Hydrodynamic Characteristics and Salinity Patterns in Estero Bay, Lee County, Florida

By Michael J. Byrne, and Jessica N. Gabaldon

Prepared in cooperation with the South Florida Water Management District

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Conversion Factors

Multiply	By	To obtain
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
acre	4,047	square meter (m^2)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile per hour (mi/hr)	1.609	kilometer per hour (km/hr)

Acronyms

ADCP	Acoustic Doppler Current Profiler
ADVM	Acoustic Doppler Velocity Meter
EDI	Equal Discharge Increments
FNU	Formazin Nephelometric Units
GIS	Geographic Information System
GPS	Global Positioning Satellite
IDW	Inverse Distance Weighted
ppt	part per thousand
SFWMD	South Florida Water Management District
SSC	Suspended Sediment Concentration
USGS	U.S. Geological Survey

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows: °C=(°F-32)/1.8

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

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Abstract

Estero Bay is an estuary (about 12 miles long and 3 miles wide) on the southwestern Florida coast, with several inlets connecting the bay to the Gulf of Mexico and numerous freshwater tributaries. Continuous stage and salinity data were recorded at eight gaging stations in Estero Bay estuary from October 2001 to September 2005. Continuous water velocity data were recorded at six of these stations for the purpose of measuring discharge. In addition, turbidity data were recorded at four stations, suspended sediment concentration were measured at three stations, and wind measurements were taken at one station. Salinity surveys, within and around Estero Bay, were conducted 15 times from July 2002 to January 2004.

The average daily discharge ranged from 35,000 to -34,000 ft^3/s (cubic feet per second) at Big Carlos Pass, 10,800 to -11,200 ft^3/s at Matanzas Pass, 2,200 to -2,900 ft^3/s at Big Hickory Pass, 680 to -700 ft^3/s at Mullock Creek, 330 to -370 ft^3/s at Estero River, and 190 to -180 ft^3/s at Imperial River. Flood tide is expressed as negative discharge and ebb flow as positive discharge.

Reduced salinity at Matanzas Pass was negatively correlated ($R^2 = 0.48$) to freshwater discharge from the Caloosahatchee River at Franklin Locks (S-79). Matanzas Pass is hydrologically linked to Hell Peckney Bay; therefore, water-quality problems associated with the Caloosahatchee River also affect Hell Peckney Bay. Rocky Bay was significantly less saline than Coconut Point and Matanzas Pass was significantly less saline than Ostego Bay, based on data from the salinity surveys. The quality-checked and edited continuous data and the salinity maps have been compiled and are stored on the U.S. Geological Survey South Florida Information Access (SOFIA) website *(http://sofia.usgs.gov).*

Introduction

Estero Bay is an estuary on the southwestern Florida coast, about 12 mi long and 3 mi wide, with several inlets connecting the bay to the Gulf of Mexico and numerous freshwater tributaries (fig. 1). The estuary serves as a nursery for juvenile fish, rookery for migratory birds, and critical habitat for endangered species, including the Florida manatee (*Trichechus manatus latirostrus*) and roseate spoonbill (*Platalea ajaja*). The estuary has diverse species composition adapted to brackish water with various salinity tolerances. Salinity is governed by diurnal tides, rainfall, wind, and controlled freshwater discharges. The hydrodynamic characteristics and salinity patterns in Estero Bay are poorly understood.

Natural systems, such as wetlands, mangroves swamps, floodplains, and oyster beds, serve vital ecological functions within Estero Bay and surrounding areas. Disruptions to these systems by draining wetlands, channelizing rivers, and altering the timing and volume of freshwater discharge to the estuary have deleterious effects on the biota adapted to the conditions prior to development. The natural system of the bay needs to be better understood in order to establish minimum flows and water levels for Estero Bay.

In 2001, the U.S. Geological Survey (USGS), in cooperation with the South Florida Water Management District (SFWMD), initiated a study to determine the hydrodynamic characteristics and salinity patterns in Estero Bay. To achieve the goals of this study, between October 2001 and September 2005, 11 hydrologic monitoring stations were established in Estero Bay and the surrounding area to produce the following data: discharge at 6 stations, stage at 8 stations, salinity and water temperature at 11 stations, turbidity at 4 stations, suspended sediment concentration at 3 stations, and wind measurements at 1 station (fig. 2 and table 1). In addition, salinity maps were created based on data from synoptic surface-water salinity surveys. The data collected as part of this study will be used to develop and calibrate a hydrodynamic model with transport to be used for bay restoration efforts.

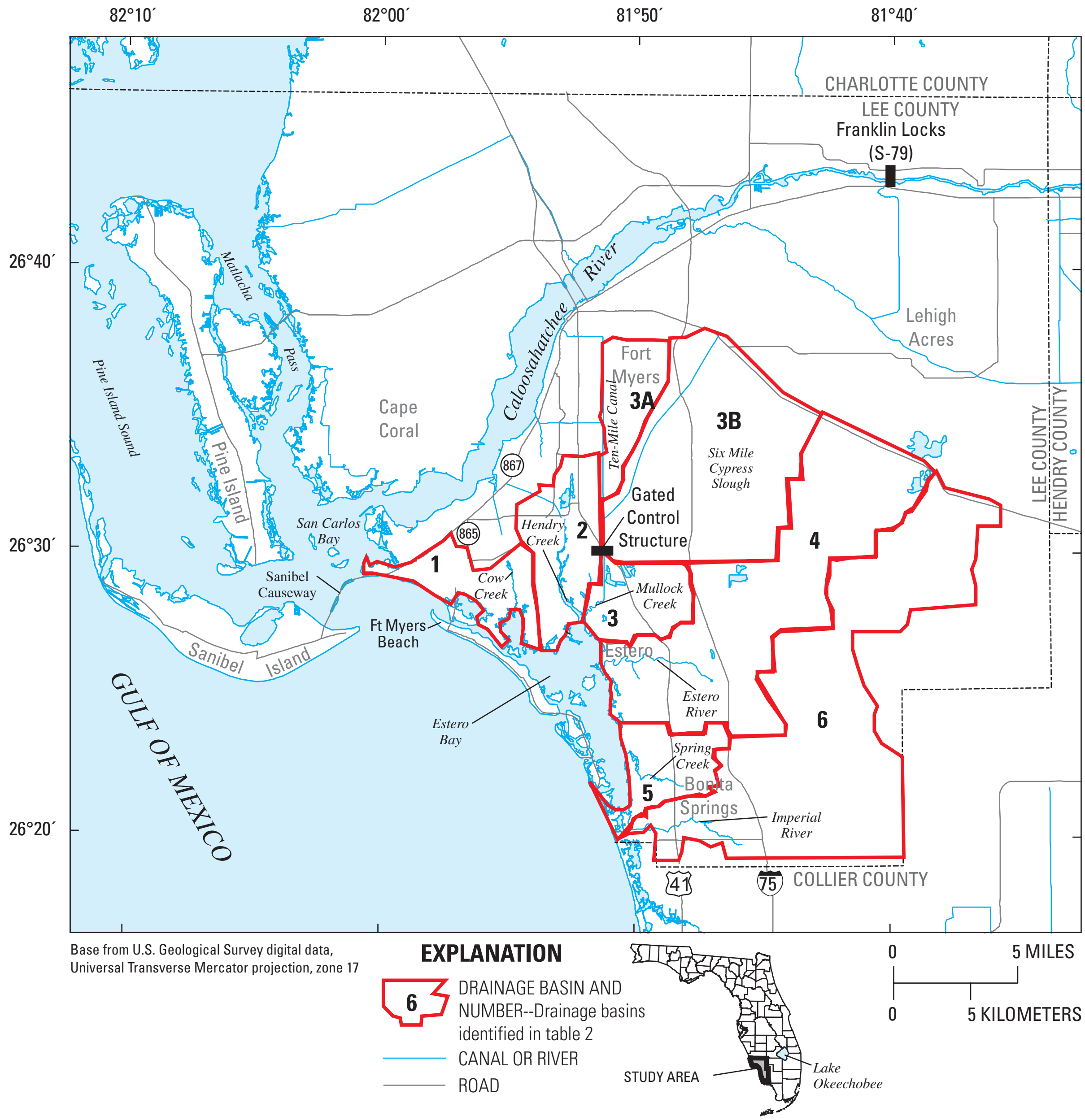


Figure 1. Location of Estero Bay, drainage basins feeding into the bay, and the regional setting, southwestern Florida.

Purpose and Scope

The purpose of this report is to describe the hydrodynamic characteristics and salinity patterns in Estero Bay and the methods used to collect, analyze, and quality assure the data from 11 hydrologic monitoring stations from October 2001 to September 2005. The types of data that were collected include water velocity (discharge), stage, salinity, water temperature, turbidity, suspended sediment concentration, and windspeed and direction. Salinity survey maps have been generated to describe the seasonal salinity patterns in and around Estero Bay for different periods from July 2002 to January 30, 2004. Hydrodynamic characteristics of the bay are described in accordance with the collected data and survey maps.

Description of Study Area

Estero Bay is located about 20 mi south of the city of Fort Myers, and encompasses 30 mi^2 (fig. 2). A series of barrier islands define the western edge of the bay, and these islands are separated by several passes, which permit the circulation of seawater from the Gulf of Mexico into the bay. Historically, these passes are ephemeral; they open and close as a result of longshore drift. All passes are now maintained to prevent future migration of the islands. Estero Bay extends southward 12 mi from Hurricane Pass to Imperial River (fig. 2). The bay has an average depth of 3 ft, but can reach a depth of 8 ft during high tides in some areas.

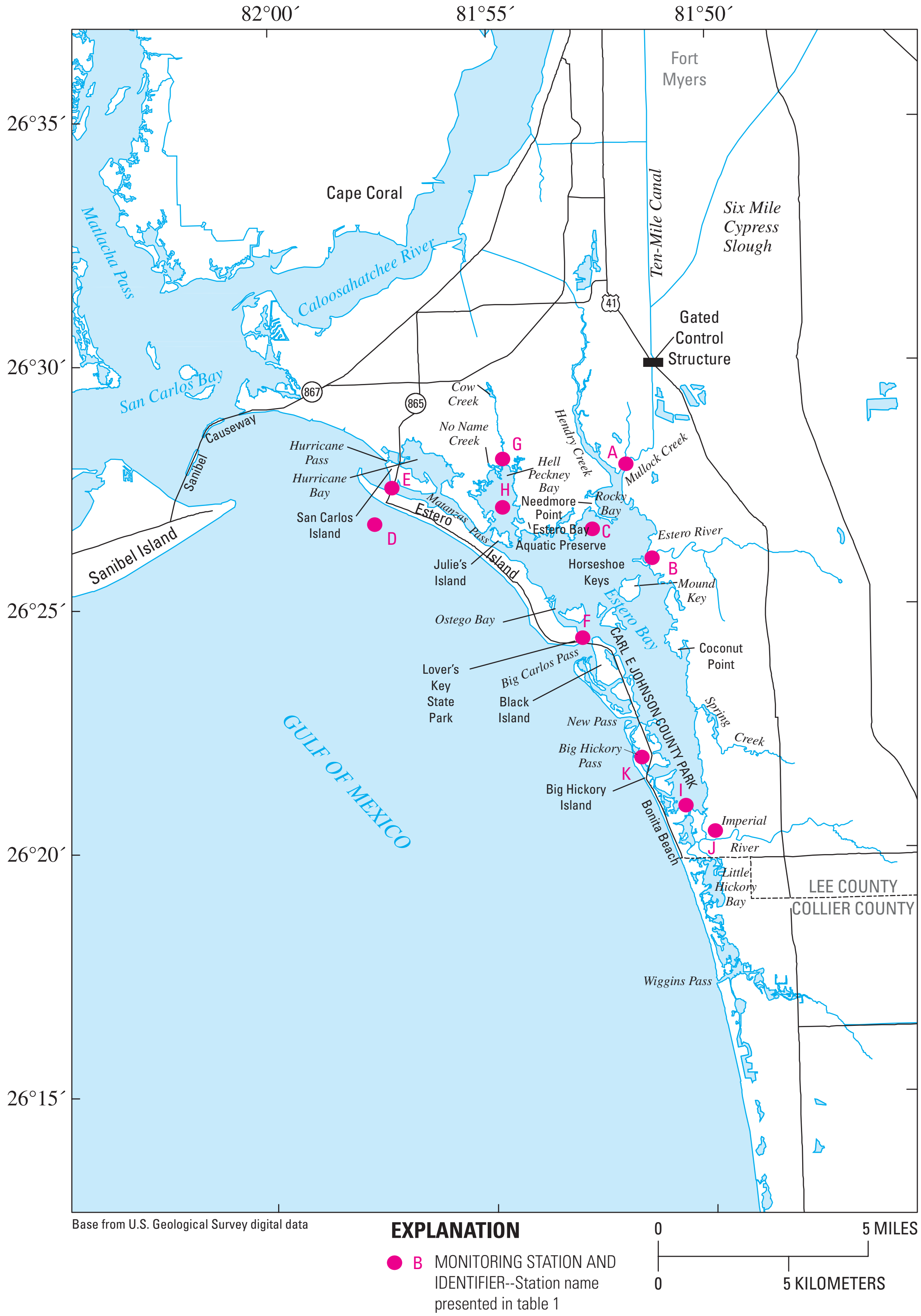


Figure 2. Study area and sampling locations.

Table 1. Monitoring stations and data collected for this study.

[USGS, U.S. Geological Survey. Data collected: 1, water velocity (discharge), in feet per second; 2, stage, in feet; 3, salinity, in parts per thousand; 4, water temperature, in degrees Fahrenheit; 5, turbidity, in nephelometric turbidity units; 6, suspended sediment concentration (SSC), in milligrams per liter; and 7, wind speed and direction, in miles per hour/degrees]

Station name	USGS station identifier	Latitude/ longitude	Period of record	Data collected	Figure 1 identifier	Location
Big Carlos Pass bridge at Estero Island,	262415081525000	26° 24′ 15″N 81° 52′ 50″W	Jan. 2002- Sept. 2005	1-4[1]	F	On southern wingwall of the drawbridge, located in the middle of the pass, in 20 ft of water
Big Hickory Pass bridge near Estero Island,	262136081512801	26° 21′ 36″N 81° 51′ 28″W	Oct. 2001- Sept. 2005	1-4[1]	K	On southern bank, 100 ft west of the bridge, in 3 ft of water.
Cow Creek east of Hurricane Bay bridge near Fort Myers Beach	262750081544400	26° 27′ 50″N 81° 54′ 44″W	Sept. 2002– Jan. 2004	3-4	G	On western bank at the mouth of Cow Creek, in 1 ft of water
Dog Key southeast of Matanzas Pass bridge near Fort Myers Beach	262657081544600	26° 26′ 57″N 81° 54′ 46″W	Sept. 2002– Jan. 2004	3-4	H	On western edge in 2 ft of water
Estero Bay near Horseshoe Keys	262620081523700	26° 26′ 20″N 81° 52′ 37″W	Oct. 2001- Sept. 2005	2-5, 7	C	In northern Horseshoe Keys, 50 ft south of channel marker 7, in 3 ft of water
Estero River near the mouth near Estero	02291610	26° 26′ 07″N 81° 51′ 02″W	Oct. 2001- Sept. 2005	1-6	B	On south bank, ½ mi. east of mouth, in 3 ft of water
Fish Trap Bay near Bonita Beach	262043081513200	26° 20′ 43″N 81° 50′ 35″W	Jan 2002- Sept. 2005	3-4	I	On eastern bank of pass, 50 ft north of Fishtrap Bay, in 2 ft of water.
Imperial River near mouth at Bonita Shores	02291510	26° 20′ 12″N 81° 49′ 53″W	Feb. 2002- Sept. 2005	1-6	J	On northern bank, ¼ mi east of mouth, in 4 ft of water
Matanzas Pass at Pass Marker G1	262740081584500	26° 27′ 40″N 81° 58′ 45″W	Apr. 2002- July 2004	2-4	D	1 mi offshore due west of Fort Myers Beach Pier in 30 ft of water (destroyed by Hurricane Charley on August 13, 2004)
Matanzas Pass bridge at Fort Myers Beach	262727081571300	26° 27′ 27″N 81° 57′ 13″W	Dec. 2001- Sept. 2005	1-4[1]	E	On western wingwall of bridge located in the middle of the pass, in 8 ft of water
Mullock Creek near the mouth near Estero	02291655	26° 27′ 50″N 81° 51′ 57″W	Dec. 2001- Sept. 2005	1-6	A	On western bank, 500 ft north of the mouth of Mullock Creek, in 4 ft of water

[1]Two salinity and water temperature probes in profile were used at Big Carlos Pass, Big Hickory Pass, and Matanzas Pass.

The Caloosahatchee River flows several miles north of Estero Bay into San Carlos Bay. The eastern section of the river is a managed canal, connecting the river to Lake Okeechobee. Lake Okeechobee is the second largest freshwater lake (730 mi^2)in the continental United States. The lake is contaminated mainly due to agricultural runoff (Doering and others, 2002). High levels of nutrients are discharged from the lake into the Caloosahatchee River, and this discharge is controlled at three locks managed by the U.S. Army Corps of Engineers. The westernmost lock, Franklin Locks (S-79), discharges freshwater into the Caloosahatchee River Estuary (fig. 1).

Sheetflow from the Caloosahatchee River is used to moderate the salinity in Estero Bay. Early inhabitants farmed the land on the banks of the river and stopped the overland flow from reaching the bay. The changes to the hydrology are now permanent (Tabb and others, 1974).

Estero Bay is a network of small interconnected bays, Hell Peckney Bay, Rocky Bay, Coconut Point, Ostego Bay, and others (fig. 2). These bays are partially separated from each other by mangrove islands, oyster beds, and mudflats. Hell Peckney Bay has two tributaries, Cow Creek and No Name and is linked with Matanzas Pass. A Pleistocene ridge running from Hendry Creek to Julie’s Island separates Hell

Figure 3. Matanzas Pass facing the Gulf of Mexico.

Figure 4. Big Carlos Pass facing Estero Bay.

Figure 5. Big Hickory Pass facing the Gulf of Mexico.

Peckney Bay from the rest of Estero Bay. Rocky Bay is located at the mouth of Hendry Creek and Mullock Creek. The western boundary of Rocky Bay is an oyster bar with a narrow channel, named Needmore Point. Coconut Point is separated from Estero River by a mudflat that extends from the mouth of Estero River to Mound Key. Ostego Bay is located near Big Carlos Pass, south of Julie's Island (fig. 2).

Water exchange between Estero Bay and the Gulf of Mexico occurs through six coastal inlets, which, from north to south, are: Hurricane Pass, Matanzas Pass, Big Carlos Pass, New Pass, Big Hickory Pass, and Wiggins Pass (fig. 2).

Hurricane Pass, near mouth, is 100 ft wide and 8 ft deep and exchanges water with San Carlos Bay and Hurricane Bay. The pass is less than 1 mi long and has both commercial fishing and recreational boat docks.

Matanzas Pass, at bridge (fig. 3), is 700 ft wide and 16 ft deep and exchanges water with San Carlos Bay and Hell Peckney Bay. The pass is 4 mi long and highly developed on one bank with a fleet of commercial shrimp boats on the other bank.

Big Carlos Pass, at bridge (fig. 4), is 1,600 ft wide and 20 ft deep and exchanges water with the Gulf of Mexico and three tributaries: Hendry Creek, Mullock Creek, and Estero River. The pass is less than 1 mi long with development of one bank and Lover's Key State Park on the other bank.

New Pass, at bridge, is 1,000 ft wide and 20 ft deep and exchanges water with the Gulf of Mexico and Spring Creek. The pass is less than 1 mi long and is between Lover's Key State Park and undeveloped Big Hickory Island (fig. 2).

Big Hickory Pass, at bridge (fig. 5), is 600 ft wide and 8 ft deep and exchanges water with the Gulf of Mexico and Imperial River. The pass is greater than 1 mi long and is between Big Hickory Island and Bonita Beach.

Wiggins Pass, near mouth, is 500 ft wide and 10 ft deep and exchanges water with the Gulf of Mexico and Imperial River. Even though this pass conveys a lot of water (based on reconnaissance), little reaches Estero Bay, because the inlet is 5 mi south of Imperial River.

Several major and minor tributaries convey fresh surface water into the bay. The tributaries are surrounded by urban development, agricultural areas, and wetlands. Each tributary contributes inflow proportional to the size of its associated drainage basin. Together, these tributaries drain about 170,000 acres of land. Table 2 lists the drainage basin size for each of the major tributaries, which are, in decreasing order of basin size: Imperial River, Mullock Creek (which includes Ten-Mile Canal and Six-Mile Cypress Slough), Estero River, Hendry Creek, Cow Creek, and Spring Creek. Each drainage basin is shown in figure 1. Artificial channels have increased surface-water discharge velocities into the estuary, which have reduced the estuary's water quality by increasing the nutrient load and decreasing salinity (Clark, 1987).

Cow Creek, near mouth, is 50 ft wide and 1 to 2 ft deep and flows into Hell Peckney Bay. Sheetflow from the Caloosahatchee River is used to drain into Cow Creek (fig. 1). Early settlers converted the land north of the creek into farmland and eliminated its hydraulic link to the Caloosahatchee River (Tabb and others, 1974).

Table 2. Drainage basins for the major tributaries of Estero Bay.

[Data from PBS&J, Inc. written commun. 1999]

Drainage basin	Size (acres)
Imperial River	54,000
Mullock Creek and canals	51,000
Mullock Creek (7,000)	
Ten-Mile Canal (9,000)	
Six-Mile Cypress Slough (35,000)	
Estero River	45,000
Hendry Creek	12,000
Cow Creek	8,000
Spring Creek	7,000

Figure 6. Mullock Creek looking upstream.

Hendry Creek, near mouth, is 300 ft wide and 1 to 3 ft deep and flows into Rocky Bay. This creek also received sheetflow from the Caloosahatchee River. Its northern headwaters lie south of the City of Fort Myers, at Lakes County Park (fig. 2). Weirs prevent the encroachment of saline surface water from entering the park's freshwater lakes.

Mullock Creek, near station, is 160 ft wide and 6 ft deep (fig. 6) and flows into Rocky Bay. Mullock Creek receives discharge from both Ten-Mile Canal and Six-Mile Cypress Slough. Discharge into the creek is controlled at a gated structure located along Ten-Mile Canal (fig. 2). The gated structure is designed to minimize the effects of flooding of nutrient-laden water on surrounding areas. Commercial and residential development is limited to the upper reaches of the creek.

Estero River, near station, is 120 ft wide and 4 ft deep (fig. 7) and flows into the southern portion of Rocky Bay. Even though the upper reaches of the tributary are developed, discharge is not restricted by weirs. Land areas adjoining the river near its mouth are protected from future development.

Spring Creek, near mouth, is 100 ft wide and 1 to 4 ft deep and discharges south of Coconut Point (fig. 2). A weir on the upper reaches prevents saltwater encroachment. The banks of this tributary have been extensively developed in recent years.

Imperial River, near station, is 250 ft wide and 10 ft deep (fig. 8) and a portion of the discharge flows to Big Hickory Pass and some discharge travels south away from Estero Bay. Weirs control freshwater discharge and prevent saltwater encroachment. Development extends from the mouth of the river to the upper reaches.

Figure 7. Estero River looking downstream.

Figure 8. Imperial River looking upstream.

Previous Studies

Previous studies of Estero Bay were published between 1971 and 1987. Tabb and others (1971) reported results of their preliminary inventory of the ecology of Estero Bay, and defined its general discharge characteristics. Tabb and others (1974) also published a more comprehensive summary of their study that describes baseline hydrologic, biological, and chemical characteristics in Estero Bay. They divided the bay into two hydrologic units (Hell Peckney Bay and Estero Bay), separated by the Pleistocene ridge that runs west of Hendry Creek through Julie's Island (fig. 1). Water quality in Hell Peckney Bay was affected by development, which reduced freshwater runoff and increased salinity. Tabb and others (1974) recorded a 4-ppt salinity range in Hell Peckney Bay and determined that the water mixed mainly with Matanzas Pass. Salinity ranged from 14 to 34 ppt in Rocky Bay, and its overall water quality was similar to that of other bays in the area.

Balough and others (1978) described the ramifications of the (then closed) Big Hickory Pass and the effects this closure had on water quality in Estero Bay. They found the closure had minimal impact on the estuary. Jones (1980) described the basic discharge characteristics, history, and morphology of Big Hickory Pass, New Pass, and Big Carlos Pass into Estero Bay. Clark (1987) described the water quality, circulation patterns, and sediment characteristics in Estero Bay and recommended immediate action to slow development around the bay.

Approach

Analyses were performed to relate salinity concentrations in Estero Bay to season and location and to relate salinity at Matanzas Pass Bridge to discharge at Franklin Locks (S-79). The analyses were conducted by utilizing multiple linear regression techniques, a statistical approach that determines the best-fit equation between one dependent variable and one or more independent variables. Regressions commonly are evaluated based on the value of certain statistical metrics, such as the P-value and the square of the correlation coefficient (R^2).

The level of significance for each independent variable in a regression model is measured by a dimensionless P-value. The smaller the P-value, the more likely the variable is significantly different (Moore and McCabe, 1993). For the purpose of this study, values exceeding 0.05 for independent variables were considered insignificant.

The correlation coefficient, R^2, is the proportion of variability in the dependent variable that is accounted for by the independent variables of the model. An adjusted R^2 value was used for evaluation in the regression analysis. Generally, an adjusted R^2 value greater than 0.89 is considered excellent and a value greater than 0.79 is considered good.

Acknowledgments

Peter Doering and Bob Chamberlain of the SFWMD coordinated the selection of station locations and helped ensure that the data collected for this study were as relevant as possible. An anonymous SFWMD researcher digitized a soils map (GIS coverage) that was base coverage for the salinity maps. Several USGS colleagues worked long hours to build the stations, make discharge measurements, and collect surface-water salinity measurements: Lars Sodervist, Craig Thompson, Gene Krupp, Linda Elligott, Brian Fagan, Bryan Ott. Special gratitude is extended to Jane Eggleston of the USGS Eastern Region Publishing Network for her guidance, assistance, and insight in bringing greater focus to this report.

Methods of Investigation

Continuous data and intermittent water samples were collected at permanently mounted stations located in Estero Bay and selected passes and tributaries. Continuous stage (water level), water velocity (for the purpose of measuring discharge), salinity, water temperature, turbidity, suspended sediment concentration, and wind measurements (speed and direction), were collected during specific periods between October 2001 and September 2005. Suspended sediment samples were collected in the tributaries near the continuous monitoring stations. In addition, synoptic salinity data were collected throughout the bay and tributaries on a seasonal basis between July 2002 and January 2004.

Monitoring Data Collection

All 11 stations built for this study obtained continuous salinity and water temperature data, 8 stations obtained stage data, 6 stations obtained water velocity data, 4 stations obtained turbidity data, and 1 station obtained windspeed and direction data (fig. 2 and table 1). Intermittent water samples for determination of suspended sediment concentration were collected at the mouths of Estero River (fig. 2, station B), Imperial River (fig. 2, station J), and Mullock Creek (fig. 2, station A). Data were logged internally at all 11 stations and at 6 stations and were transmitted by way of satellite telemetry. The types of data collected and methods of collection are discussed below. Data are summarized later in this report. Tables, including all data collected during this study, are presented online at *http://sofia.usgs.gov/exchange/estero_bay_ap/*

Three different methodologies were used to measured stage continuously at eight stations during the study. At six stations (Matanzas Pass, Big Carlos Pass, Big Hickory Pass, Mullock Creek, Estero River and Horseshoe Keys) stage was measured with an incremental shaft encoder inside an 8-in polyvinyl chloride stilling well. At the last two stations (Matanzas Pass Boundary and Imperial River), stage was measured with a submersible pressure transducer and an acoustic Doppler velocity meter (ADVM), respectively. On August 13, 2004, Hurricane Charley destroyed three stations: Big Carlos Pass, Big Hickory Pass, and Matanzas Pass boundary. The first two stations were rebuilt and stage was measured with a submersible pressure transducer; the third station was not rebuilt. The established datum for stage at six stations was NGVD 1929; two stations, Estero River and Matanzas Pass at Pass Marker (fig. 2, stations B and D), were set to an arbitrary datum. The datum at four stations—Matanzas Pass, Big Carlos Pass, Big Hickory Pass and Imperial River (fig. 2, stations E, F, J, and K)—were established using historic benchmarks and differential levels. The datum at two stations—Mullock Creek and Horseshoe Keys (fig 2, stations A and C)—were established using global positioning satellite (GPS) measurements.

Water velocity was measured continuously, using an ADVM, at six of the USGS monitoring stations. The stage and velocity measurements were used to compute continuous discharge at Big Carlos Pass, Big Hickory Pass, and Matanzas Pass (fig. 2, stations F, K, and E) and at Mullock Creek, Estero River, and Imperial River (fig. 2, stations A, B, and J).

Continuous discharge is a product of measured velocity, termed index velocity and stage-dependent cross-sectional area. Rated index velocity is determined by comparing mean velocity to index velocity using multiple linear regression techniques (table 3). Mean velocity was determined from discharge measurements made from an Acoustic Doppler Current Profiler. The ADCP measurements were made over the full tidal range, with periodic measurements made for verification purposes. The ADCP was also used to create the stage-dependent cross-sectional area. Ebb tide or seaward flow of water is considered positive discharge and flood tide is considered negative discharge. Estimated monthly net discharge is the mean of all 15-minute values (computed unit values) for the month.

Conductance and water temperature were recorded by using water-quality monitoring probes. At Matanzas Pass, Big Carlos Pass, and Big Hickory Pass, the probes were placed at two different depths to determine if the water column was stratified. The probes automatically compute salinity based on conductance and water temperature (Greenberg, 1995). Salinity values are accurate to ±1.0 percent, or ±0.1 ppt, whichever is greater. Water temperature instrument accuracy was ±0.15 percent of the reading (Yellow Springs Incorporated, undated). Data for continuous monitors were collected and processed in accordance with USGS protocols (Wagner and others, 2000).

Turbidity is a quantification of the cloudiness of water, which is a function of suspended matter as measured by a turbidity probe in formazin nephelometric units. The turbidity probe has an optical 90º scatter, a mechanical cleaning wiper, and an accuracy of ±5 percent of the reading or two FNU (formazin nephelometric units) whichever is greater (Yellow Springs Incorporated, undated). These probes are susceptible to biofouling that reduces the quality of the turbidity record by producing erratic spikes and drifts. The biofouling problem was greatest when salinity exceeded 15 ppt and water temperature exceeded 25 °C. Turbidity measurements made during this study were not used in the analysis due to frequent errant data and low suspended matter, which approached the limitations of the instrument (Patino and Byrne, 2004).

Suspended sediment samples were collected at stations Mullock Creek, Estero River and Imperial River (fig. 2) with turbidity probes and ADVMs. The purpose of this sampling was to determine the effectiveness of measuring turbidity, as a surrogate for suspended sediment concentration, in estuarine water. Point samples were collected near the station instrumentation (Patino and Byrne, 2004) using a horizontal Van Dorn bottle (Wildlife Supply Company, 1999). Depth-integrated samples were collected near the instrumentation using a DH-78 sampler (U.S. Interagency Committee on Water Resources, Subcommittee on Sedimentation, 1965) and in cross section using the equal discharge increments (EDI) method (Guy, 1970). Suspended sediment concentrations were determined by the USGS sediment laboratory at the USGS Water Science Center in Kentucky using methods of Guy (1969).

Table 3. Index velocity ratings for discharge stations used for this study.

[V, mean velocity; Vi, index velocity]

Site name	Figure 1 identifier	Period of record	Rating equation	Coefficient of determination
Big Carlos Pass	F	06/30/03 - 08/13/04	V=0.887Vi – 0.133	0.981
Big Hickory Pass	K	10/01/01 - 08/13/04	V=0.725Vi – 0.004	.989
		11/03/04 - 09/30/05	V=1.136Vi + 0.096	.989
Estero River	B	10/01/01 - 09/30/05	V=0.898Vi – 0.043	.985
Imperial River	J	01/01/02 - 09/30/05	V=0.960Vi – 0.0	.960
Matanzas Pass Bridge	E	02/01/02 - 09/30/05	V=0.662Vi + 0.004	.993
Mullock Creek	A	10/01/01 - 09/30/05	V=0.779Vi – 0.096	.995

Figure 9. Flow-through chamber, for salinity survey, mounted to the transom of the boat.

A wind sensor was installed at the Horseshoe Keys station (station C, fig. 2). This sensor was positioned 18 ft above land surface, and was used to continuously measure windspeed and direction from October 2001 to September 2005. The windspeed sensor uses a three-cup anemometer to produce a frequency of closures proportional to windspeed and a balanced anodized aluminum vane assembly to derive wind direction (Met One Instruments, 1996). Using this instrument, windspeed accuracy is ±0.25 mi/hr at winds below 22.7 mi/hr, and ±1.1 percent at winds above 22.7 mi/hr; wind direction accuracy is ±4.0^{o}. These windspeed records were intended to provide further information in characterizing the hydrodynamics in Estero Bay. However, this instrument failed to read values in excess of 327^{0} during several months of the study and recorded more than 1 year of erroneous values due to electronic failure. Therefore, most of the results of the measurements recorded by this instrument were inconsistent and considered unreliable.

Salinity Surveys and Map Analysis

Surface-water salinity and temperature were measured throughout Estero Bay, its tributaries, San Carlos Bay, and the mouth of the Caloosahatchee River by boat with a water-quality probe mounted in a flow-through chamber 4 in. below the transom (fig. 9). Synoptic surveys were conducted frequently (14 times) and over a range of conditions from July 24, 2002, to January 30, 2004. A data logger was used to record the salinity, water temperature, and GPS location for each of the surveys. Two boats were used to reduce the time (about 5 hours) that was required to collect 5,000 data points for each survey (fig. 10).

The salinity data from each survey were mapped by converting the georeferenced data to a geographic information system (GIS) layer to be added to a base map (Environmental Systems Research Institute, 1998). A base map is a GIS layer with geographic features such as islands, rivers, and roads, referenced to latitude and longitude. The salinity GIS layer, with a color scale representative of the salinity range of the 14 surveys, is added to the base map using computer software by Environmental Systems Research Institute, Inc. (Environmental Systems Research Institute, 1998). To interpolate data between measured points, the inverse distance weighted (IDW) method was used to estimate salinity in the areas not directly measured. The IDW method relies on the assumption that the closest point is the best estimator for the unknown value and assigns the most weight to the closest point. In rare instances due to hydrologic boundaries, such as islands, mudflats, and riverbanks, the closest point is a poor predictor of salinity. Line barriers (described further in Environmental Systems Research Institute, 1998) are then needed to prevent the interpolation of data across the hydrologic boundaries (fig. 11).

Four areas of Estero Bay were selected to determine the presence of statistical variability of salinity in the embayments: Rocky Bay and Coconut Point were selected to represent the conditions near the tributaries, and Matanzas Pass and Ostego Bay were selected to represent the conditions near the passes (fig. 2). Seasonality was represented by data from 11 of the 14 surveys. The dates of the surveys for each of the areas are shown in table 4. Note the spring period had only one value; therefore, the springtime results may not be representative.

Hydrodynamic and Salinity Characteristics in Estero Bay

The hydrodynamic and salinity characteristics of Estero Bay are defined by the mixing of saltwater from the Gulf of Mexico, freshwater from the tributaries, overland sheetflow, rainfall, and export from evaporation. The characteristics were primarily determined by measuring discharge and salinity at six stations—three stations at passes connecting Estero Bay to the Gulf of Mexico (Matanzas Pass, Big Carlos Pass and Big Hickory Pass) and three stations at the mouths of tributaries (Mullock Creek, Estero River, and Imperial River). The three passes not measured (Hurricane Pass, New Pass, and Wiggins Pass) also influence the hydrodynamic and salinity characteristics of Estero Bay, but their direct influence on Estero Bay can only be estimated. In addition, freshwater import from numerous tributaries, overland sheetflow, rainfall, and export from evaporation, were not measured for this study, so their influence can only be estimated. Although turbidity and wind are typically useful tools to describe hydrodynamic characteristics, various sampling problems affected the reliability of these measurements.

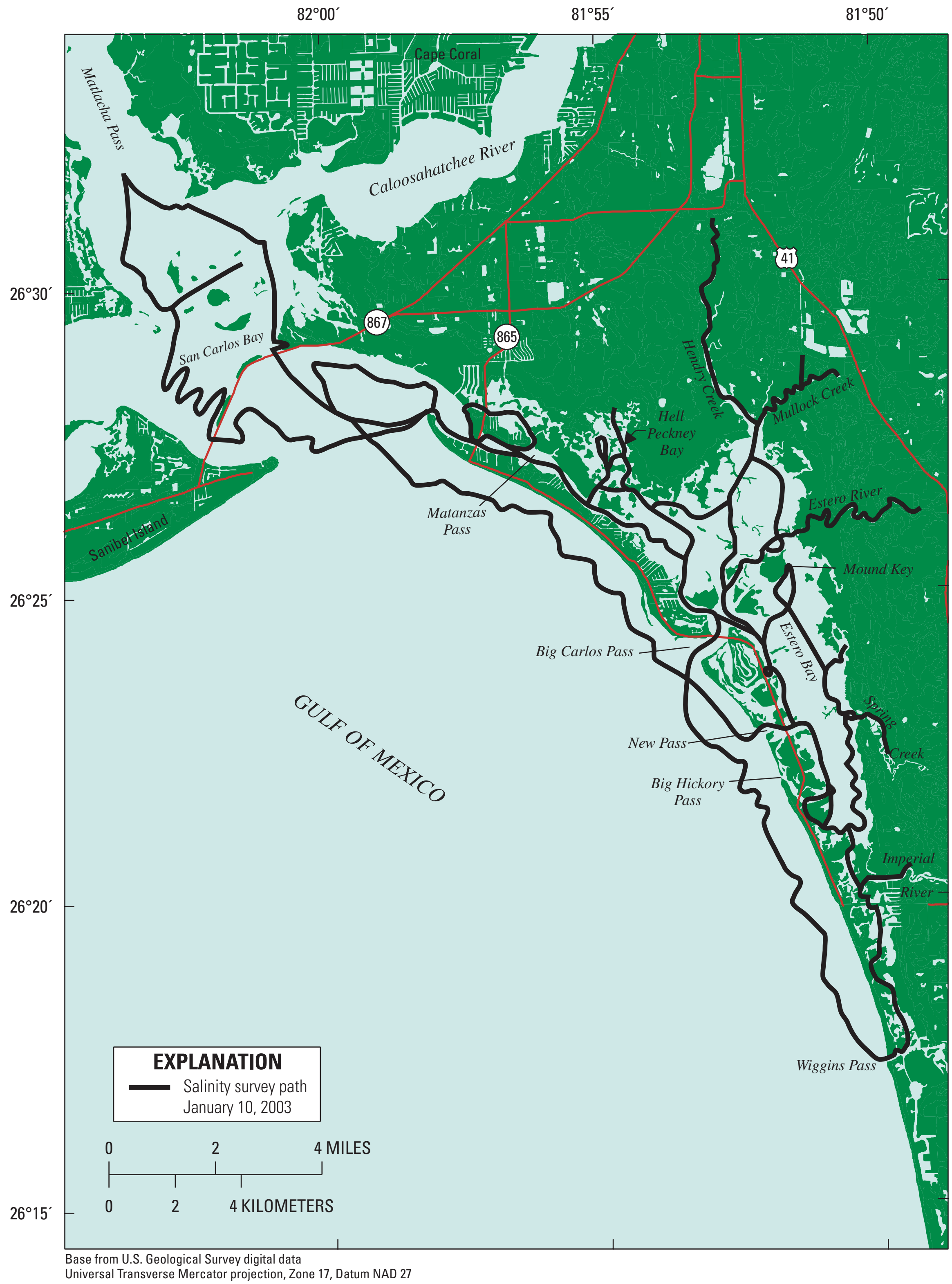


Figure 10. Boat path for the salinity survey, October 10, 2003.

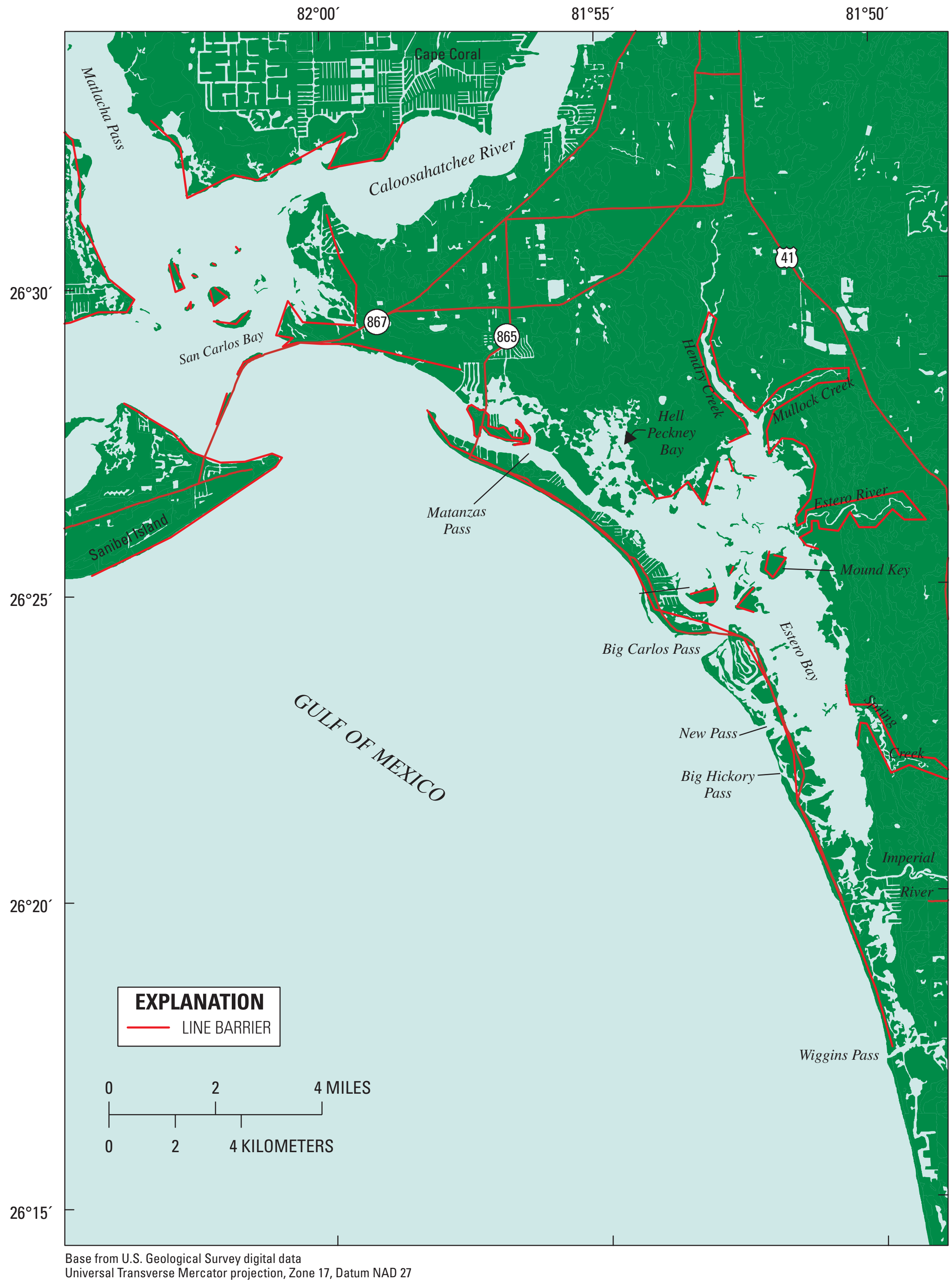


Figure 11. Line barriers in and around Estero Bay.

Table 4. Dates used to represent seasons for salinity surveys in Estero Bay.

Summer	Fall	Winter	Spring
08-19-02	11-25-02	01-10-03	06-03-03
09-13-02	10-10-03	03-07-03	
07-23-03	12-05-03	01-30-04	
08-29-03			

Discharge and Salinity at Passes and Tributaries

Big Carlos Pass is a dominant conveyance to Estero Bay; tidal discharge through this pass is three times greater than Matanzas Pass and 15 times greater than Big Hickory Pass. The average daily discharge ranged from about 35,000 to -34,000 ft^3/s (table 5). Water from Big Carlos Pass is exchanged with several tributaries (including Hendry Creek, Mullock Creek and Estero River) and numerous bays. Net discharge was positive during the wet season from June to November and negative during the dry season from December to May (fig. 12). Direction of flow at this pass is governed by tributary discharge.

At Big Carlos Pass, salinity was lowest during the wet season from June to November and highest during the dry season from December to May. Generally, salinity ranged from 25 to 35 ppt (fig. 13). As with all the passes measured, the water column was well mixed and there was no vertical stratification in salinity.

Matanzas Pass failed to exhibit a seasonal discharge pattern and mean monthly discharge was consistently negative (fig. 12). Negative discharge suggests that tributary discharge from Cow Creek and No Name Creek is insignificant. The average daily discharge at Matanzas Pass ranged from about 10,800 to -11,200 ft^3/s (table 5). Generally, the water discharging into Matanzas Pass extends to the Pleistocene ridge at Julie's Island, and to Cow Creek and No Name Creek in Hell Peckney Bay. Discharge at this pass is governed by external forces, mainly the Caloosahatchee River. The impact of the Caloosahatchee River discharge exceeds the impact from Cow Creek and No Name Creek.

Matanzas Pass is less saline than Big Carlos Pass and Big Hickory Pass due to the water discharging into Matanzas Pass. Salinity ranged from 22 to 34 ppt (fig. 13). Freshwater discharge from the Caloosahatchee River reduces the salinity in the Gulf of Mexico near the mouth of Matanzas Pass. It was determined by multiple linear regression ($R^2 = 0.48$) that Caloosahatchee River (Franklin Locks) discharge is negatively correlated with salinity at Matanzas Pass (fig. 14.).

Big Hickory Pass is a minor inlet that exchanges water with Imperial River. The average daily discharge ranged from about 2,200 to -2,900 ft^3/s (table 5). This inlet lacks a seasonal trend in discharge, and the general discharge trend is negative net discharge. Tributary discharge has limited influence at this pass (fig. 12). Typical salinity values ranged from 26 to 36 ppt (fig. 13).

Hurricane Pass, New Pass, and Wiggins Pass are also points where water from the Gulf of Mexico can exchange with Estero Bay. Hurricane Pass is adjacent to Matanzas Pass and receives water from a nearby canal and Hurricane Bay. Discharge from this pass appears to be less than Matanzas Pass. New Pass is located between Big Hickory Pass and Big Carlos Pass and appears to discharge more water than Big Hickory Pass and less water than Big Carlos Pass. The water from New Pass is exchanged with Spring Creek and the surrounding bays. Wiggins Pass exchanges water with Imperial River; due to its location, however, this pass has a minor effect on conditions in Estero Bay.

Imperial River, Mullock Creek, and Estero River all followed a similar seasonal trend in which discharge is positive in the wet season and negative in the dry season. Discharge to and from Mullock Creek ranged from 680 to -700 ft^3/s (table 5), which is two times as great as Estero River (about 330 to -370 ft^3/s) and three times as great as Imperial River (about 190 to -180 ft^3/s). Average negative net flow in Mullock Creek and Estero River (fig. 15) may be a result of wind-driven events coupled with increased overland discharge. Salinity was lowest during the summer (July-September) and highest during fall (November-December) and spring (March-May). Annually, salinity typically ranged from 5 to 25 ppt, and generally decreased upstream from the monitoring stations. Mullock Creek was less saline than Estero River (fig. 16) due in part to the contribution of freshwater discharge from Ten-Mile Canal and Six-Mile Cypress Slough. Imperial River was the least saline system of all three tributaries. This river receives regulated discharge and is also isolated from the passes.

Table 5. Tidal discharge recorded at selected tributaries and passes in Estero Bay.

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

Name	Ebb and flood tide		Date of extreme maximum discharge
	Average daily maximum discharge (ft^3/s)	Extreme maximum discharge (ft^3/s)	
Big Carlos Pass	35,154	75,000	09-06-02
	-34,081	-106,000	03-16-03
Big Hickory Pass	2,187	4,710	12-26-04
	-2,862	-11,900	04-12-04
Estero River	331	645	10-01-03
	-372	-1,020	09-26-04
Imperial River	190	951	09-20-02
	-181	-1,090	09-24-04
Matanzas Pass	10,762	35,100	08-13-04
	-11,157	-59,400	08-13-04
Mullock Creek	677	2,170	09-06-02
	-701	-1,640	02-27-05

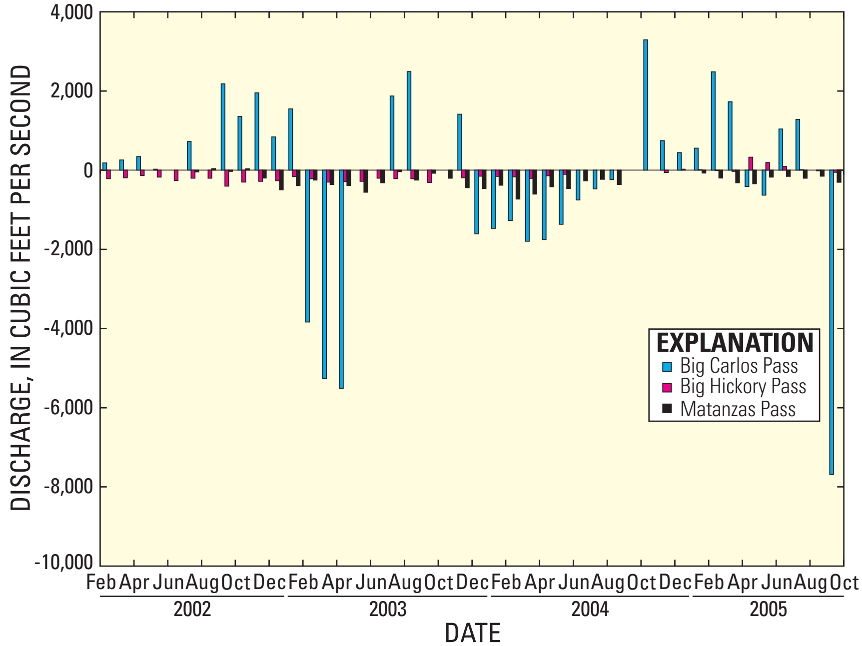


Figure 12. Mean monthly discharge at selected passes during the study period.

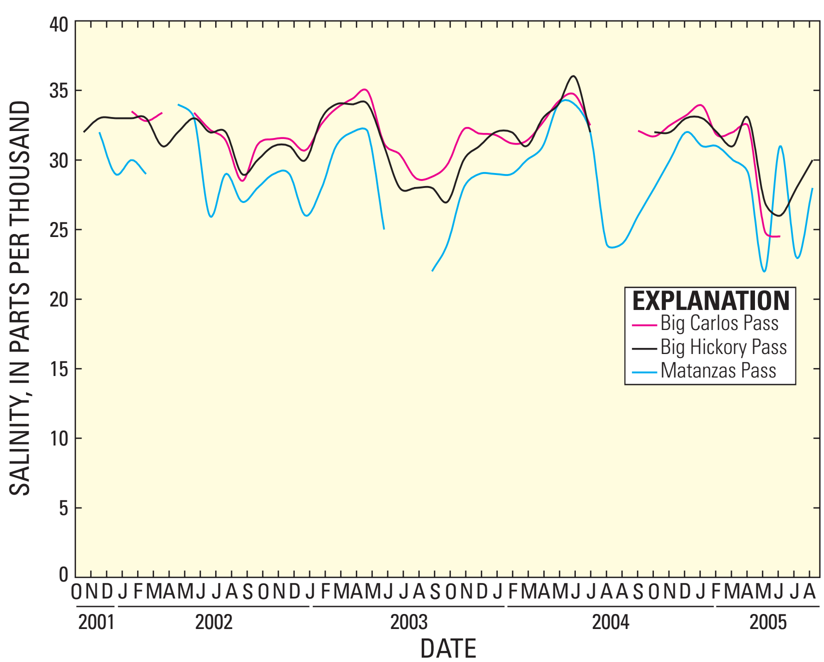


Figure 13. Mean monthly salinity at selected passes during the study period.

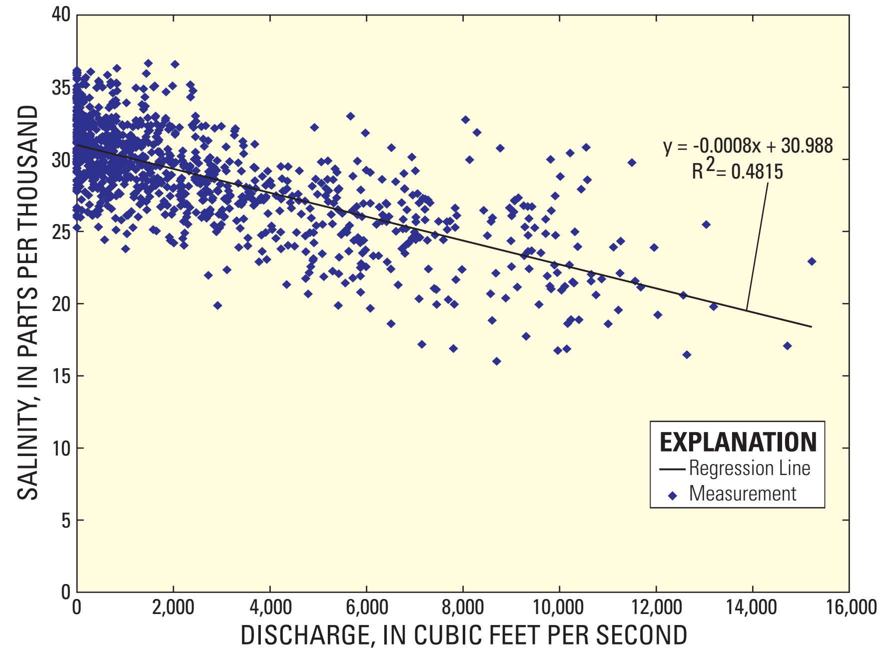


Figure 14. Relation between S-79 discharge and Matanzas Pass salinity.

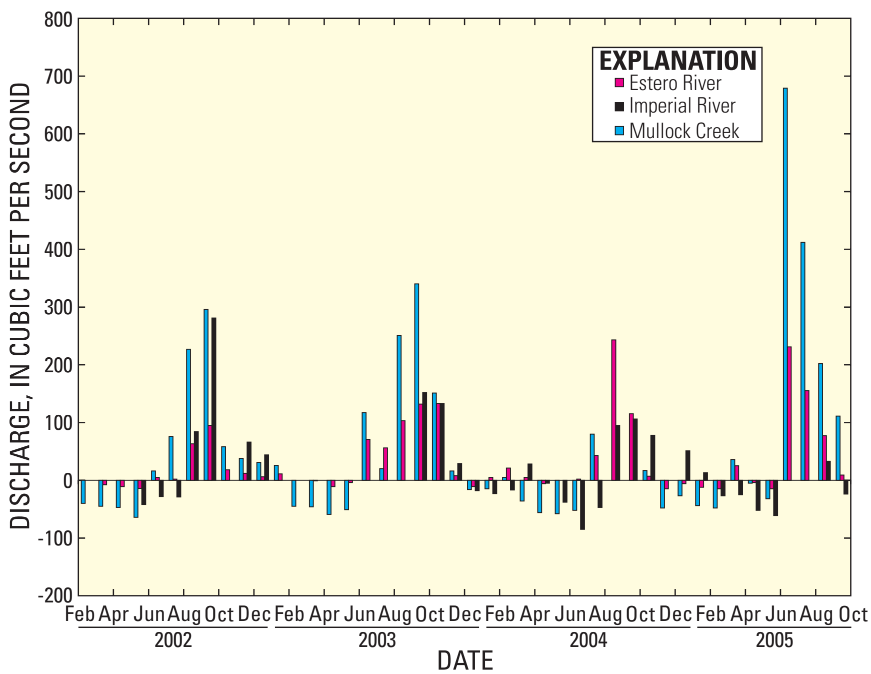


Figure 15. Mean monthly discharge at selected tributaries during the study period.

Turbidity and Suspended Sediment Concentration

The comparison of turbidity and suspended sediment concentration in streams with low suspended sediment concentrations offers limited scientific information. The suspended sediment concentration values typically detected at the study stations were near the lower instrument detection limits. Greater suspended sediment concentration would, therefore, be necessary to establish a strong relation with turbidity in this tidal environment. The adjusted R^2 value of 0.51 for turbidity to suspended sediment concentration at Mullock Creek suggests that turbidity still is a promising surrogate for suspended sediment concentration (fig. 17); however, the correlation is poor due to unexplained variances.

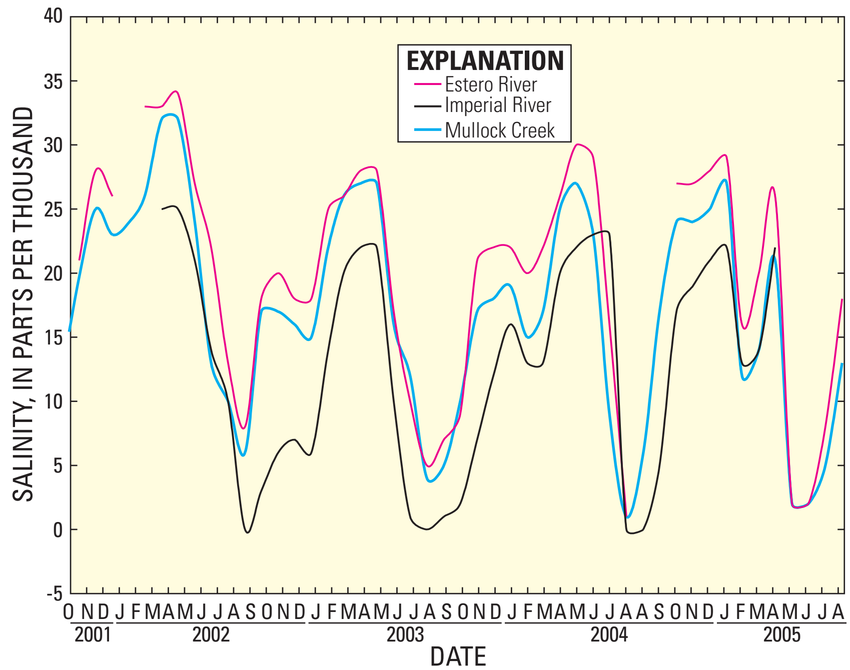


Figure 16. Mean monthly salinity at selected tributaries during the study period.

Windspeed and Direction

Average monthly windspeed and direction, as measured at the Horseshoe Keys station (fig. 2 and table 1, station C), ranged from 8.0 to 9.4 mi/hr, blowing from the north-northwest (table 6). Daily oscillations in windspeed are typical and often exceed 20 mi/hr.

Salinity Patterns in Estero Bay

Salinity maps, which were prepared based on the periodic salinity surveys, provide a means of describing the variability of salinity within the smaller embayments and throughout Estero Bay. Hydrologic barriers, such as the Pleistocene ridge from Hendry Creek to Julie's Island, mangrove islands, mudflats and oyster bars (fig. 18), and anthropogenic changes affect salinity patterns and help create small distinct bays, each with its own salinity range. The survey data can also be used to describe salinity patterns within the small embayments and near the mangrove fringe (figs. 19a-n).

The inner bays have varying salinity conditions dependent on proximity to tributaries and passes and also the location of hydrologic barriers. Four areas of Estero Bay were selected to demonstrate some of the varying salinity conditions, namely, Rocky Bay, Coconut Point, Ostego Bay and Matanzas Point (fig. 2). Data from 11 of the salinity surveys were compared to determine if there were statistically significant differences throughout the year (fig. 20).

Rocky Bay is the least saline area of Estero Bay. This is due in part to the oyster bar present at Needmore Point. This oyster bar constricts outflow from Hendry Creek and Mullock Creek, and redirects the flow southward toward Estero River and Mound Key (figs. 19a-c, e-f, j-l, and n). Needmore Point also redirects the discharge from Big Carlos Pass, and thus, reduces direct saltwater exchange between Big Carlos Pass and Rocky Bay.

Coconut Point, is separated from Rocky Bay by a mud flat that extends from the mouth of Estero River to Mound Key and prevents Estero River discharge from mixing with this embayment. Therefore, the Coconut Point area is distinctly different from Rocky Bay, because its salinity is only affected by overland flow and water exchange with New Pass (figs. 19b-f, k-l, and n).

Ostego Bay is located along Estero Island, southeast of Julie's Island and southwest of Needmore Point. This bay is isolated hydrologically from Matanzas Pass and Rocky Bay by the previously mentioned Pleistocene ridge and Needmore Point. Ostego Bay receives little tributary discharge, and its salinities are typically higher than those of Matanzas Pass and more similar to salinities in Big Carlos Pass (figs. 19a, e, and h).

Matanzas Pass salinity, as previously mentioned, is governed by discharge from the Caloosahatchee River. Little natural overland tributary discharge reaches the pass and the water circulates around Hell Peckney Bay (figs 19a, and i-j).

Comparison of the bays reveals significant differences in salinity throughout these bays. Rocky Bay was least saline in the winter, summer and fall. Matanzas Pass was least saline in the summer. Except for winter, Matanzas Pass was less saline than Ostego Bay.

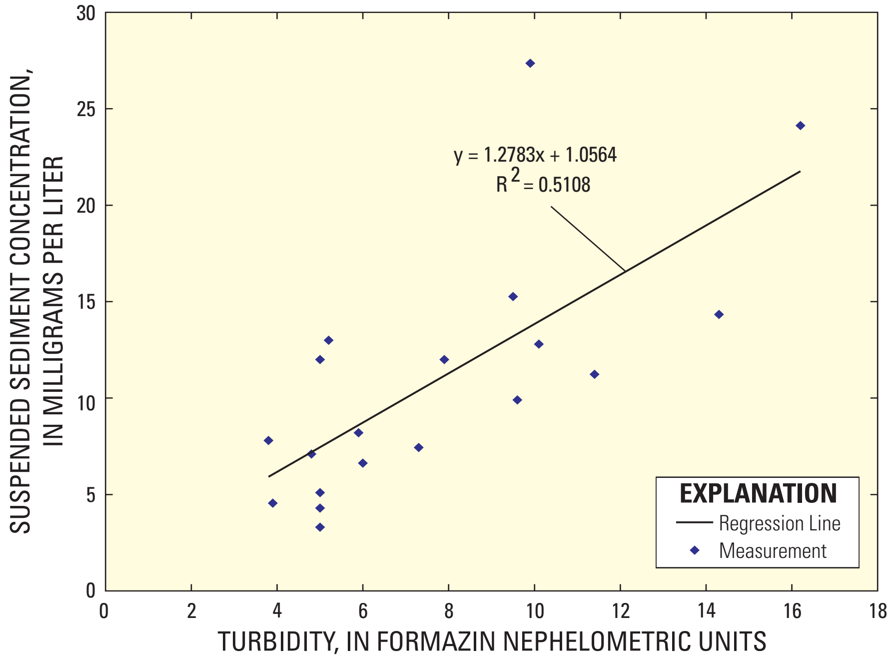
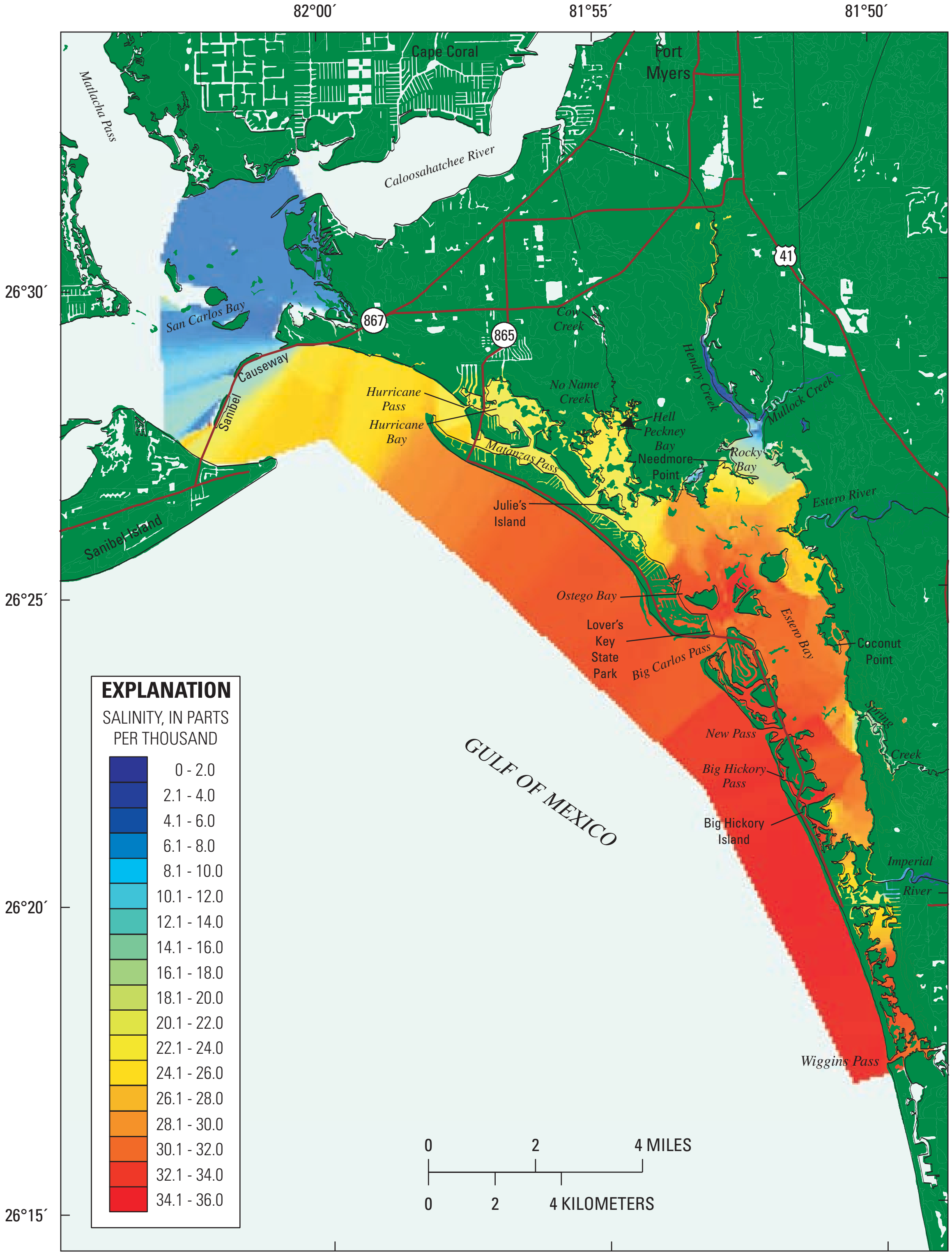


Figure 17. Relation between suspended sediment concentration and turbidity at Mullock Creek.

Table 6. Average monthly water temperature and wind measurements in Estero Bay near Horseshoe Keys.

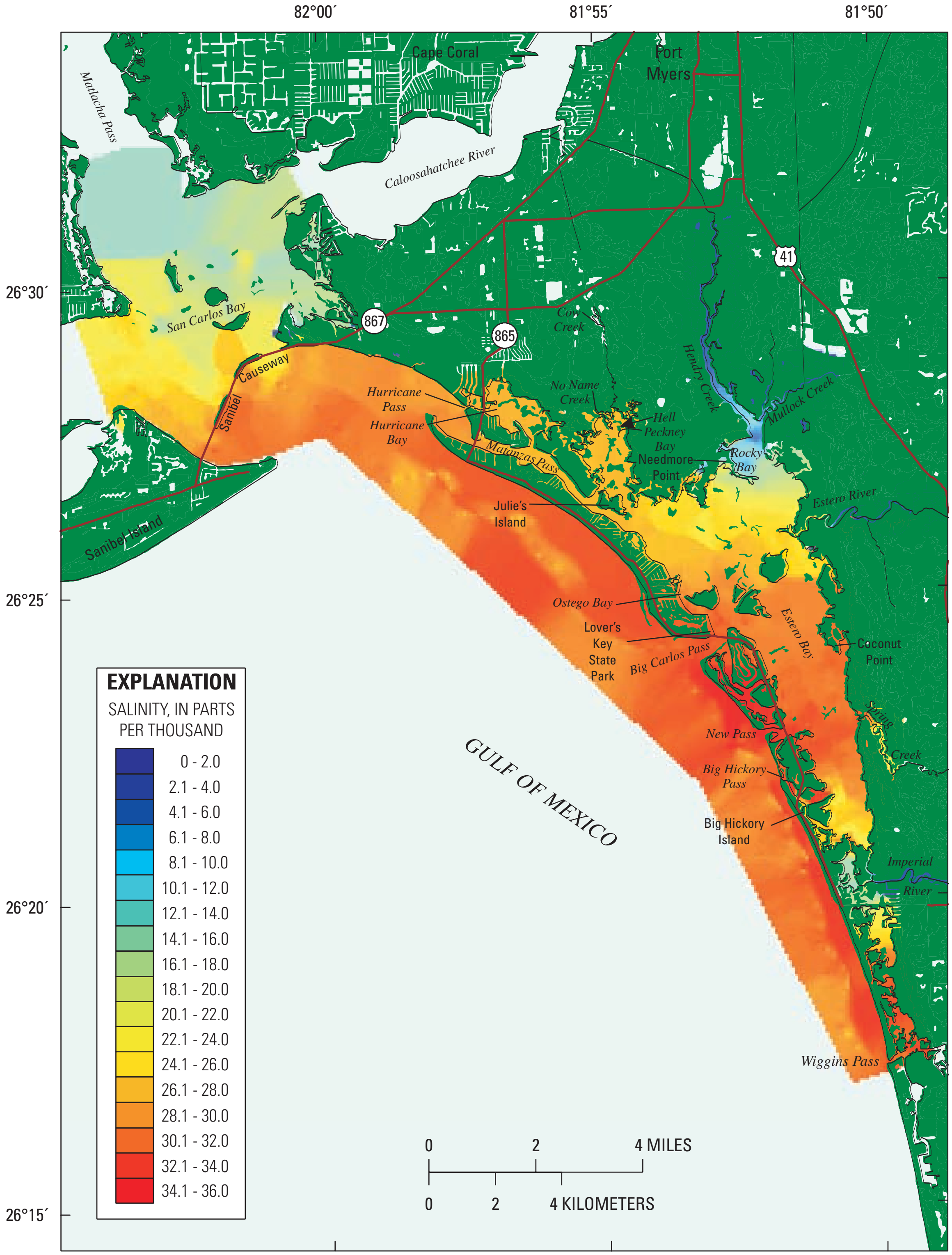
Month	Water temperature (degrees Celsius)	Average wind direction	Average windspeed (mi/hr)
January	18.0	North	8.0
February	20.2	North	8.4
March	21.8	Northwest	9.4
April	24.9	North	9.3
May	28.2	Northwest	8.8
June	29.4	Northwest	8.1
July	30.9	Northwest	8.2
August	30.7	Northwest	7.5
September	29.6	Northwest	9.2
October	27.9	Northwest	8.1
November	23.4	West	8.5
December	19.7	Northwest	8.2

Figure 18. Large mudflat near the mouth of Mullock Creek.



Base from U.S. Geological Survey digital data
Universal Transverse Mercator projection, Zone 17, Datum NAD 27

Figure 19a. Salinity patterns in Estero Bay, July 24-26, 2002.



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Universal Transverse Mercator projection, Zone 17, Datum NAD 27

Figure 19b. Salinity patterns in Estero Bay, August 19, 2002.

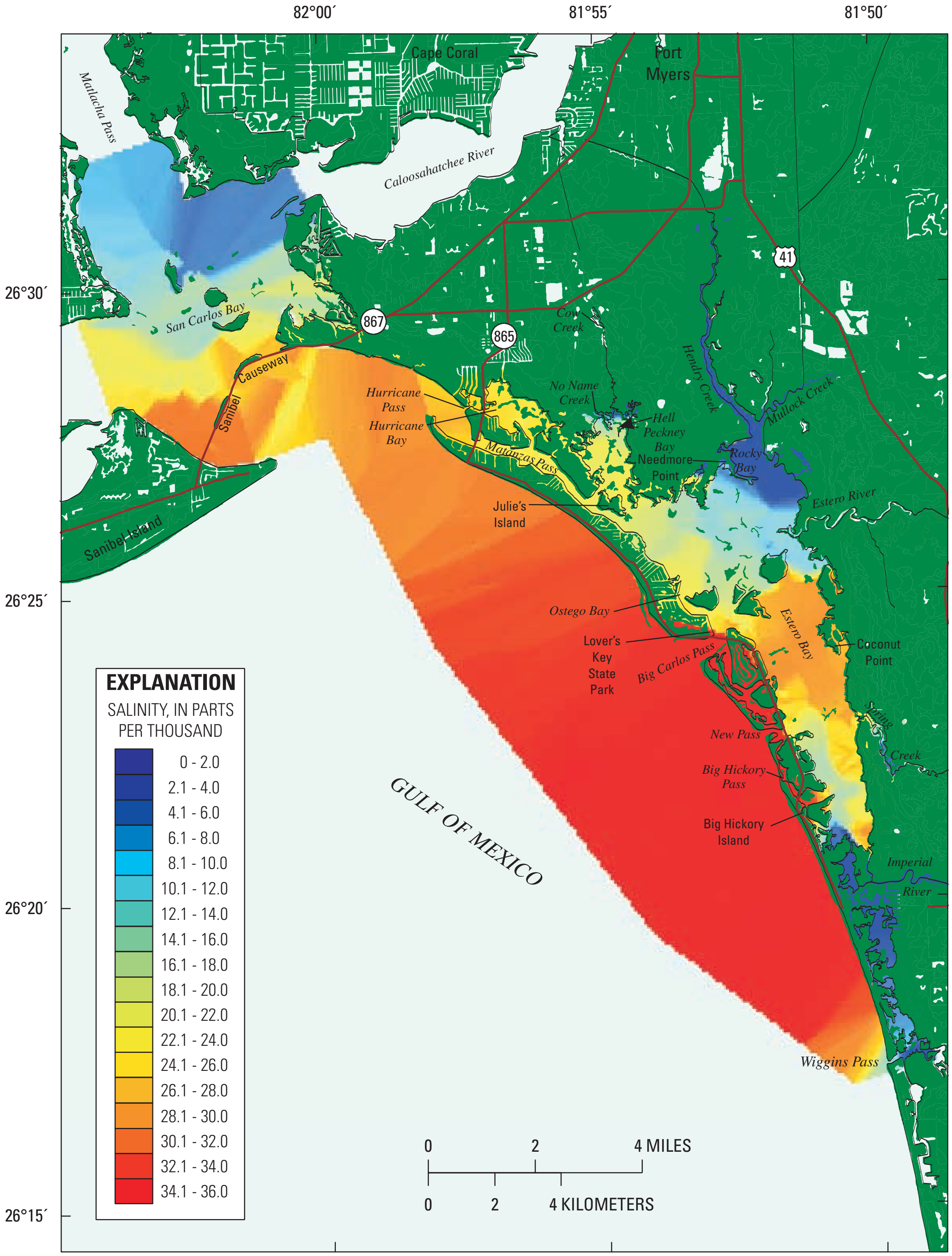

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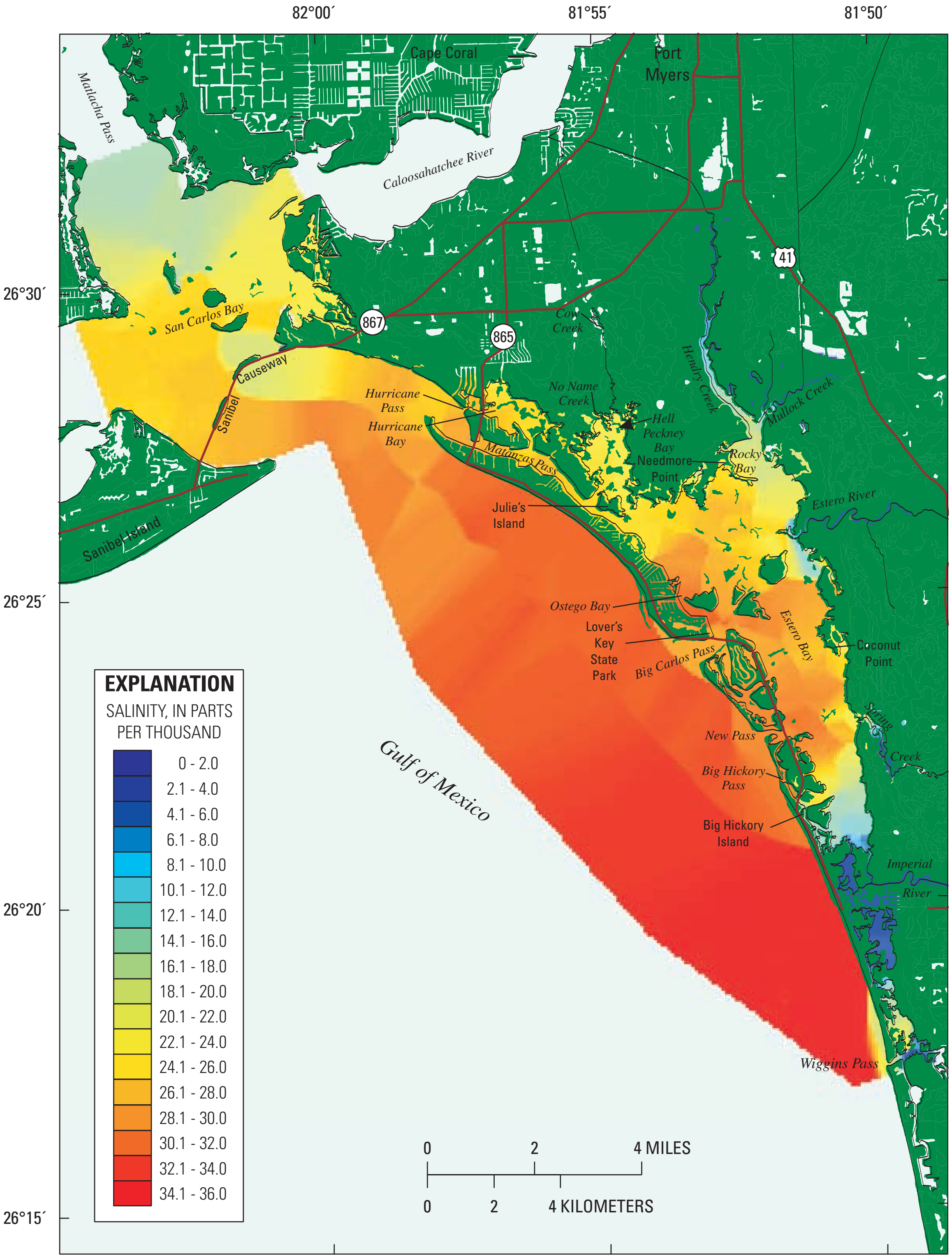
Figure 19c. Salinity patterns in Estero Bay, September 13, 2002.



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Universal Transverse Mercator projection, Zone 17, Datum NAD 27

Figure 19d. Salinity patterns in Estero Bay, October 16, 2002.

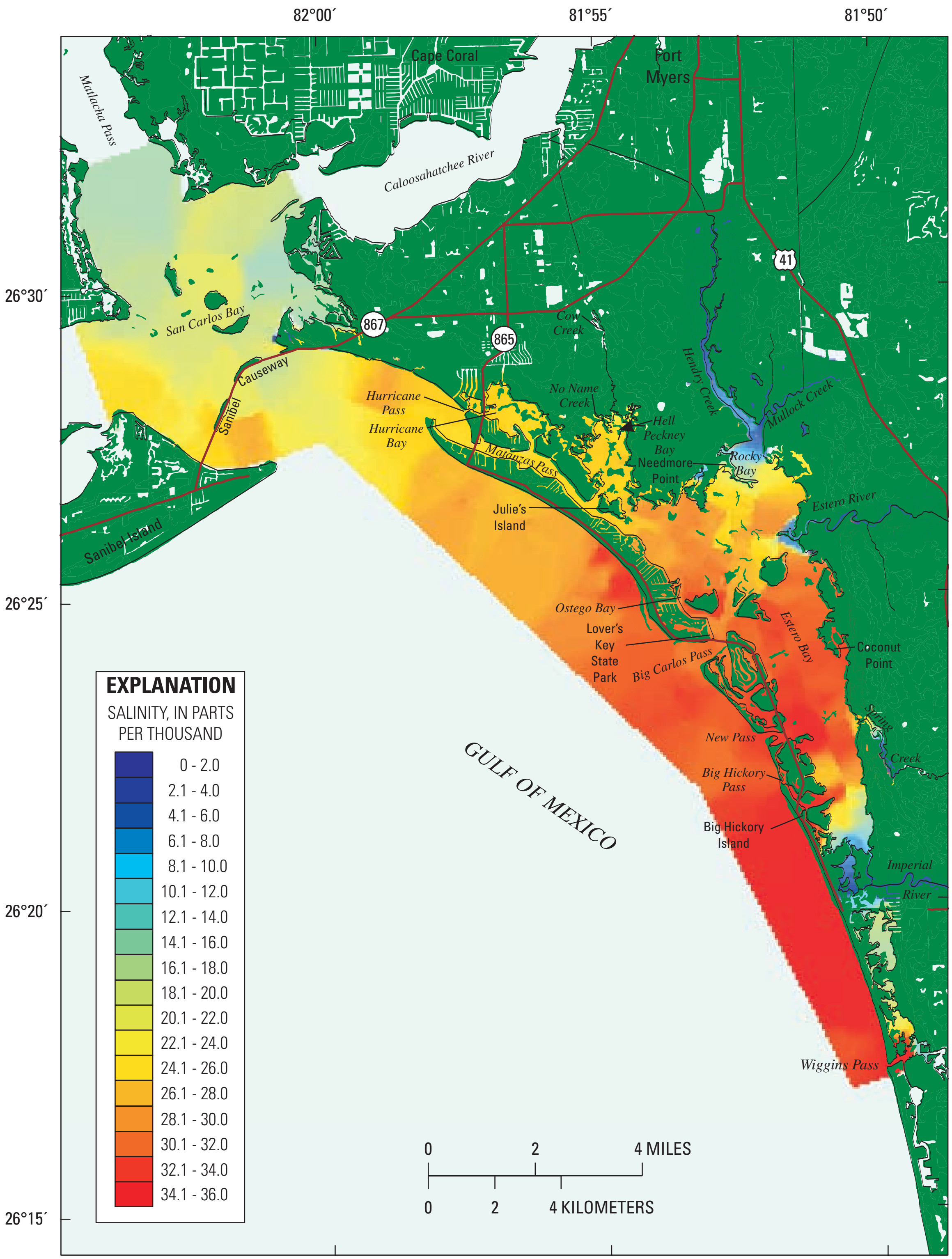

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Figure 19e. Salinity patterns in Estero Bay, November 25, 2002.

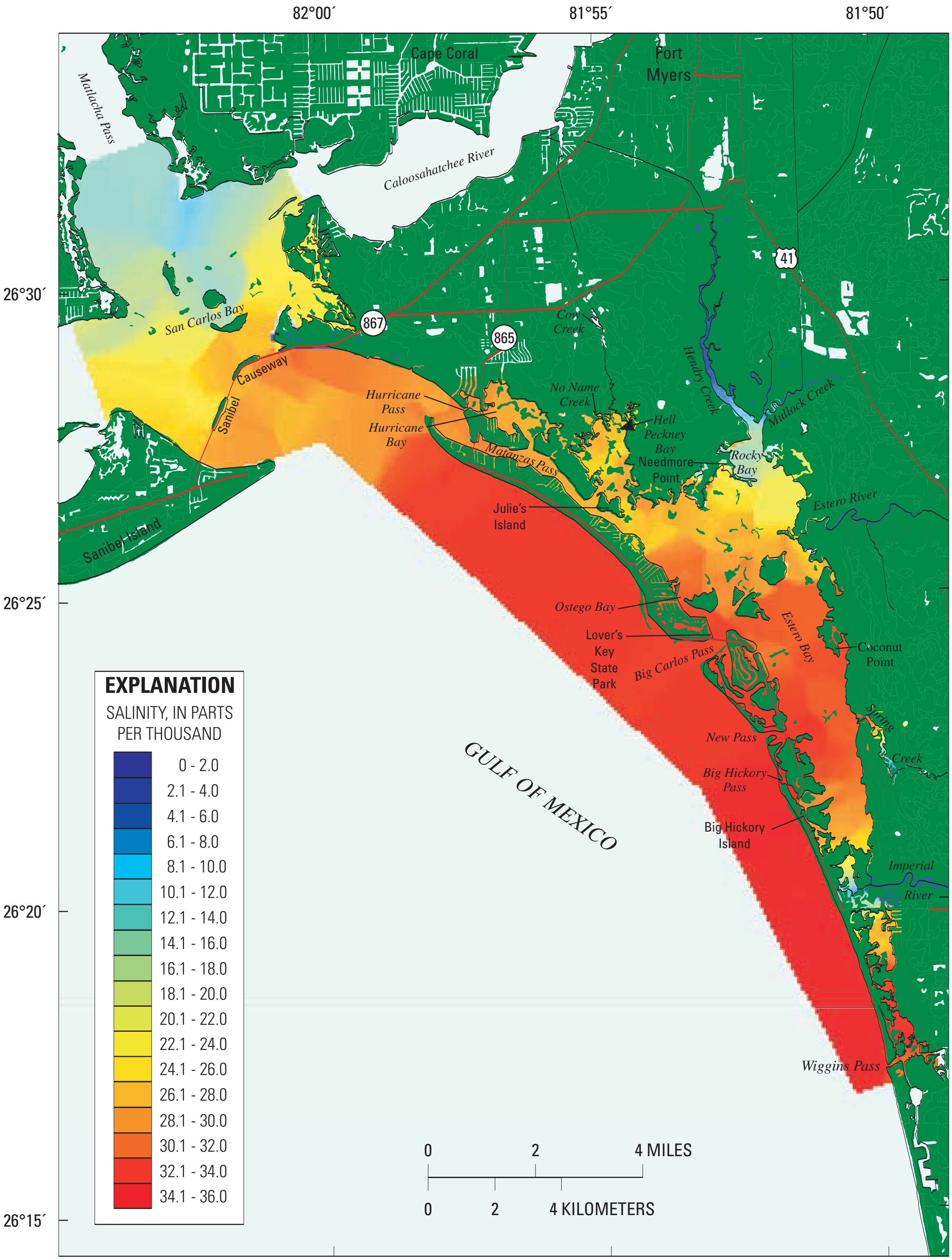

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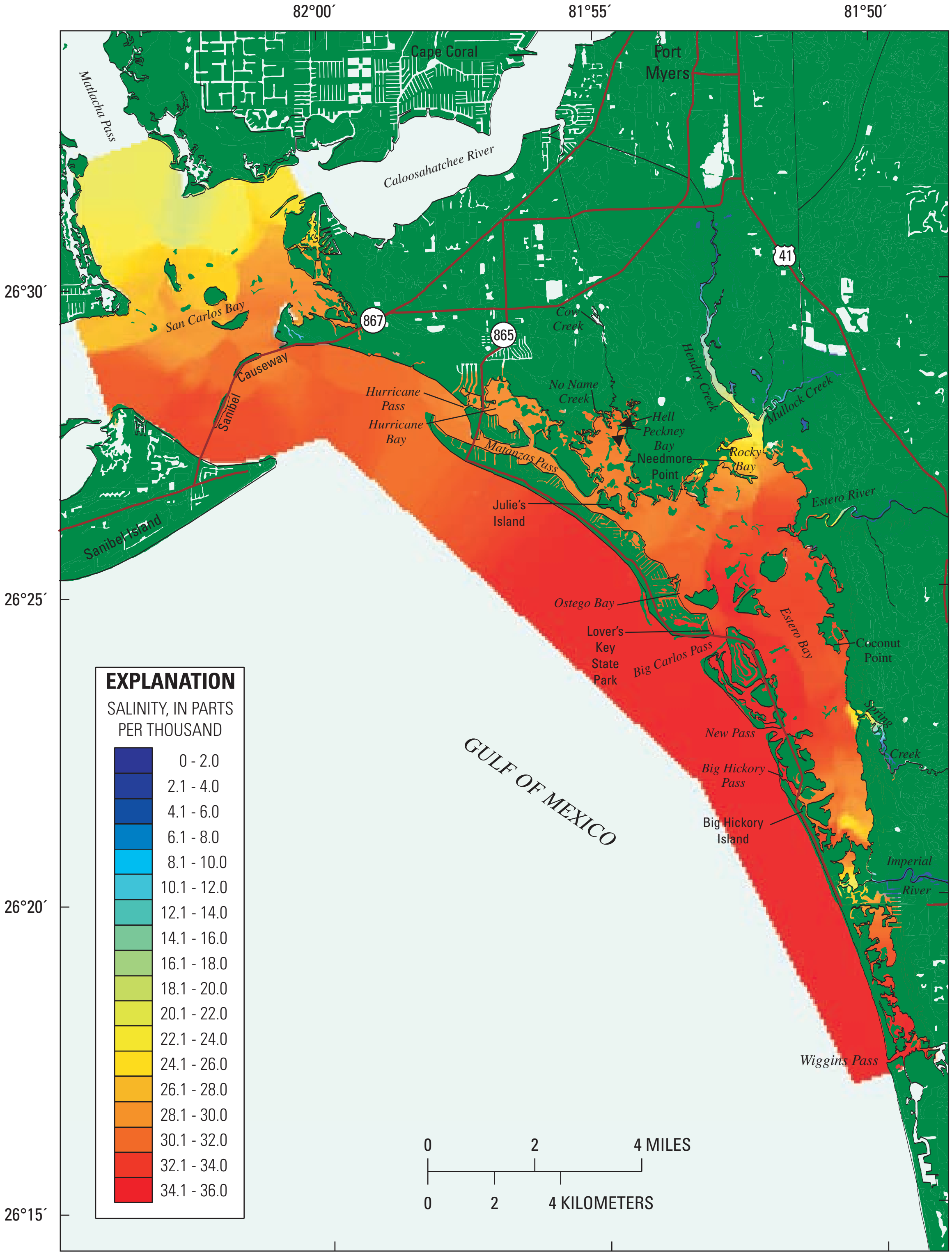
Figure 19f. Salinity patterns in Estero Bay, January 10, 2003.



Base from U.S. Geological Survey digital data
Universal Transverse Mercator projection, Zone 17, Datum NAD 27

Figure 19g. Salinity patterns in Estero Bay, March 7, 2003.

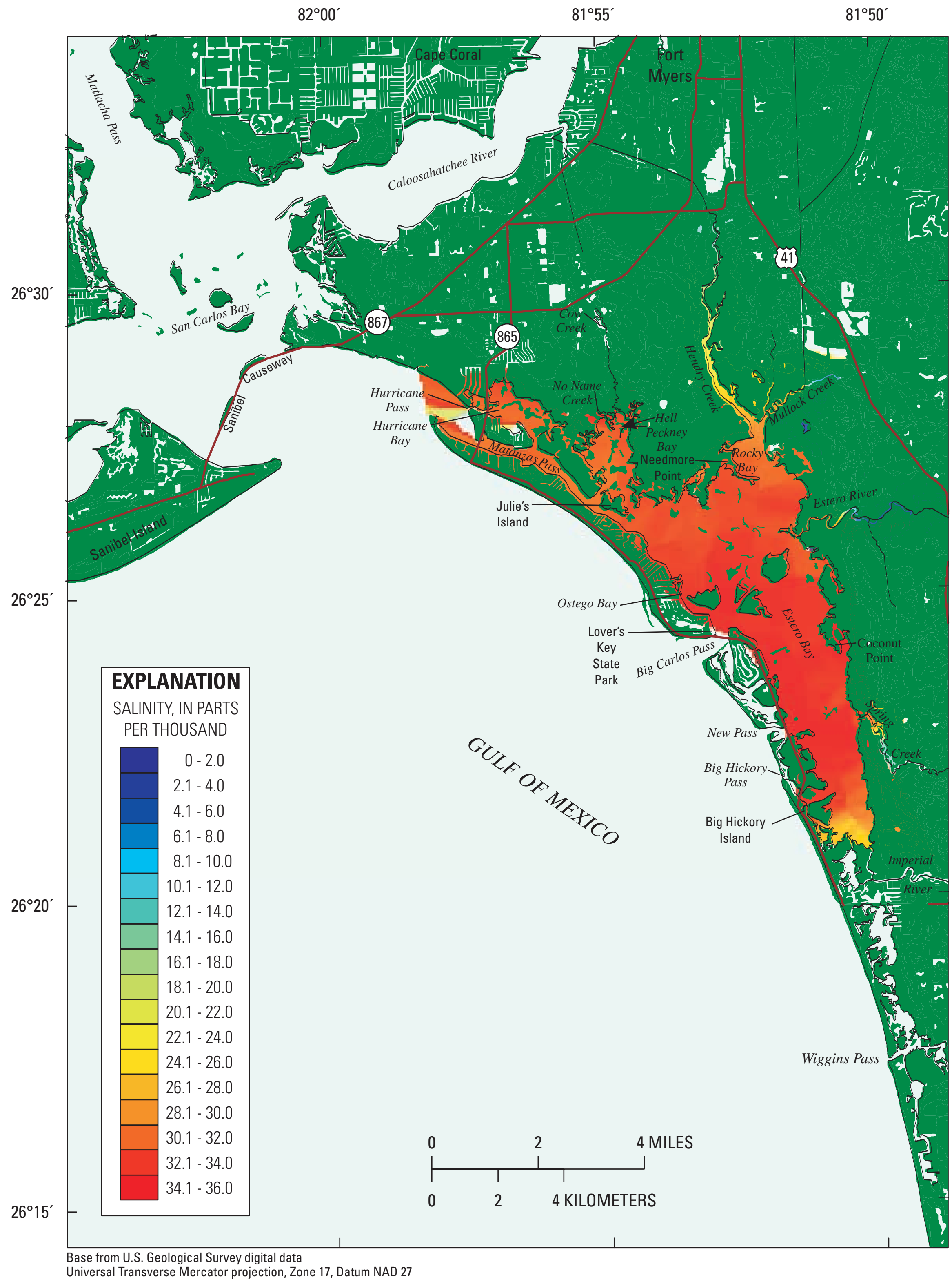


Figure 19h. Salinity patterns in Estero Bay, April 24, 2003.

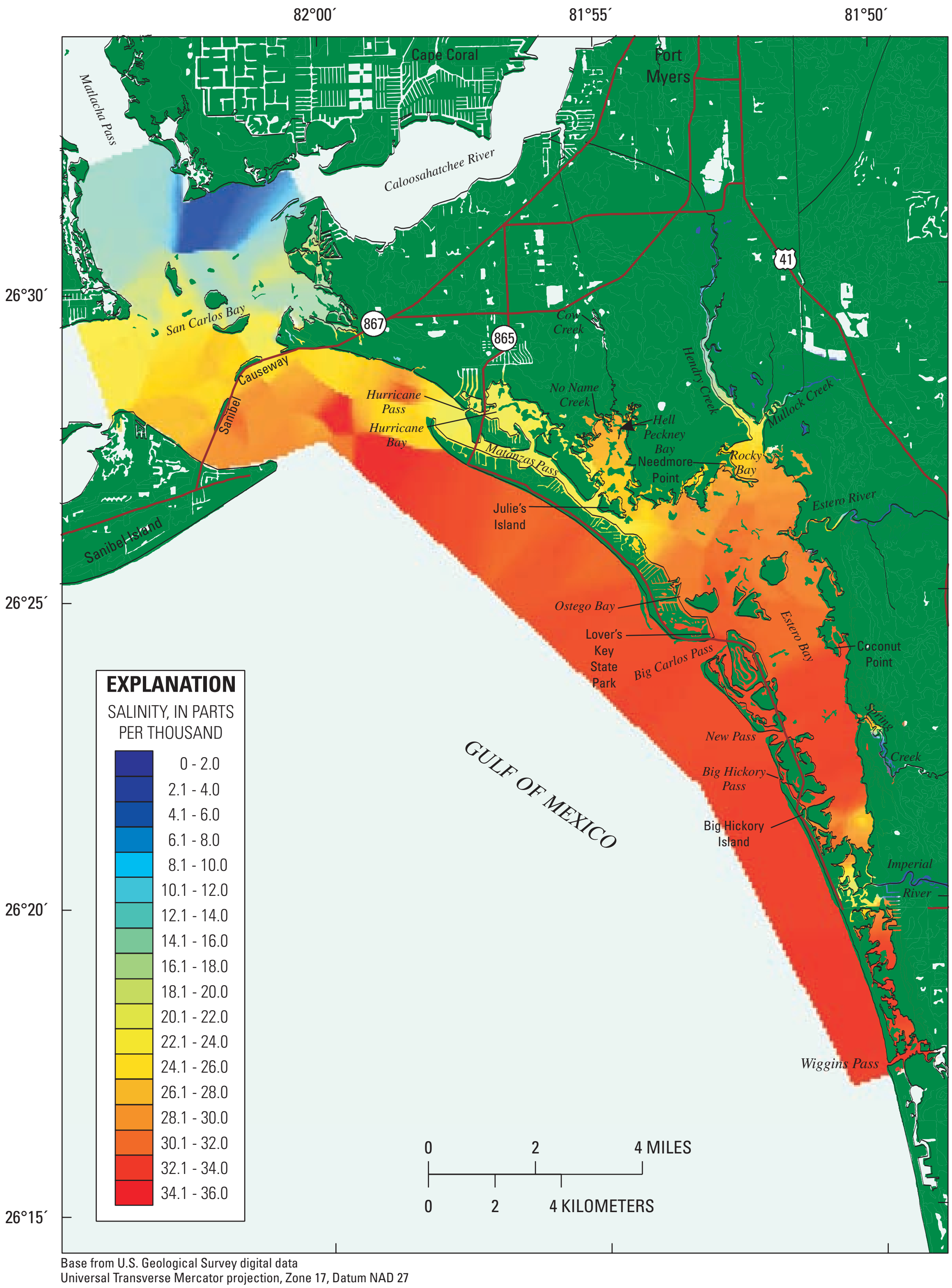


Figure 19i. Salinity patterns in Estero Bay, June 3, 2003.

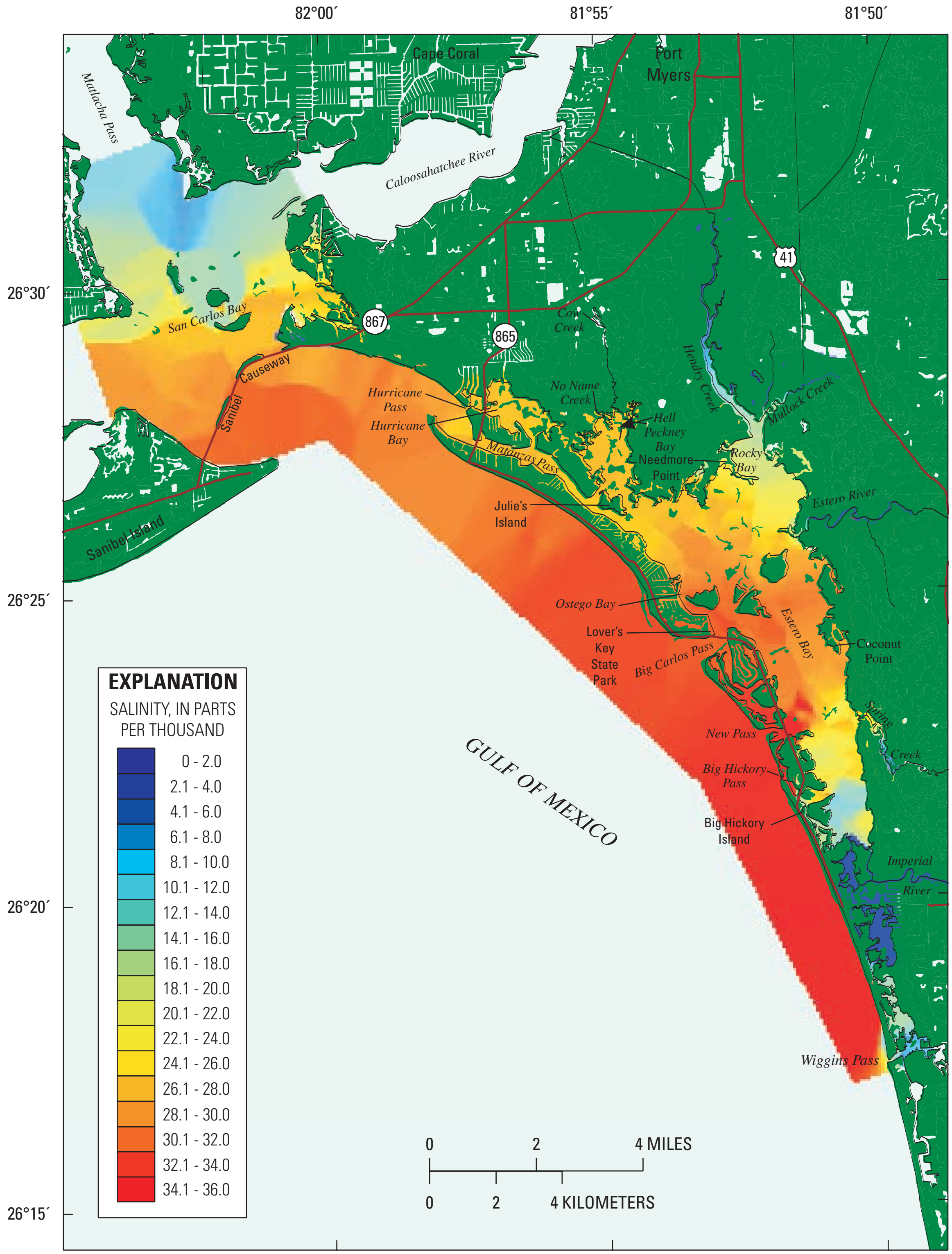


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Figure 19j. Salinity patterns in Estero Bay, July 23, 2003.

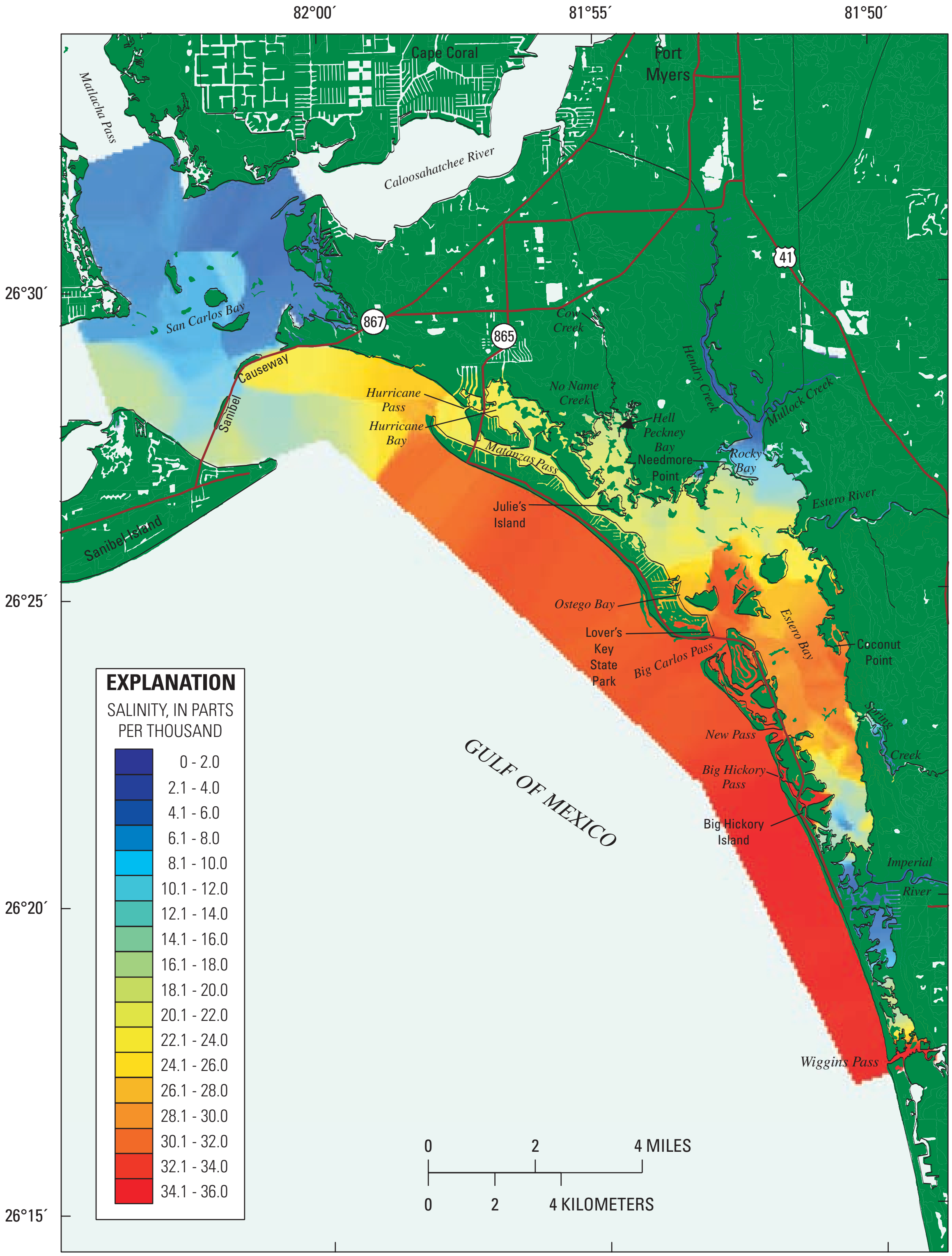

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Figure 19k. Salinity patterns in Estero Bay, August 29, 2003.

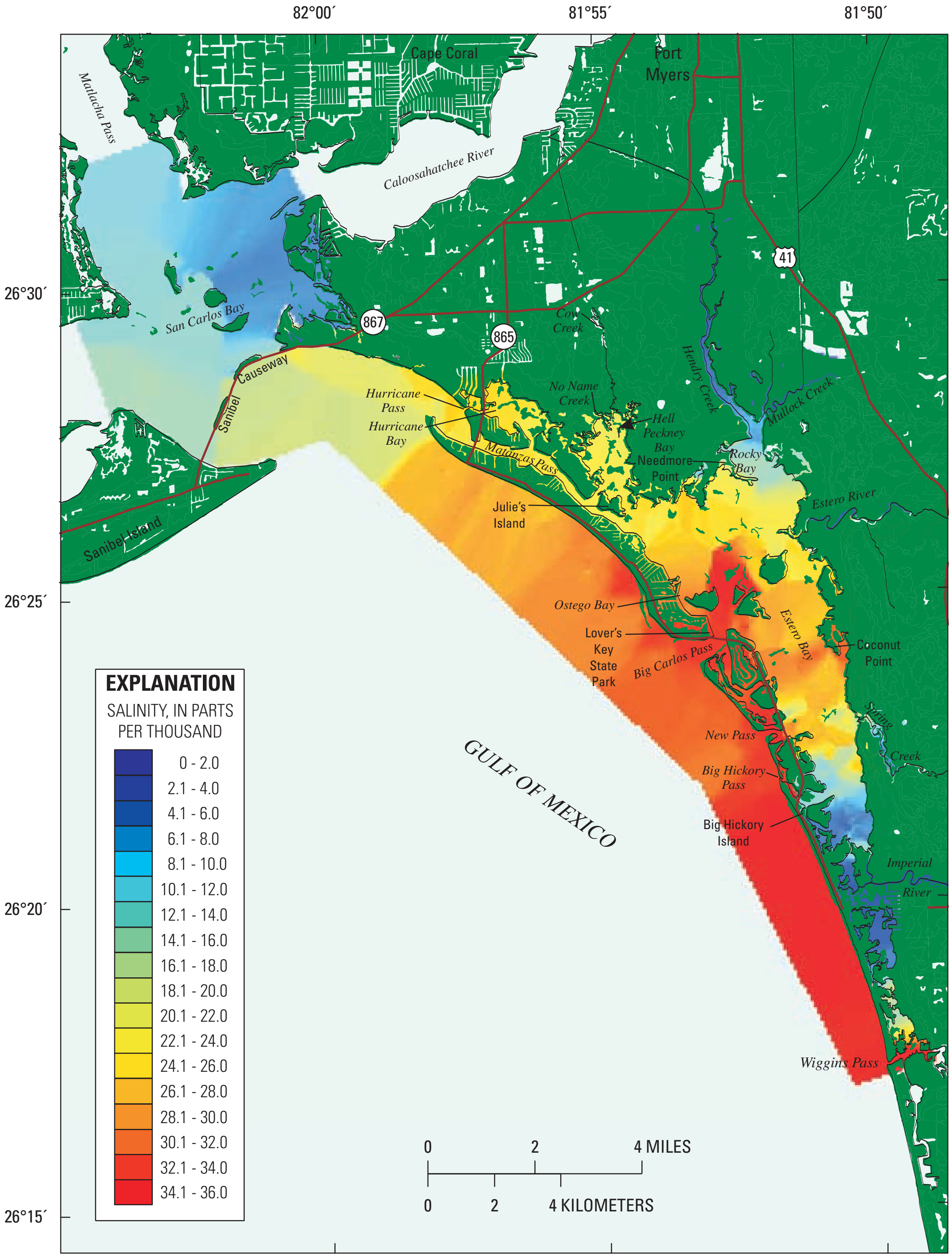

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Figure 19I. Salinity patterns in Estero Bay, October 10, 2003.

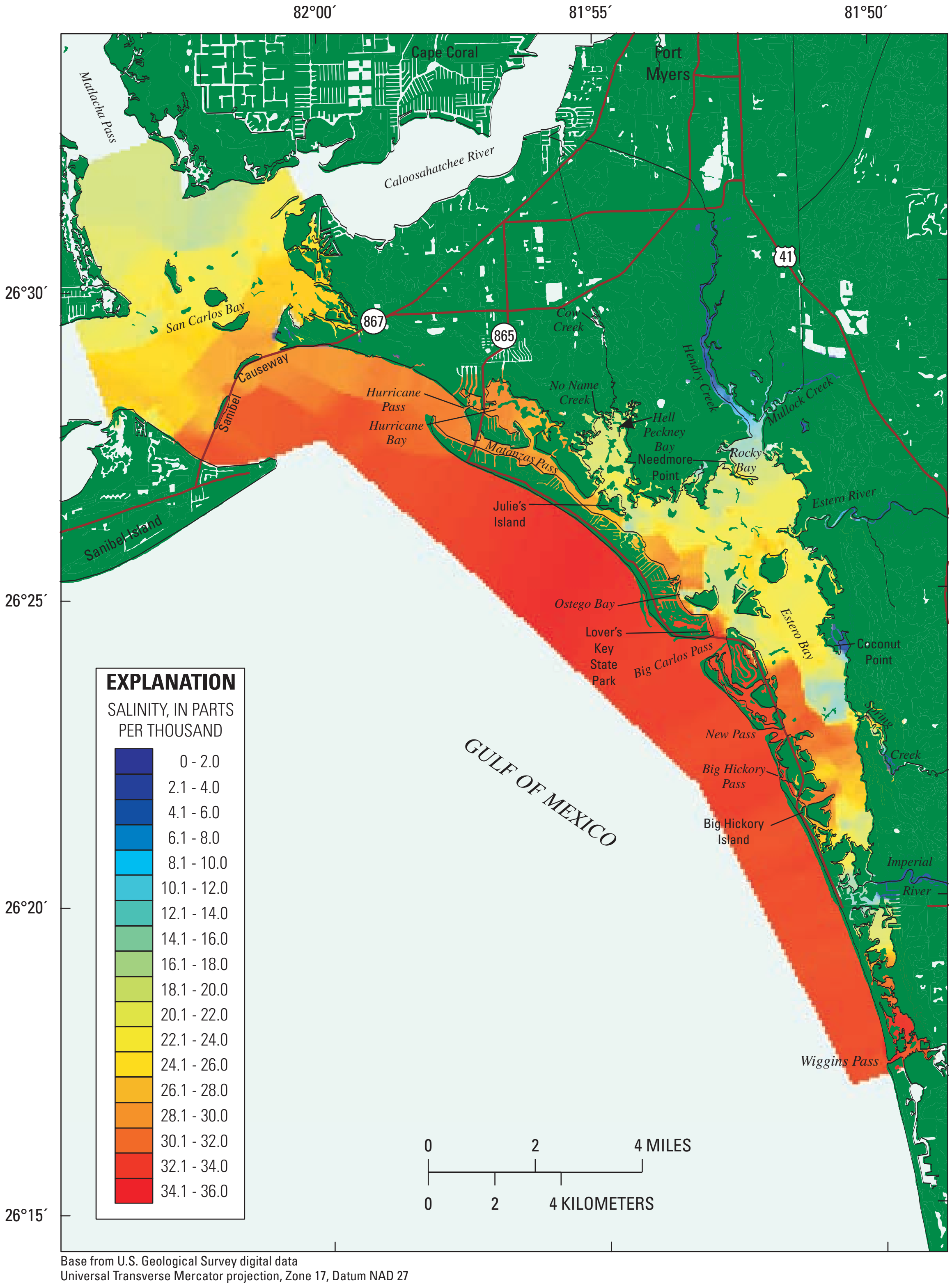

Figure 19m. Salinity patterns in Estero Bay, December 5, 2003.

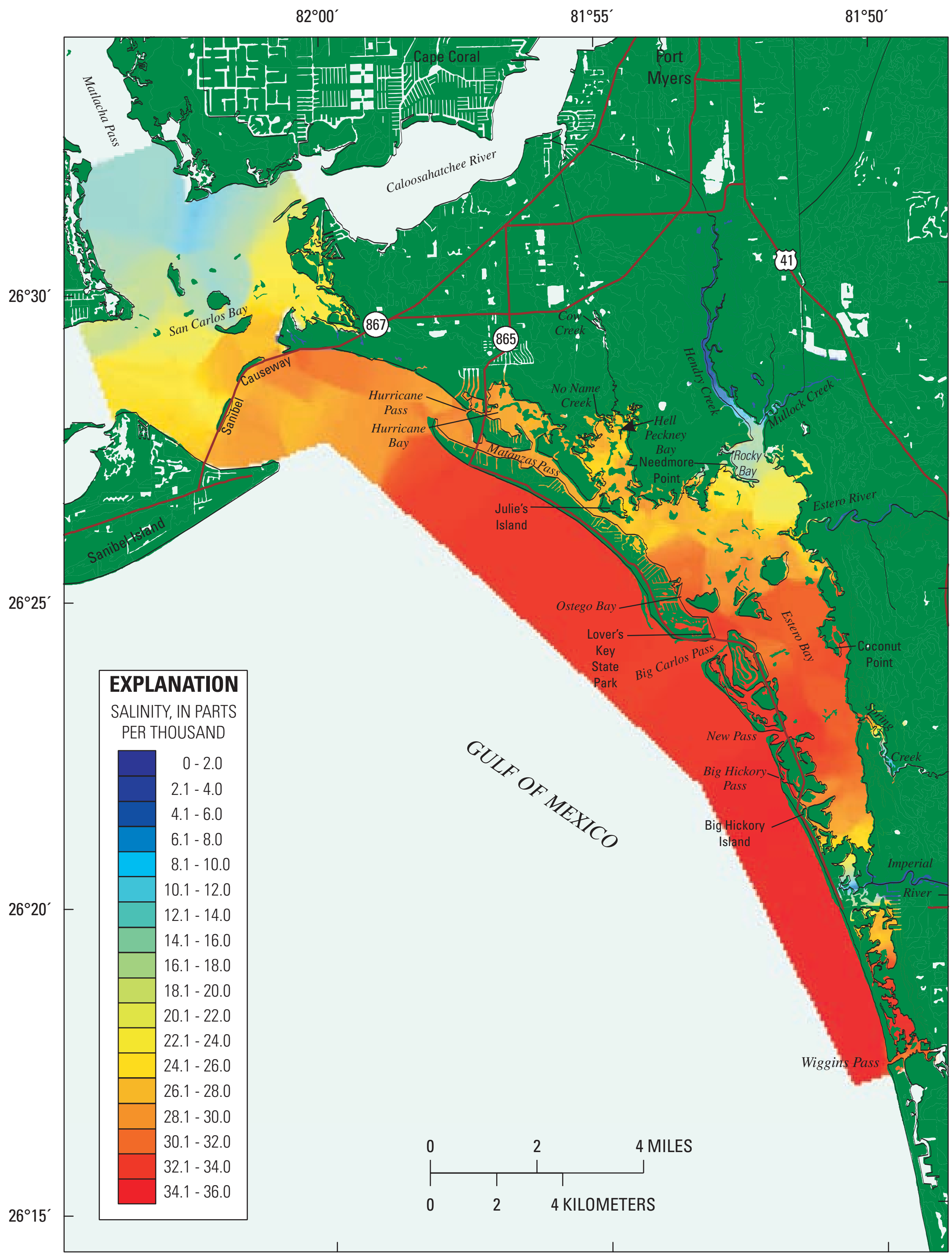

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Figure 19n. Salinity patterns in Estero Bay, January 30, 2004.

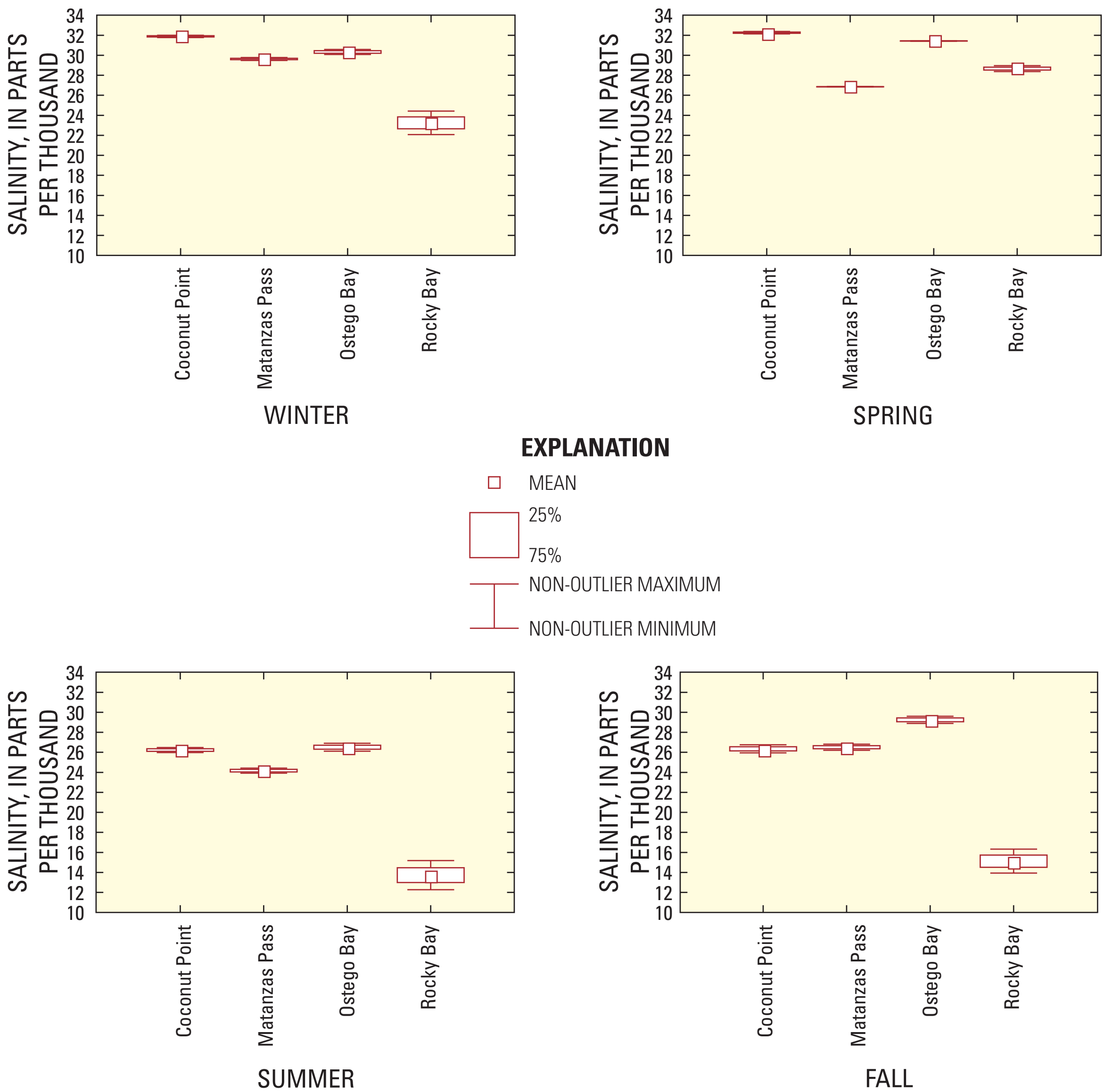

Figure 20. Statistical variability of salinity based on season and location.

Summary

Estero Bay is an estuary on the southwestern Florida coast, about 12 mi long and 3 mi wide, with several inlets connecting the bay to the Gulf of Mexico and numerous freshwater tributaries. Continuous stage and salinity data were recorded at eight gages in Estero Bay estuary from October 2001 to September 2005. Continuous velocity data were recorded at six of these stations for the purpose of computing discharge. Turbidity data were recorded at 4 stations, suspended sediment was measured at 3 stations, and windspeed and direction were recorded at 1 station. Salinity surveys of Estero Bay and the surrounding area, were conducted 14 times from July 2002 to January 2004.

Discharge magnitude at Big Carlos Pass was 3 times greater than Matanzas Pass and 15 times greater than Big Hickory Pass. The average daily discharge at Big Carlos Pass ranged from 35,000 to -34,000 ft^3/s at Big Carlos Pass, from 10,800 to -11,200 ft^3/s at Matanzas Pass, and from 2,200 to -2,900 ft^3/s at Big Hickory Pass. Discharge magnitude at Mullock Creek was 2 times greater than Estero River and 3 times greater than Imperial River. Average daily discharge ranged from 680 ft^3/s to -700 ft^3/s at Mullock Creek, from 330 to -370 ft^3/s at Estero River, and from 190 to -180 ft^3/s at Imperial River.

Big Carlos Pass and the three tributaries exhibited seasonal trends—positive discharge (ebb tide) during the wet season and negative discharge (flood tide) during the dry season. Matanzas Pass and Big Hickory Pass lacked any seasonal trend and mainly exhibited negative discharge for the period of record.

Monthly mean salinity ranged from 25 to 35 ppt at Big Carlos Pass, from 22 to 34 ppt at Matanzas Pass, and from 26 to 36 ppt at Big Hickory Pass. Salinity ranged from 1 to 32 ppt at Mullock Creek, from 1 to 34 ppt at Estero River and from 1 to 34 ppt at Imperial River. Generally, water was least saline in Matanzas Pass and Imperial River was the least saline tributary.

Reduced salinity at Matanzas Pass was negatively correlated ($R^2 = 0.48$) to freshwater discharge from the Caloosahatchee River at Franklin Locks (S-79). Matanzas Pass is hydrologically linked to Hell Peckney Bay; therefore, the water-quality problems associated with the Caloosahatchee River also impact Hell Peckney Bay.

Fifteen salinity maps were created from the salinity survey data collected in Estero Bay and the surrounding areas. Various salinity conditions can be observed throughout the estuary. Salinity, near the mouth of Matanzas Pass, is reduced during periods of high freshwater discharge from the Caloosahatchee River. Also during periods of high freshwater discharge from the tributaries, Rocky Bay becomes less saline whereas Coconut Point salinity remains elevated. Rocky Bay was significantly less saline than Coconut Point and Matanzas Pass was significantly less saline than Ostego Bay. The quality-checked and edited continuous data and the salinity maps have been compiled and stored on the USGS South Florida Information Access (SOFIA) website, which can be accessed at *http://sofia.usgs.gov*

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