WLO south of Calumet, and discharge ranged from 2,050 to 20,300 ft^3/s with an average of 9,460 ft^3/s. Flow was to the west in the GIWW east of Jaws Bay west of Franklin, and average discharge was 8,230 ft^3/s, with a maximum of 17,000 ft^3/s. Discharge at both these locations on the GIWW increased predictably with increasing stage of the LAR at Morgan City. In the GIWW west of Jaws Bay near Cypremort, average discharge was 3,310 ft^3/s and flow was always to the west. In the GIWW at Cypremort, average discharge was 1,350 ft^3/s to the west, but discharge as high as 2,830 ft^3/s was measured flowing eastward to Jaws Bay.

Discharge along the GIWW was highest where it crossed the LAR and WLO. Water flowed east and west in the GIWW, in decreasing volumes with increasing distance from the source. Discharge tended to increase as same-day average stage of the LAR at Morgan City increased beyond 3 ft (feet) above NAVD88 at most of the sites between HNC and Jaws Bay. At sites in the GIWW east of HNC, discharge did not increase predictably. For all measurements made when the LAR at Morgan City was 3 ft or more above NAVD88, average discharge was about 3,100 ft^3/s in the GIWW east of HNC at Houma and 2,880 ft^3/s east of Bayou Lafourche at Larose. When the LAR at Morgan City reached 3 to 4 ft above NAVD88, discharge in the GIWW became more predictable. The flow of freshwater along most of the GIWW studied was enhanced not so much by absolute high stage of the LAR at Morgan City as by the total time the LAR at Morgan City was 3 ft or more above NAVD88. The LAR at Morgan City is 3 ft or more above NAVD88 for about 7 months in a normal year.

The GIWW not only moves freshwater along the coast, but also carries saltwater when there are several days of reversed flow in north-to-south trending ship channels such as the HNC. Saltwater then can flow laterally in the GIWW when normal hydraulic gradients resume and reach areas which contain marsh plants that have a low tolerance for salt.

Localized runoff and drainage contributed to flow along segments of the GIWW on both sides of Morgan City. When the LAR at Morgan City was less than 3 ft above NAVD88, water flowed along the prevailing gradients, to the east between Bay Wallace and the HNC and to the west between WLO and Jaws Bay. However, frequently more water left the GIWW at the downstream end of the segments than entered, indicating that flow was sustained by water draining from areas adjacent to the GIWW. Substantial volumes of water left the GIWW through the HNC and at the opening to Jaws Bay. As local runoff increased, the volume of water leaving the GIWW through the HNC increased, whereas at Jaws Bay, the volume of water leaving the GIWW increased steadily as water entering the GIWW west of WLO near Calumet increased. As local runoff increased, the GIWW between Houma and Bayou Lafourche shifted from storing to draining water. In contrast, the GIWW between Jaws Bay and Cypremort stored increasing volumes of water as runoff increased. Here, there was a net inflow of water at low LAR stage which decreased rapidly and steadily as the volume of river water entering at WLO increased.

The flow of water from the LAR to the GIWW has changed over time. Aggradation of the bed of the LAR since the 1950’s has raised water levels where the river joins the Avoca Island Channel Cutoff by about 2 to 2.5 ft. The aggraded riverbed has increased the time when the stage of LAR at Morgan City is at least 3 ft above NAVD88. Lateral flow in the GIWW presently (1999) occurs for longer periods than in the 1950's. Infilling of the riverbed also has increased the absolute difference in stage between the LAR and adjacent waters, so that the GIWW predictably can move water to points farther away from the source. During 1997-99, more water was flowing in the GIWW west of HNC at Houma relative to a given stage of the LAR at Morgan City than at the same location in 1982-83.

Flow in the GIWW results from differences in stage along the GIWW and adjacent surface-water bodies. In the coastal zone, stage narrowly fluctuates around Gulf of Mexico levels most of the time. Where the GIWW crosses the LAR and WLO, stage typically reaches 3 to 4 ft above NAVD88. Stage differences between LAR and the rest of the coast induce flow in the GIWW and allow LAR water to penetrate distant reaches of the coast for several months each year. Monthly-average stage at sites on the GIWW east of Morgan City to the HNC and west of Morgan City to Jaws Bay tracked stage of the LAR reasonably well. The correlation was better and the response greater closer to the LAR.

The spring flood of the LAR was the dominant influence on flow in and near the GIWW, raising water levels high above levels in surrounding waters. Seasonal and event-driven fluctuations in Gulf of Mexico levels changed stage along the coast and impacted gradients. Stage in and near the GIWW also was affected by winds, precipitation, and storms. Together, the factors influenced water-level gradients along the GIWW and controlled the direction and movement of water from the LAR to the GIWW and from the GIWW to adjacent waters.

East of the LAR, suspended-sediment concentrations averaged about 162 mg/L (milligrams per liter) at the two sites closest to the LAR, at the Avoca Island Cutoff Channel and at Bayou Penchant south of Morgan City. The water entering the GIWW through Bayou Boeuf at railroad bridge at Amelia averaged 91 mg/L of suspended sediments. The water in the GIWW near Bay Wallace east of Morgan City to the HNC was intermediate in concentrations (108 to 114 mg/L), reflecting the mixture of the two water types. Concentrations of suspended sediment in the GIWW near Bay Wallace east of Morgan City, and on both sides of the HNC were comparable, but in the GIWW east of Larose they increased by about 45 percent. To the west of WLO, suspended-sediment concentrations averaged between 167 and 191 mg/L.

Freshwater flow affected salinity patterns in the GIWW and areas immediately adjacent to it in the study area. Monthly-average salinity at many coastal sites was correlated with monthly-average stage of the LAR at Morgan City. In the GIWW east of HNC at Houma and at Côte Blanche 4 salinity was near zero whenever stage of the LAR at Morgan City was 2 ft or more above NAVD88. At HNC at Dulac and Vermilion Bay near Cypremort Point, maximum monthly-average salinity progressively decreased as stage of the LAR at Morgan City increased. When the LAR at Morgan City was 5 ft or more above NAVD88, salinity remained below 3 parts per thousand. At these four sites, salinity during the fall months was appreciably higher than during the rest of the year. Salinity patterns at sites distant from the GIWW--Caillou Lake (Sister Lake), HNC at Dulac, and Vermilion Bay near Cypremort Point--were similar, with maximum salinity decreasing with increasing stage of the LAR at Morgan City.

The differences in stage between the intersections of the LAR and WLO with the GIWW and the GIWW, and between the GIWW and adjacent surface-water bodies, strongly influence the local and regional surface-water hydrology of large parts of coastal Louisiana. The stage differences, and the resulting flows affect the north to south, and east to west movement of water, much of it fresh, in major bayous and canals that criss-cross the wetlands. Long-term measurements of stage and discharge in the GIWW and adjacent surface-water bodies are needed to more fully characterize the surface-water hydrology and to better incorporate the flows into the ongoing efforts relating to coastal wetland restoration. This is perhaps most easily achieved if stage and discharge measurements in the GIWW are integrated into long-term monitoring programs of coastal Louisiana waters. Studies are also needed to understand how the water flowing in the GIWW may affect the wetlands. To date, the effect of the freshwater flow and associated water-quality in the GIWW for the integrity and health of adjacent wetlands is largely unknown.

When the LAR at Morgan City is 3 or more ft above NAVD88, the GIWW effectively distributes freshwater and sediments from the LAR and WLO to points in coastal Louisiana 30 to 50 mi east and west of Morgan City. The freshwater and sediments, some of which originate indirectly from the Mississippi River, are important building blocks for wetlands and could prove valuable in ongoing efforts to restore coastal Louisiana.

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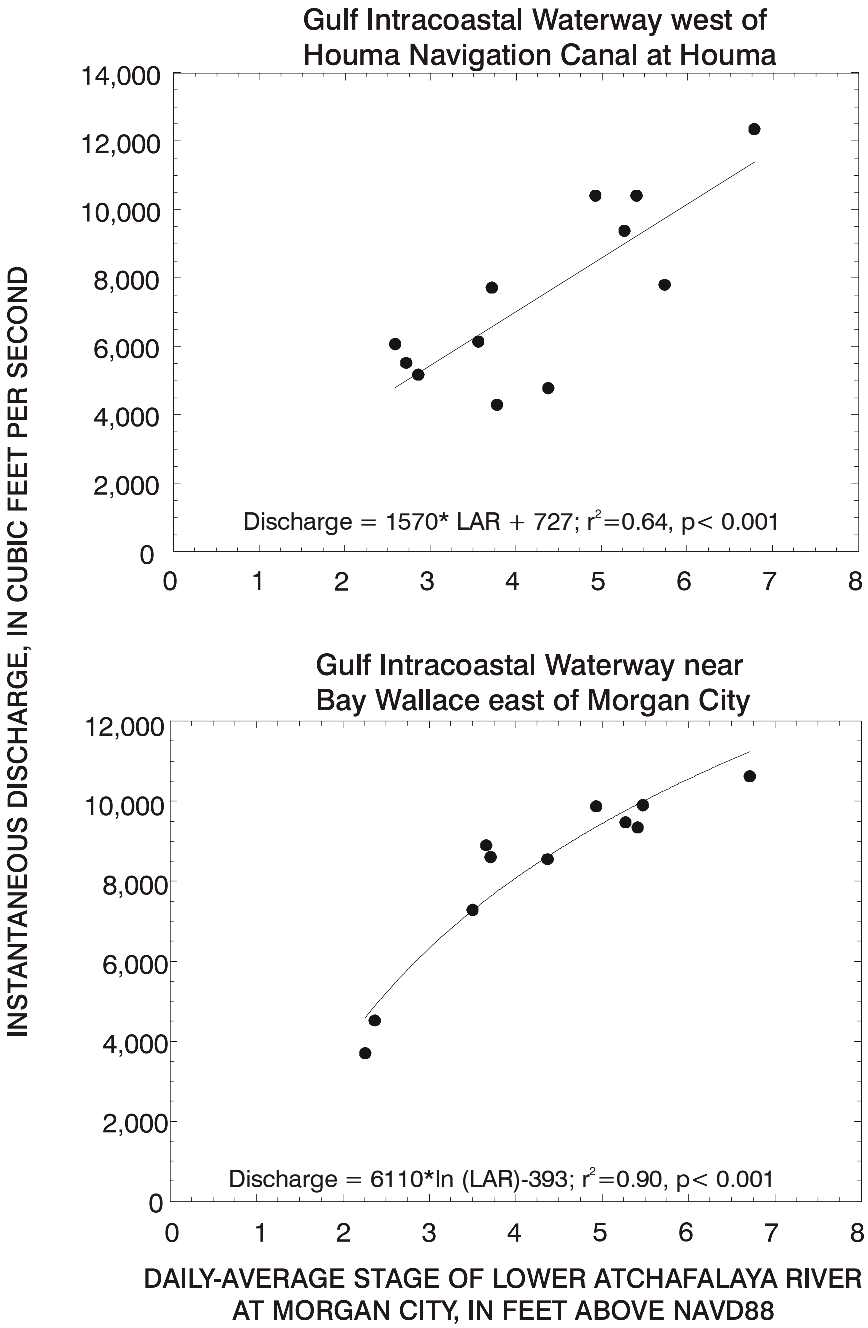
APPENDIX:

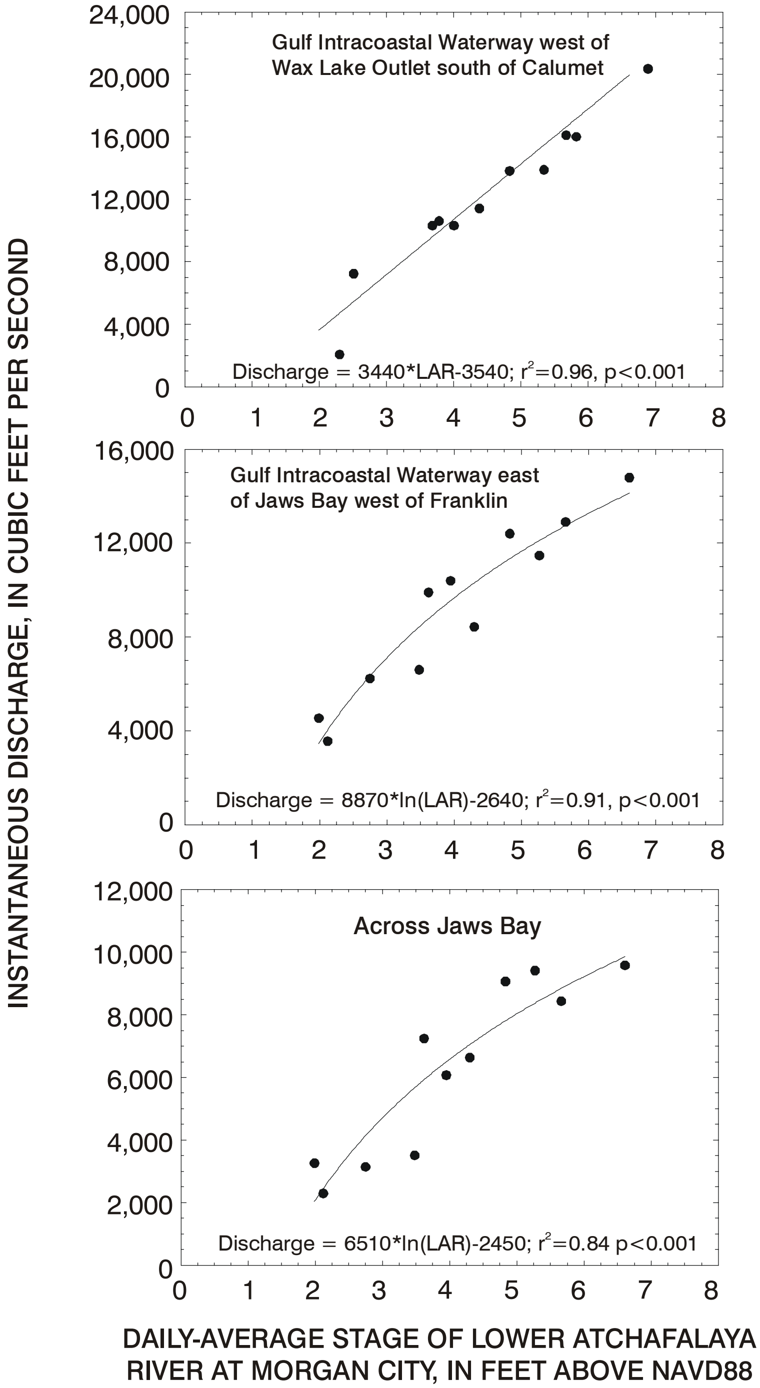
Regression Equations



EXPLANATION

LAR is daily-average stage of the Lower Atchafalaya River at Morgan City
r^2 is correlation coefficient, p is level of significance

Figure A1. Regressions of daily-average stage of the Lower Atchafalaya River at Morgan City against same-day instantaneous discharge measurements in the Gulf Intracoastal Waterway west of Houma navigation Canal at Houma and near Bay Wallace east of Morgan City.



EXPLANATION

LAR is daily-average stage of the Lower Atchafalaya River at Morgan City; r^2 is correlation coefficient, p is level of significance

Figure A2. Regressions of daily-average stage of the Lower Atchafalaya River at Morgan City against same-day instantaneous discharge measurements at selected sites in the Gulf Intracoastal Waterway west of Wax Lake Outlet.