Greater Everglades Priority Ecosystems Science Initiative

Prepared in cooperation with the U.S. Fish and Wildlife Service

Effects of Variations in Flow Characteristics Through W.P. Franklin Lock and Dam on Downstream Water Quality in the Caloosahatchee River Estuary and in McIntyre Creek in the J.N. “Ding” Darling National Wildlife Refuge, Southern Florida, 2010–13

Scientific Investigations Report 2016–5033

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

Cover. Clockwise from top: Boat leaving Punta Rassa at the beginning of a water-quality survey, McIntyre Creek monitoring station, and streambank at the mouth of McIntyre Creek.

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By Amanda C. Booth, Lars E. Soderqvist, and Travis M. Knight

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U.S. Department of the Interior
SALLY JEWELL, Secretary

U.S. Geological Survey
Suzette M. Kimball, Director

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Conversion Factors

[Inch/Pound to SI]

Multiply	By	To obtain
	Length	
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
	Area	
acre	4,047	square meter (m^2)
acre	0.004047	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
mile per hour (mi/h)	1.609	kilometer per hour (km/h)
	Volume	
acre-foot (acre-ft)	1,233	cubic meter (m^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as
°F = (1.8 × °C) + 32.

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

°C=(°F-32)/1.8

Supplemental Information

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

Datum

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

Elevation, as used in this report, refers to the distance above the vertical datum.

Abbreviations

A_{254}	absorbance at 254 nanometers
FDOM	fluorescence of chromophoric dissolved organic matter
FNU	formazin nephelometric unit
GIS	geographic information system
NWIS	National Water Information System
ppb	part per billion
ppt	part per thousand
QSE	quinine sulfate equivalent
RWTE	rhodamine WT equivalent
SOFIA	South Florida Information Access
USFWS	U.S. Fish and Wildlife Service
USGS	U.S. Geological Survey

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Abstract

The U.S. Geological Survey studied water-quality trends at the mouth of McIntyre Creek, an entry point to the J.N. “Ding” Darling National Wildlife Refuge, to investigate correlations between flow rates and volumes through the W.P. Franklin Lock and Dam and water-quality constituents inside the refuge from March 2010 to December 2013. Outflow from Lake Okeechobee, and flows from Franklin Lock, tributaries to the Caloosahatchee River Estuary, and the Cape Coral canal system were examined to determine the sources and quantity of water to the study area. Salinity, temperature, dissolved-oxygen concentration, pH, turbidity, and chromophoric dissolved organic matter fluorescence (FDOM) were measured during moving-boat surveys and at a fixed location in McIntyre Creek. Chlorophyll fluorescence was also recorded in McIntyre Creek. Water-quality surveys were completed on 20 dates between 2011 and 2014 using moving-boat surveys.

Franklin Lock contributed the majority of flow to the Caloosahatchee River. Between 2010 and 2013, the monthly mean flow rate at Franklin Lock ranged from 29 cubic feet per second in May 2011 to 10,650 cubic feet per second in August 2013. Instantaneous near-surface salinity in McIntyre Creek ranged from 12.9 parts per thousand on September 26, 2013, to 37.9 parts per thousand on June 27, 2011. Salinity in McIntyre Creek decreased with increasing flow rate through Franklin Lock. Flow rates through Franklin Lock explained 61 percent of the variation in salinity in McIntyre Creek. Salinity data from moving-boat surveys also indicate that an increase in flow rate at Franklin Lock decreases salinity in the Caloosahatchee River Estuary, and a reduction or elimination in flow increases salinity. The FDOM in McIntyre Creek was positively correlated with flow at Franklin Lock, and 54 percent of the variation in FDOM can be attributed to the flow rate through Franklin Lock. Data from moving-boat surveys indicate that FDOM increases when flow volume from Franklin Lock increases. The highest FDOM recorded during a survey was at Billy’s Creek. Chlorophyll fluorescence was positively correlated with flow at Franklin Lock, with 23 percent of the variation explained by the flow rate at Franklin Lock. An increase in flow rate at Franklin Lock resulted in a decrease in pH (21 percent of variation explained by flow rates). Data from the pH surveys indicate an increase in pH with distance from Franklin Lock. Turbidity and dissolved oxygen near the surface in McIntyre Creek were not correlated with flow rate at Franklin Lock. Moving-boat surveys did not document a change in turbidity or dissolved oxygen with a change in distance from the Franklin Lock. Correlations between Franklin Lock flow rate and water quality in McIntyre Creek indicate that releases at Franklin Lock affect water quality in the Caloosahatchee River Estuary and Ding Darling Refuge.

Introduction

The C–43 Canal was constructed in 1881 to connect the Caloosahatchee River to Lake Okeechobee, mitigate flooding caused by Lake Okeechobee, and connect eastern and western Florida by means of a navigable waterway. Three lock-and-dam structures—Moore Haven Lock and Dam, Ortona Lock and Dam, and W.P. Franklin Lock and Dam—were constructed to control surface-water flow rates and elevations in the lake, C–43 Canal, and Caloosahatchee River (figs. 1 and 2). Moore Haven Lock and Dam is one of the largest outflow points from Lake Okeechobee. Moore Haven Lock and Dam is referred to as “Moore Haven” and W.P Franklin Lock and Dam is referred to as “Franklin Lock” for the remainder of this report.

The delivery of water to the Caloosahatchee River is highly managed and regulated by the U.S. Army Corps of Engineers. In order to protect the structural integrity of the

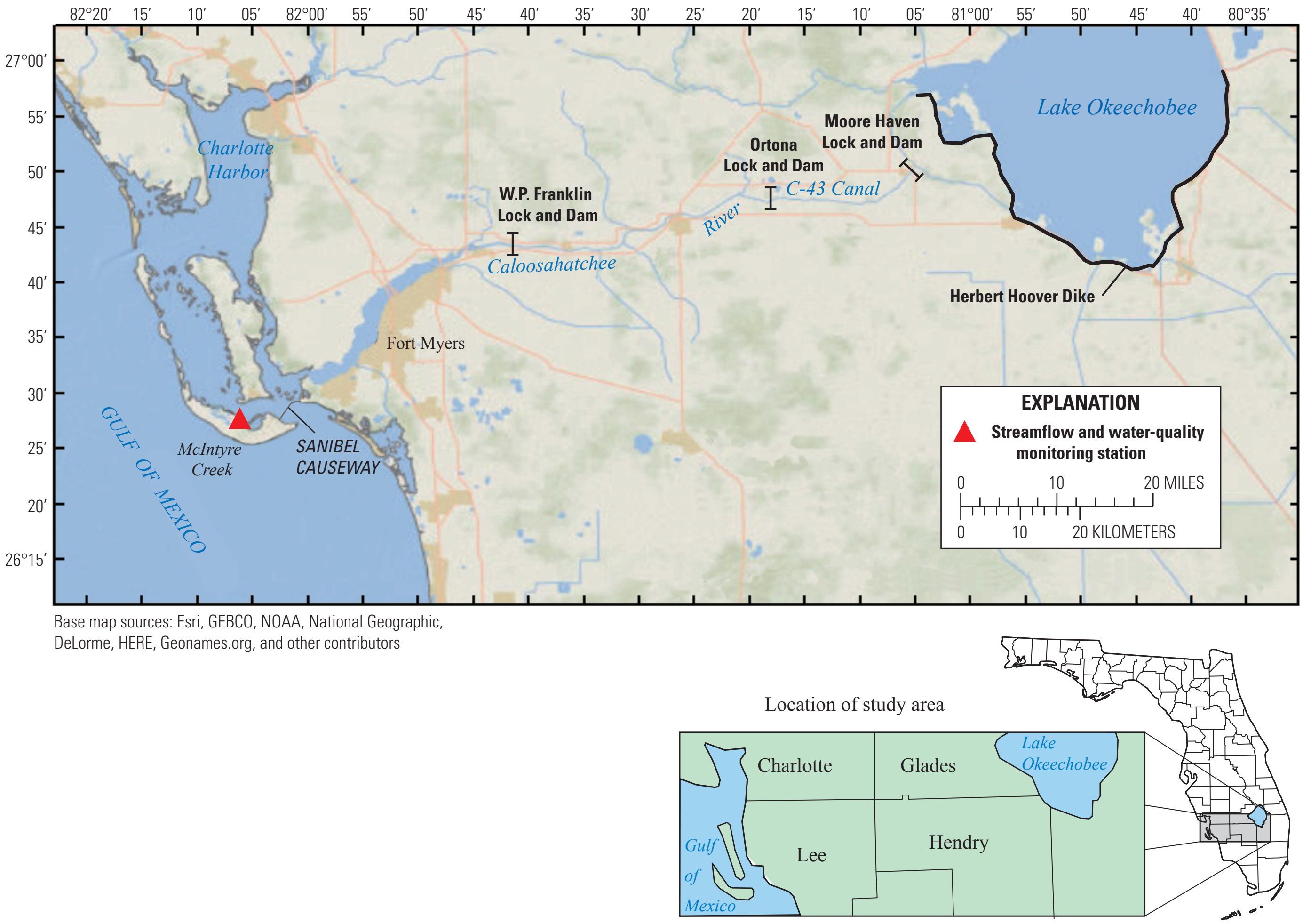


Figure 1. Lake Okeechobee, Moore Haven Lock and Dam, Ortona Lock and Dam, and W.P. Franklin Lock and Dam.

Figure 2. W.P. Franklin Lock and Dam. (Photograph by Eduardo Patino, U.S. Geological Survey.)

Herbert Hoover Dike, which surrounds Lake Okeechobee (fig. 1), the U.S. Army Corps of Engineers maintains the surface-water elevation in Lake Okeechobee between 12.5 and 15.5 feet (ft) as of May 2014. Flood control, public safety, navigation, water supply, and ecological health are all considered when deciding to retain water in the lake or release it to the Caloosahatchee River. During the wet season, it is possible for inflows into Lake Okeechobee to cause the lake-surface elevation to rise faster than the lake can be drained by existing control structures, such that the storage capacity behind the Herbert Hoover Dike is exceeded and the dike is vulnerable to collapse, particularly during a hurricane (South Florida Water Management District, 2014). Under these conditions, large volumes of water are released from Lake Okeechobee through outflow control structures, including the Franklin Lock. Periodic high flows through Franklin Lock reduce salinity in the lower Caloosahatchee River, which is estuarine downstream of this lock. During the dry season, flows are reduced or eliminated, causing an increase in salinity. Populations of oysters and seagrass, each a keystone species in the ecosystem, are affected by the resulting variations in salinity (Doering and others, 2002; Barnes, 2005; Tolley and others, 2005).

Additional alterations to the Caloosahatchee River were implemented downstream of Franklin Lock following construction of the C–43 Canal. Dredging and channelization of the Caloosahatchee River began in the 1930s. During the 1960s, the Sanibel Causeway was constructed to connect Sanibel Island to the mainland (fig. 1; South Florida Water Management District, Florida Department of Environmental Protection, and Florida Department of Agriculture and Consumer Services, 2009). The channelization of the Caloosahatchee River and construction of the causeway have been hypothesized to cause the collapse of the bay scallop population in Pine Island Sound as a result of decreased salinities (Arnold, 2009).

The J.N. “Ding” Darling National Wildlife Refuge (“Ding Darling Refuge,” hereafter) was established in 1945 to protect and provide “pristine subtropical habitat for the benefit of wildlife.” The refuge provides important habitat to more than 270 species of birds, 102 species of fish, 60 species of reptiles and amphibians, and 33 species of mammals. Numerous threatened and endangered species can be found in the refuge, including eastern indigo snakes, American alligators, American crocodiles, wood storks, Florida manatees, Atlantic loggerhead sea turtles, Atlantic green sea turtles, hawksbill sea turtles, Kemp’s ridley sea turtles, leatherback sea turtles, piping plovers, and smalltooth sawfish. The refuge serves as a major tourist attraction for Sanibel Island, with more than 700,000 visitors in 2010 (U.S. Fish and Wildlife Service, 2010).

The degradation of water quality in Ding Darling Refuge caused by the quality, quantity, and timing of flows through the Franklin Lock was identified as one of the primary threats to the refuge by the U.S. Fish and Wildlife Service (2010). To address this issue, the U.S. Geological Survey (USGS) initiated a study in March 2010 to identify water-quality trends at the mouth of McIntyre Creek, a principal waterway in the refuge, and investigate relations between flow through Franklin Lock and water quality in the refuge. The study was conducted as part of the Greater Everglades Priority Ecosystems Science Initiative and in cooperation with the U.S. Fish and Wildlife Service (USFWS). During the study, water quality in McIntyre Creek from 2010 to 2013 was measured and correlations between water quality in McIntyre Creek and flow rate at Franklin Lock were determined. Moving-boat water-quality surveys were conducted from 2011 to 2014 in the Caloosahatchee Estuary and nearby areas.

Purpose and Scope

The primary purpose of this report is to document basic water-quality dynamics at the mouth of McIntyre Creek and characterize the correlations between water quality in the Caloosahatchee River Estuary and McIntyre Creek and flows through Franklin Lock. In addition, the report summarizes available flow data in the study area between 2010 and 2013, and quantifies flow through Franklin Lock relative to monitored tributary flow.

Flow, water-surface elevation, salinity, temperature, dissolved-oxygen concentration, pH and turbidity data are presented and discussed for McIntyre Creek, which was monitored from March 2010 to December 2013. Chlorophyll fluorescence and fluorescence of chromophoric dissolved organic matter (FDOM) for McIntyre Creek are also discussed and are available from August 2011 to October 2013. Data are available for download from the National Water Information System Web interface (NWIS) (http://fl.water.usgs.gov/infodata/nwisweb.html).

Spatial distributions of selected water-quality characteristics in the Caloosahatchee River and downstream estuaries are also presented and were determined from moving-boat water-quality surveys completed from 2011 through 2014. These survey data, which are discussed herein, were used to construct maps of salinity, temperature, dissolved oxygen concentration, pH, turbidity, and FDOM and can be accessed through the South Florida Information Access (SOFIA) Web site at http://sofia.usgs.gov/exchange/ding_wqs/index.php (Booth and others, 2014). Methods of data collection and analysis; seasonal variations in flow rate, flow volume, and water quality; study limitations; and implications for future investigations are also discussed.

Description of Study Area

The Ding Darling Refuge is 15 miles (mi) southwest of Fort Myers, Florida, on Sanibel Island. The refuge is 6,407 acres in extent and includes open estuarine waters, seagrass beds, mudflats, mangrove islands, and interior freshwater habitats (U.S. Fish and Wildlife Service, 2010). McIntyre Creek is located in the refuge on the eastern side of Sanibel Island (fig. 3). In addition to McIntyre Creek, the study area includes the Caloosahatchee River Estuary, parts of the Gulf of Mexico, and Charlotte Harbor (fig. 3).

The Caloosahatchee River Estuary is defined as the tidal Caloosahatchee River, San Carlos Bay, Matlacha Pass, and Pine Island Sound for the purpose of this report (fig. 3). The area receives semidiurnal, mixed tides that range from 1 to 4 ft. Tidal amplitudes are greatest near the Gulf of Mexico.

The tidal Caloosahatchee River extends 26 mi from the Franklin Lock to Shell Point, where the river flows into San Carlos Bay. Between Franklin Lock and Beautiful Island, the river is about 500 ft wide, having an average depth of about 20 ft. Between Beautiful Island and Shell Point, the river is wider (about 8,200 ft wide at the mouth), having an average depth of about 5 ft (Scarlatos, 1988). In addition to Franklin Lock, the tidal Caloosahatchee River receives inflows from numerous tributaries.

San Carlos Bay is located at the mouth of the Caloosahatchee River (fig. 3). The bay is south of Pine Island Sound and Matlacha Pass and is crossed by the Sanibel Causeway. San Carlos Bay is connected to the Gulf of Mexico to the south, and its depth ranges from 1 to 25 ft.

Matlacha Pass is east of Pine Island, west of Cape Coral, south of Charlotte Harbor, and north of San Carlos

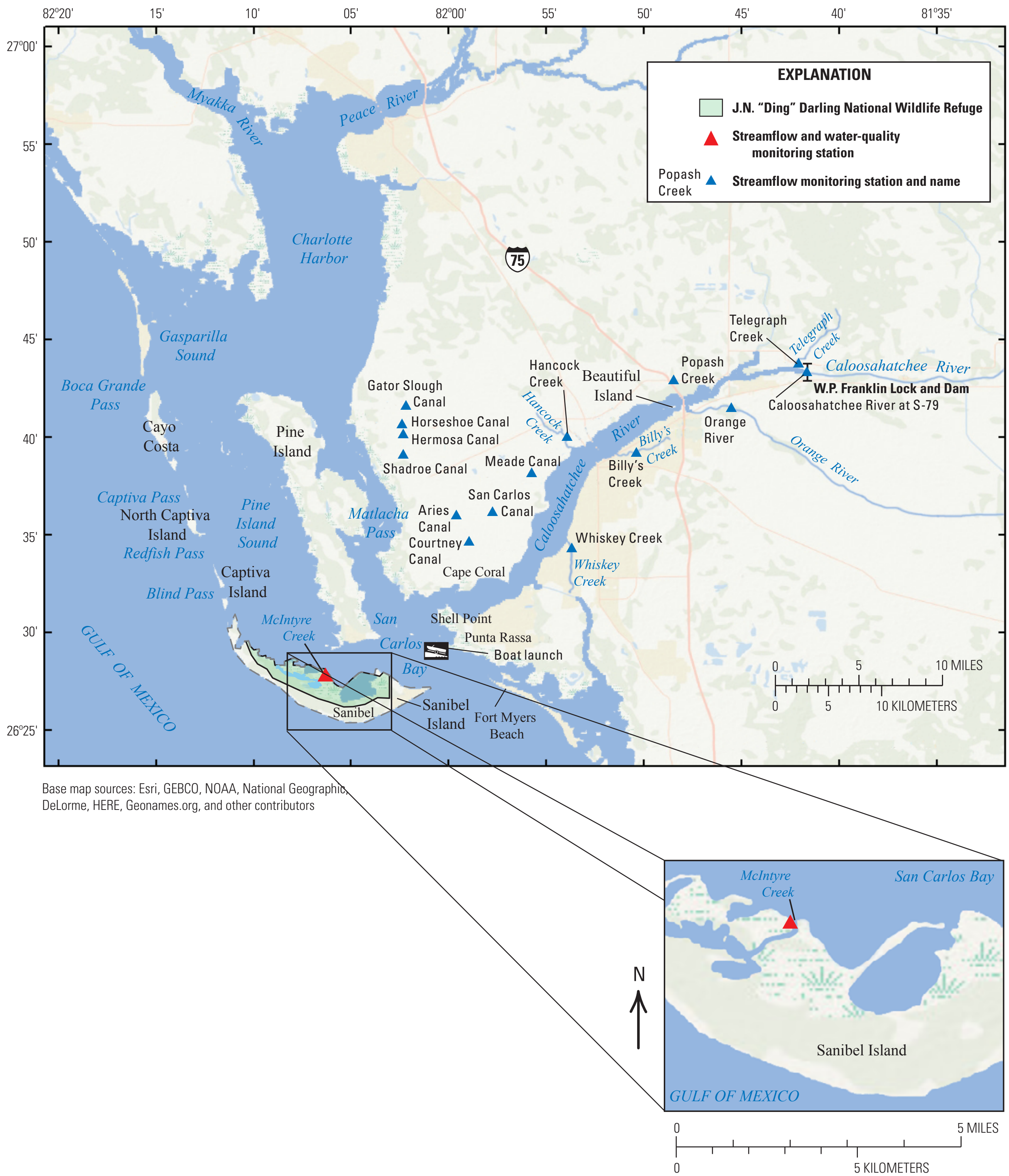


Figure 3. Study area showing the McIntyre Creek monitoring station.

Bay (fig. 3). The waterway is 13 mi long and 1.2 mi wide, and has a depth of 4 to 14 ft in the channel and about 2 ft near the shorelines. A major source of freshwater flow to Matlacha Pass is the Cape Coral canal system, which is composed of four main canals (Russell and Kane, 1995). The Caloosahatchee River and Matlacha Pass are the largest contributors of water to San Carlos Bay.

Pine Island Sound is west of Pine Island, south of Charlotte Harbor, and north of San Carlos Bay (fig. 3). To the west, Sanibel Island, Captiva Island, North Captiva Island, and Cayo Costa separate Pine Island Sound from the Gulf of Mexico. Multiple passes connect Pine Island Sound to the Gulf of Mexico. Pine Island Sound is 18 mi long, 4.5 mi wide, with depths ranging from 1 to 16 ft. Pine Island Sound receives freshwater directly from rainfall and from runoff draining the surrounding islands.

Although not within the study area, Lake Okeechobee has a substantial effect on the Caloosahatchee River Estuary because of its connection to the Caloosahatchee River by means of the Caloosahatchee Canal. Water released from Lake Okeechobee enters the Caloosahatchee surface-water system at Moore Haven. In addition to Moore Haven, major outflows from Lake Okeechobee are measured at the following USGS streamflow monitoring stations: St. Lucie Canal below S–308, near Port Mayaca, Levee 8 Canal near Canal Point, Miami Canal at S–354 and S–3 at Lake Harbor, Hillsboro Canal below S–351 near South Bay, North New River Canal below S–351 near South Bay and Industrial Canal at Clewiston (fig. 4).

Methods of Data Collection and Analysis

Flow rate, flow volume, and water quality were measured at a continuous monitoring station in McIntyre Creek. Surface-water flow rate and volume were also measured at continuous monitoring stations at a number of tributaries to the Caloosahatchee River, outflows from Lake Okeechobee, and inflows into Matlacha Pass (table 1). Water quality in the Caloosahatchee River Estuary was measured by means of moving-boat surveys.

Base map sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 4. Lake Okeechobee outflow stations.

Table 1. USGS site names, site identifiers, period of record, flow category, and current computation method.

[USGS, U.S. Geological Survey. Flow categories: LO, Lake Okeechobee outflows; IC, inflows to the tidal Caloosahatchee River; IM, inflows to Matlacha Pass. Current computation method: IV, index velocity; TIV, tidal index velocity; LG, vertical lift gates; BW, broad-crested weir]

Site name	USGS site identifier	Period of record	Flow category	Current computation method
Caloosahatchee Canal DWS of S-77 at Moore Haven (Moore Haven Lock and Dam)	02292010	May 2008 to present	LO	IV
St. Lucie Canal BLW S-308, near Port Mayaca	02276877	April 1931 to September 1952, October 1981 to present	LO	IV
Levee 8 Canal near Canal Point	265501080364900	August 1996 to present	LO	IV
Miami Canal at S-354 and S-3 at Lake Harbor	02286400	December 1939 to June 1943, October 1957 to present	LO	IV
Hillsboro Canal below S-351 near South Bay	02280500	March 1957 to present	LO	IV
North New River Canal below S-351 near South Bay	02283500	February 1957 to present	LO	IV
Industrial Canal at Clewiston	264514080550700	August 1976 to present	LO	IV
McIntyre Creek at Sanibel Island	02293249	March 2010 to October 2013	IC	TIV
Caloosahatchee River at S-79, near Olga (Franklin Lock and Dam)	02292900	May 1966 to present	IC	LG
Telegraph Creek at State Highway at Olga	022929176	November 2007 to April 2013	IC	TIV
Orange River near Buckingham	02293055	November 2007 to April 2013	IC	TIV
Popash Creek at Leetana Road, near North Fort Myers	02293090	December 2007 to April 2013	IC	TIV
Billy's Creek at Fort Myers	02293190	February 2008 to May 2013	IC	TIV
Hancock Creek at Pondella Road, North Fort Myers	264006081534400	April 2008 to April 2013	IC	TIV
Whiskey Creek at Fort Myers	02293230	April 1994 to present	IC	LG and BW
Aries Canal at Cape Coral	02293240	October 1989 to August 2013	IC	BW
Meade Canal at Cape Coral	02293214	November 1986 to April 2013	IC	BW
Courtney Canal at Cape Coral	02293243	November 1986 to July 2013	IC	BW
San Carlos Canal at Cape Coral	02293241	November 1986 to April 2013	IC	BW
Shadroe Canal at Cape Coral	02293345	October 1987 to May 2013	IM	BW
Hermosa Canal at Cape Coral	02293347	January 1987 to July 2013	IM	BW
Horseshoe Canal at Cape Coral	02293346	January 1987 to May 2013	IM	BW
Gator Slough at SR 765 at Cape Coral	02293264	May 1984 to October 1997, June 2000 to September 2013	IM	BW

Continuous Monitoring

A variety of techniques and methods was required to measure, analyze, and verify surface-water flow (table 1). Techniques and methods used at monitoring stations to measure the flow through control structures having vertical lift gates, broad-crested weirs, or both are provided in Rantz and others (1982). Monitoring stations where flow was affected by backwater, either from tidal action or control structures, required the installation of velocity meters to determine flow using the index velocity method (Morlock and others, 2002; Ruhl and Simpson 2005; Levesque and Oberg, 2012). Tidally affected flow records were filtered using the Godin low-pass filter to remove tidal signals (U.S. Geological Survey, 2010). Daily mean values of flow for all locations identified in table 1 can be accessed through the NWIS Web interface (http://fl.water.usgs.gov/infodata/nwisweb.html).

Salinity, temperature, dissolved oxygen concentration, pH, and turbidity were measured in McIntyre Creek. Salinity, in parts per thousand (ppt); dissolved oxygen concentration, in milligrams per liter (mg/L); pH, in standard pH units; and turbidity, in formazin nephelometric units (FNU), were measured with a YSI 6600 V2 sonde (YSI Incorporated, 2011) at 15-minute intervals. The sonde was initially deployed in a floating probe holder with sensors approximately 1.5 ft below the water surface (fig. 5*A*). On August 24, 2010, the sonde was removed from the water column because of heavy biological fouling and placed in a pump system (fig. 5*B*). Between 15-minute samples, the pump system shuts off, causing water to drain from the sensors. This drying, combined with the lack of light in the pump system, greatly reduced fouling on the sensors. The intake pipe for the pump system was located in the discontinued floating probe holder approximately 1.5 ft

A

B

Figure 5. *A*, McIntyre Creek monitoring station and, *B*, instruments in the pump system.

below the water surface. On July 14, 2011, a Turner C3 sensor was installed in the pump system to measure FDOM and chlorophyll fluorescence. Temperature and salinity were measured near the substrate using another sonde. Water-quality sensors were inspected every 4 to 8 weeks. Drift and fouling corrections were determined and applied on the basis of formulas provided in Wagner and others (2006).

Moving-Boat Water-Quality Surveys

Twenty moving-boat water-quality surveys were conducted during 2011–14. Six surveys were completed per year to capture the following conditions: peak of the wet season; transition to the dry season; peak of the dry season; transition to the wet season; and hydrologic events, such as algal blooms and large releases from the Franklin Lock. Field protocols for measuring water-quality characteristics using a moving boat were modified from those of Soderqvist and Patino (2010) to remove the instruments from the water column and incorporate the use of multiple instruments.

The water-quality surveys began in San Carlos Bay near Punta Rassa; entered the Gulf of Mexico and returned to the bay; proceeded clockwise through Pine Island Sound, Charlotte Harbor, and Matlacha Pass; entered the Cape Coral canal system; returned to San Carlos Bay near Sanibel Causeway; proceeded upstream along the Caloosahatchee River while briefly entering several tributaries, and ended at Franklin Lock. Surveys were planned to capture ebb tide at tributaries. A 21-ft Parker outboard motor boat, used during each of the surveys, moved at a speed of 3 to 20 miles per hour (fig. 6). Surveys lasted between 6 and 10 hours, covered 90 mi, and included up to 7,000 data-collection points.

Water was collected using a brass thru-hull fitting on the underside of the boat. A Shurflo wash-down pump delivered water to the instruments. Water-quality sensors were mounted to the pump platform (fig. 7). Water entered the sensors through the bottom of the flow-through chambers

Figure 6. Boat leaving Punta Rassa at the beginning of a water-quality survey.

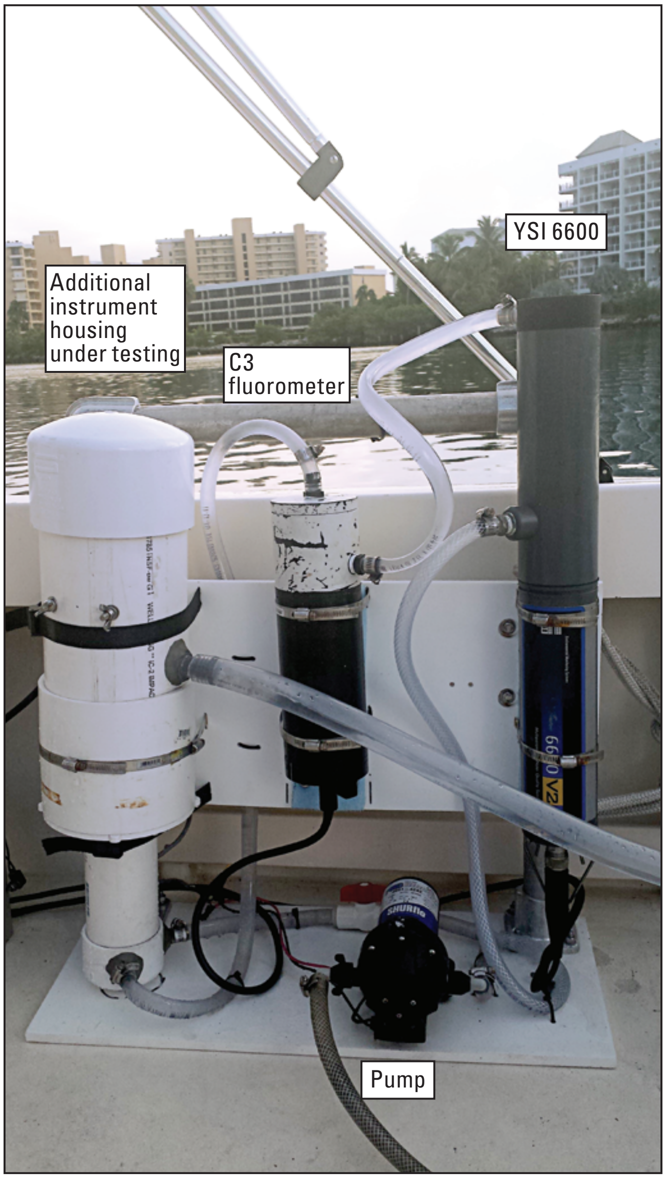


Figure 7. Water-quality sensors and pump system used for moving-boat surveys.

and exited through the top to minimize interference from bubbles. Location was recorded every 5 seconds using a global positioning system. Salinity, temperature, dissolved oxygen concentration, pH, and turbidity were recorded every 5 seconds with a YSI 6600 water-quality sonde and FDOM was recorded every 15 seconds with a Turner C3 submersible fluorometer. Sensor calibration verifications were performed less than 24 hours prior to surveys in accordance with protocols outlined in Wagner and others (2006) and manufacturer recommendations (YSI Incorporated, 2011; Turner Designs, 2012). To ensure no bias existed in the flow-through system, multiple data verifications were performed using a reference probe deployed in the water column. Instrument response time was about 30 seconds. Location data were not time-corrected because daily variations in water-quality conditions caused by tidal action exceeded location bias from system lag.

Data were analyzed and processed after field collection to remove erroneous data using procedures outlined in Soderqvist and Patino (2010). Sensor and coordinate data were imported into Environmental Systems Research Institute (Esri) ArcMap Geographical Informational System (GIS) program as point data. Booth and others (2014) mapped and tabulated specific conductance, temperature, dissolved oxygen concentration, pH, turbidity, and FDOM for 20 surveys from September 30, 2011, to December 30, 2014 (http://sofia.usgs.gov/exchange/ding_wqs/index.php).

Fluorescence Data Calculations

Instantaneous, 15-minute FDOM were recorded in the field as relative fluorescence units (Turner Designs, 2012). FDOM were corrected for temperature and turbidity with equations from Downing and others (2012), and converted to parts per billion (ppb) quinine sulfate equivalents units (QSE). After conversion, a correction was applied to account for inner filter effects using absorbance at 254 nanometers (A_{254}) (Downing and others, 2012). Because A_{254} is a laboratory value and continuous data are not available, a proxy for A_{254} was developed by plotting laboratory-calculated A_{254} with temperature- and turbidity-corrected FDOM (fig. 8). Laboratory-calculated A_{254} was determined from 88 samples collected during moving-boat surveys and in McIntyre Creek. The following equation was used to estimate absorbance: $A_{254} = (10^{-5} \times FDOM^2 - 0.0029 \times FDOM + 0.0299)$, with a coefficient of determination of 0.92 and a standard error of 1.81.

All samples were included in the analysis, with the exception of those from Telegraph Creek, which exhibited the largest variance in the relationship between FDOM and A_{254} and, therefore, was not included in the development of a proxy for A_{254} calculations. Telegraph Creek FDOM is not represented in the maps. Additional data from August 30, 2013, were not used to develop the relationship between FDOM and A_{254}, because the samples were frozen and rebottled and thus potentially compromised because of freeze-thaw effects (Spencer and others, 2007).

Instrument drift was monitored with PTSA (1, 3, 6, 8-pyrenetetrasulfonic acid tetrasodium salt) and Turner Designs solid standards. Drift was negligible and no corrections were required. Fouling corrections were determined using procedures outlined in Wagner and others (2006). Instantaneous 15-minute FDOM data are available in NWIS.

Instantaneous, 15-minute chlorophyll fluorescence data provided in NWIS were recorded in relative fluorescence units. Temperature corrections of 0.014 relative fluorescence units per °C were applied linearly by the instrument per manufacturer recommendations (Turner Designs, 2012). Data were converted to rhodamine WT equivalent units (RWTE) to standardize multiple sensors. Conversions were determined using serial dilutions of 400 ppb rhodamine WT (from Turner Designs) and deionized water. Negligible instrument drift was ensured by using solid standards. Fouling corrections were determined following procedures outlined in Wagner and others (2006).

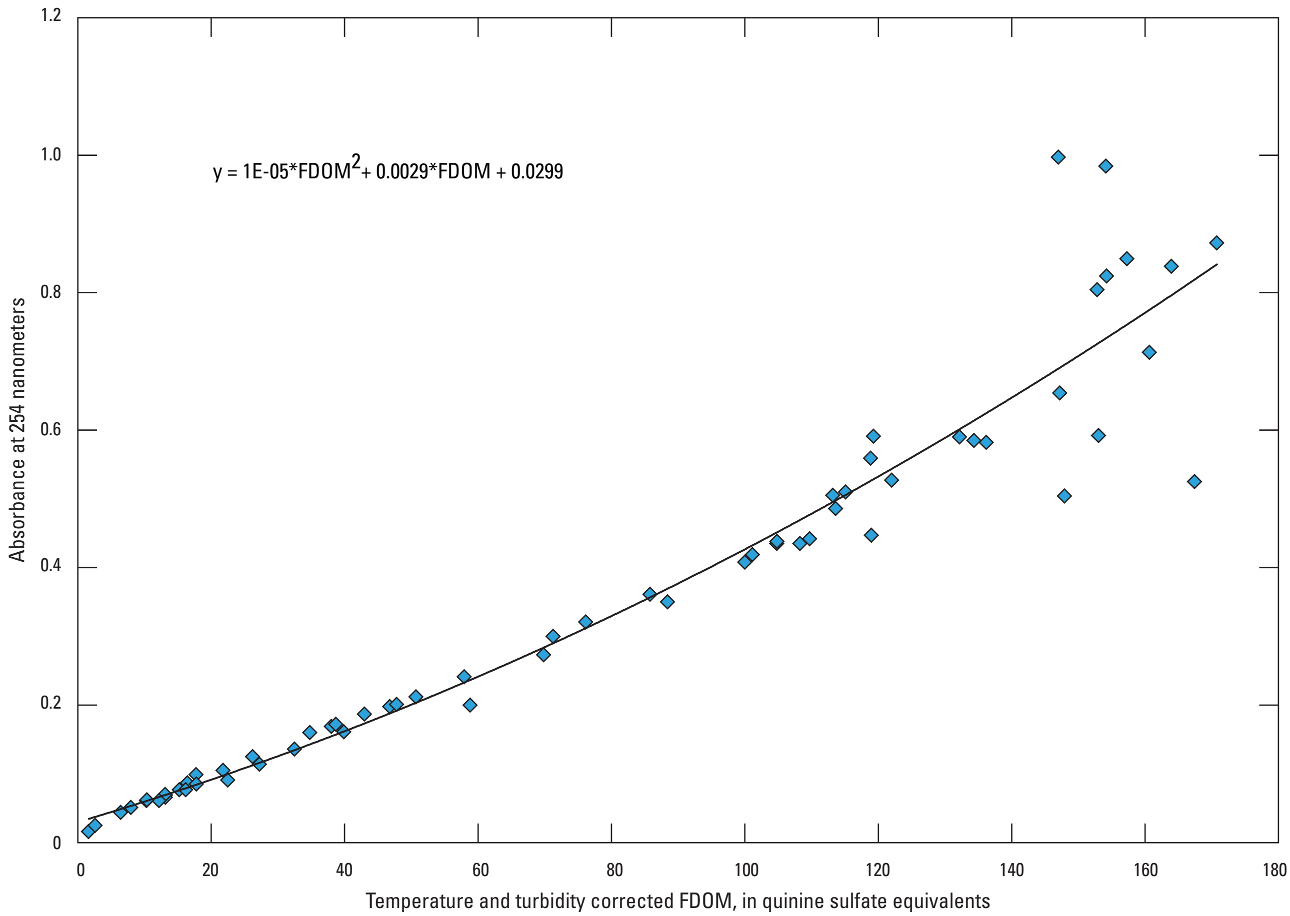


Figure 8. Absorbance at 254 nanometers (A_{254}) and temperature- and turbidity-corrected fluorescence of chromophoric dissolved organic matter (FDOM).

Flow Volume and Rate

Annual and monthly mean flow volumes during the study period are referenced to water years, which begin October 1 and end September 30. For example, water year 2012 extends from October 1, 2011, to September 30, 2012. During 2010, 2012, and 2013 more water was released through Moore Haven than through any other Lake Okeechobee outflow control structure; 2011 was a drought year during which flows were atypical (fig. 9). During water year 2013, about 63 percent of the outflow from Lake Okeechobee was discharged to the Caloosahatchee River through Moore Haven. In addition, flow through Moore Haven during water year 2013 was almost three times greater than flow through the St. Lucie Canal at S–308, the second greatest outflow from Lake Okeechobee during that year. Total Lake Okeechobee outflow volume was derived from the sum of outflow volume measured at the following USGS monitoring stations: Moore Haven, St. Lucie Canal below S–308, near Port Mayaca, L–8 Canal near Canal Point, Miami Canal at S–354 and S–3 at Lake Harbor, Hillsboro Canal below S–351 near South Bay, North New River Canal below S–351, near South Bay and Industrial Canal at Clewiston (table 1).

During 2010–13, there was a net water gain to the reach of the Caloosahatchee River between Moore Haven and Franklin Lock. Flow from Lake Okeechobee, as measured by the flow volume through Moore Haven, accounted for 21 to 52 percent of the flow through Franklin Lock, with a greater percentage of flow attributed to Lake Okeechobee during wet years. During the study period, annual flow volumes at Moore Haven and Franklin Lock were highest in 2013 (2,610,000 acre-feet [acre-ft] at Franklin Lock and 1,367,000 acre-ft at Moore Haven), and lowest in 2011 (393,700 acre-ft at Franklin Lock and 94,040 acre-ft at Moore Haven) (fig. 10).

During the study period, flows through Franklin Lock were highest in 2013, mostly during the peak wet-season months of July to September. Flows through Franklin Lock were lowest in 2011. The highest monthly mean flow rate was 10,650 cubic feet per second (ft^3/s) in August 2013, more than three times greater than the August monthly mean for the period of record (water years 1966–2013). The lowest monthly mean flow rate was 29 ft^3/s in May 2011. The monthly mean flow rate was less than the period-of-record average monthly flow rate during all of water year 2011 (fig. 11). During the study period, the number of no-flow days per year ranged from 22 days in 2013 to 151 days in 2011 (fig. 12).

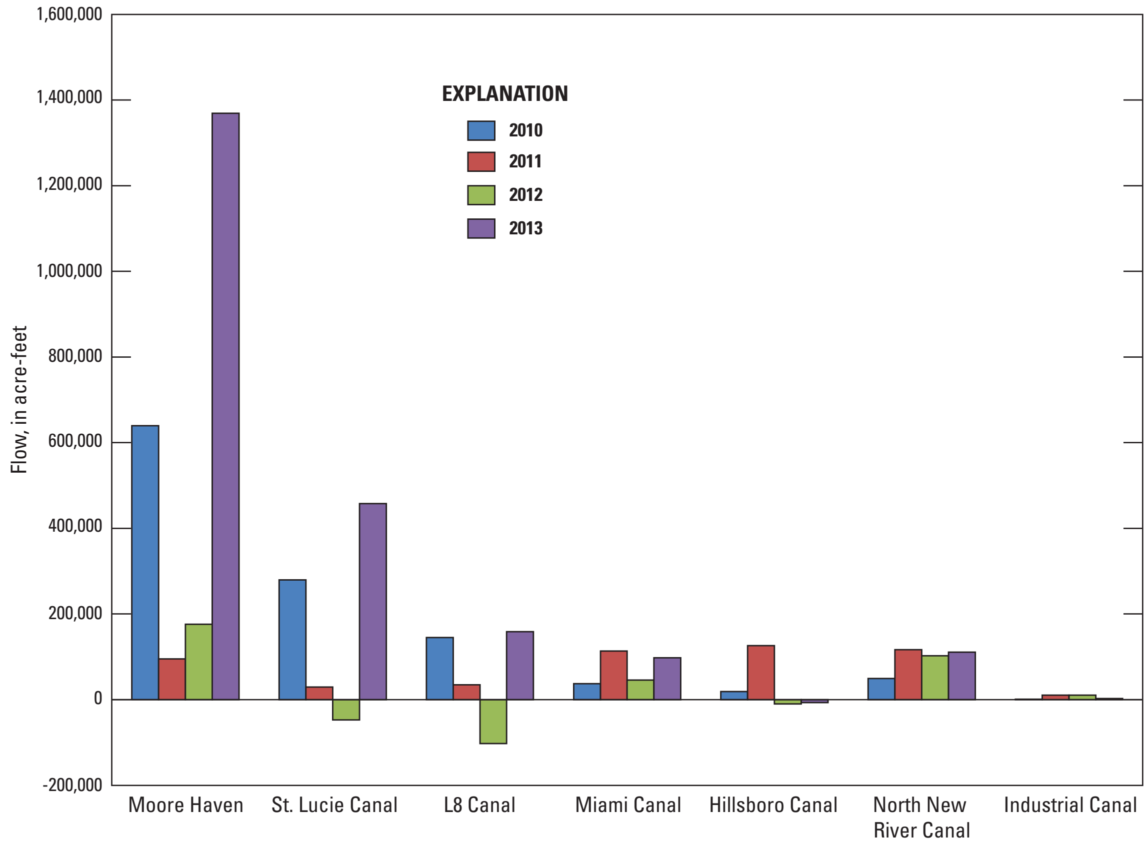


Figure 9. Lake Okeechobee outflows at monitored locations during water years 2010–13.

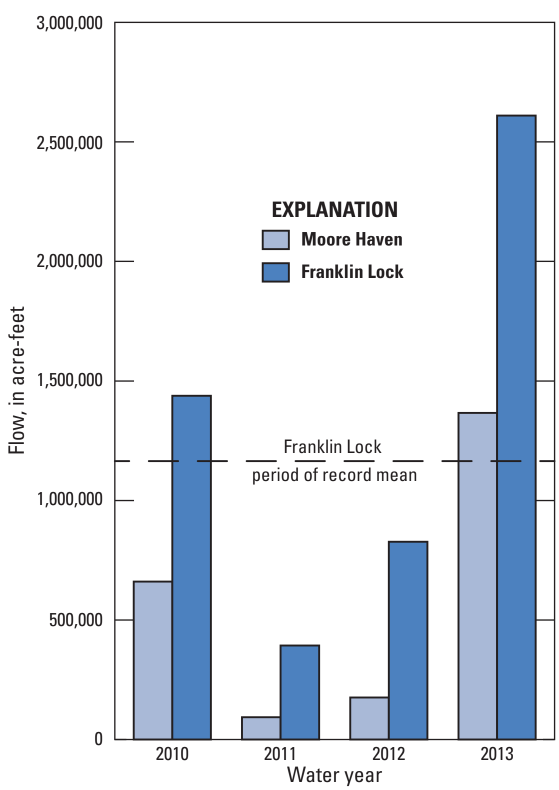


Figure 10. Annual flow volume at Moore Haven Lock and Franklin Lock during water year 2010.

During 2010–12, Franklin Lock was the largest contributor of freshwater flow to the tidal Caloosahatchee River. Inflow volume to the tidal Caloosahatchee River was calculated using the following USGS streamflow monitoring stations: Telegraph Creek, Orange River, Popash Creek, Hancock Creek, Billy's Creek, Whiskey Creek, Aries Canal, Courtney Canal, San Carlos Canal, and Meade Canal. Total inflow volume ranged from 117,400 acre-ft in 2011 to 183,700 acre-ft in 2010, compared to 393,700 acre-ft in 2011 and 1,438,000 acre-ft in 2010 at Franklin Lock (fig. 13). The record for water year 2013 is incomplete for tributary data and therefore is not presented herein. The percentage of flow volume from the tributaries compared to flow volume through Franklin Lock ranged from 13 percent in 2010 to 30 percent in 2011, indicating that the tributaries contribute a larger percentage of water during the drier years compared to wetter years.

From 2010 to 2013, flow volume from the Cape Coral canal system (calculated using the following USGS streamflow stations: Shadroe, Hermosa, Horseshoe and Gator Slough Canals) was substantially less than that through Franklin Lock. Flow volume from the canal system ranged from 32,910 acre-ft in 2011 to 84,340 acre-ft in 2013, compared to 393,700 and 2,610,000 acre-ft, respectively, at Franklin Lock. The flow volume from these canals was 3 to 8 percent of flow volume at Franklin Lock (fig. 14). Flow from Matlacha Pass moves to the north and to the south; therefore, flows from the Cape Coral canal system do not directly represent flows to San Carlos Bay.

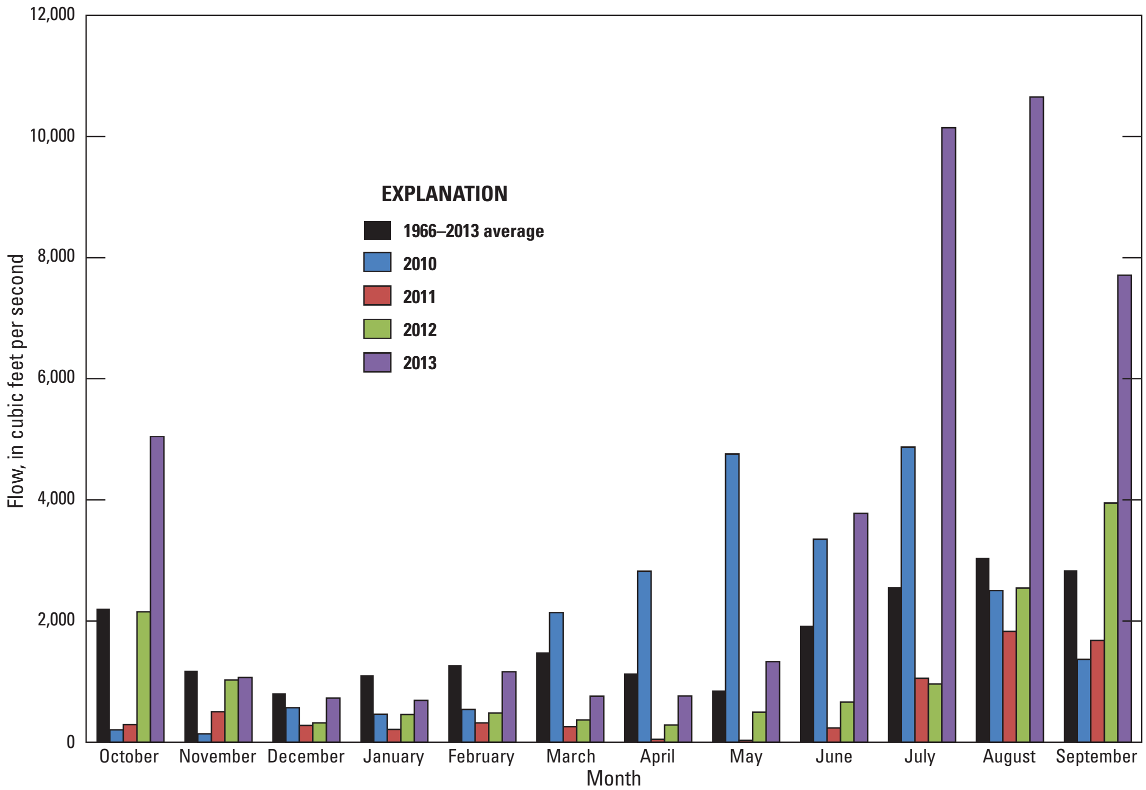


Figure 11. Period-of-record average monthly flow rate and the monthly mean flow rate at Franklin Lock by water year.

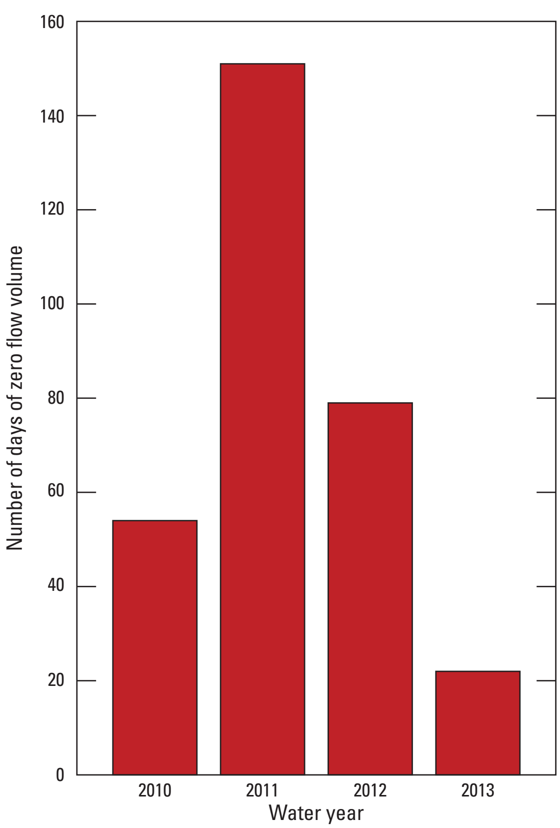


Figure 12. Number of days of zero flow at Franklin Lock during water years 2010–13.

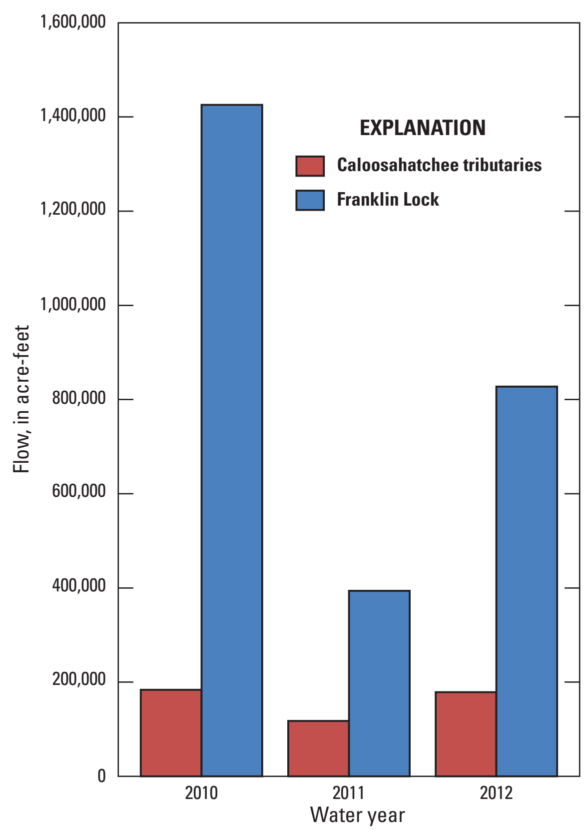


Figure 13. Annual flow volume through Franklin Lock and monitored tributaries during water years 2010–12.

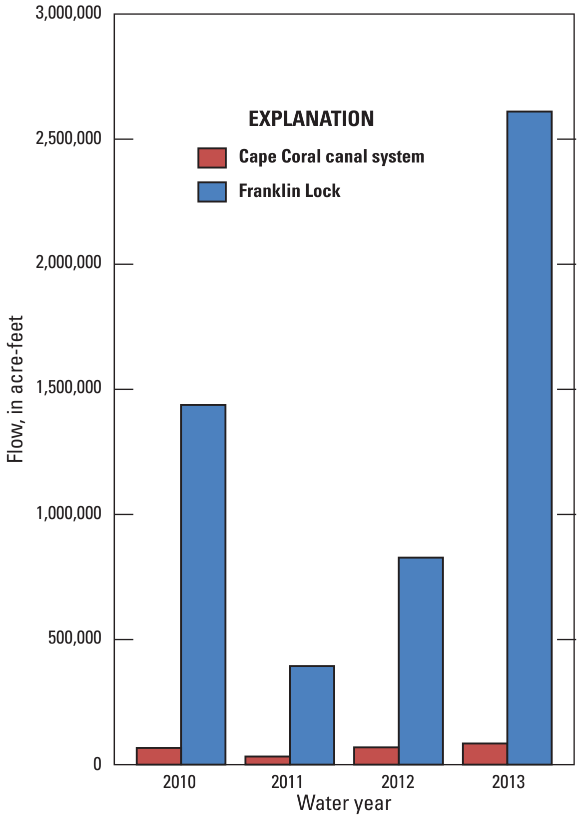


Figure 14. Annual flow volume from Cape Coral Canals compared to Franklin Lock during water years 2010–13.

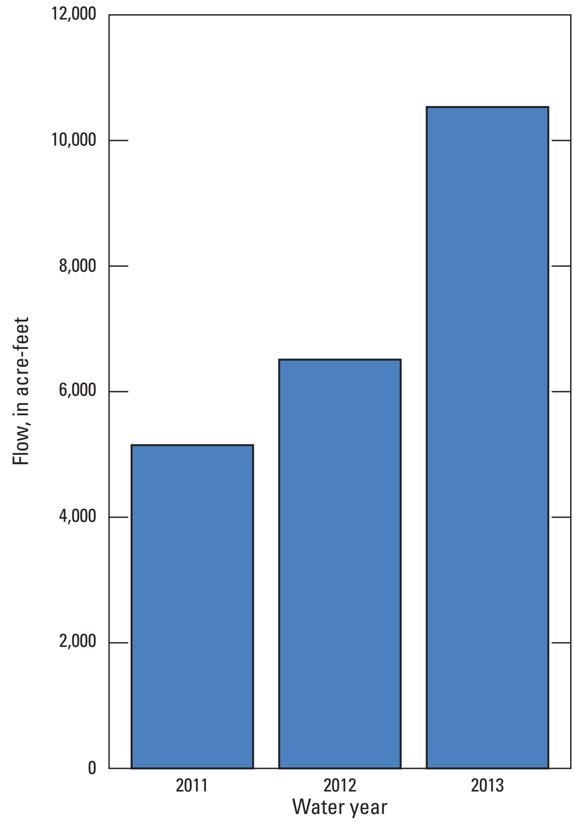


Figure 15. Annual flow volume at McIntyre Creek during water years 2011–13.

Positive flow in McIntyre Creek is considered inflow to Pine Island Sound and negative flow is inflow to Ding Darling Refuge. During the study period, annual flow volumes in McIntyre Creek were highest in 2013, totaling 10,530 acre-ft. The next highest annual flow volume was 6,511 acre-ft in 2012 followed by 5,147 acre-ft in 2011 (fig. 15). Flow data in McIntyre Creek are incomplete for 2010. The maximum daily value of filtered flow observed in McIntyre Creek was 489 ft^3/s, recorded on October 19, 2011; the minimum daily value was –330 ft^3/s, recorded on August 27, 2012.

McIntyre Creek is one of several creeks within the Ding Darling Refuge. These creeks are connected by numerous small channels and back bays, and internal exchange between creeks may occur. Flow measured at McIntyre Creek thus may not represent the net flow into and out of the refuge.

Water-Quality Characteristics

The study period included years in which flow from the Franklin Lock was greater than or less than the period-of-record average (1966–2013). Flow through Franklin Lock was lowest during 2011, and greatest during 2013; flow at Franklin Lock was below average for 2012. At McIntyre Creek, salinity and temperature data were measured near the water surface and near the channel bottom; analysis of the data indicated that stratification was insubstantial. The Pearson correlation coefficient was greater than 0.99 for the daily mean values of near-surface and near-bottom salinity, and for near-surface and near-bottom temperature; therefore, only near-surface temperature and salinity data are presented and discussed. All water-quality statistics are referenced to water years.

Temperature

Monthly mean temperature in McIntyre Creek ranged from 31.5 ºC in June 2010 to 15.1 ºC in December 2011 (fig. 16). The maximum instantaneous temperature recorded was 35.2 ºC on August 19, 2010 and the minimum instantaneous temperature recorded was 9.7 ºC on December 15, 2010.

Maximum temperatures recorded during moving-boat surveys ranged from 22.5 ºC on December 6, 2012 (near Franklin Lock) to 34.9 ºC on July 25, 2012 (near Orange River). Minimum temperatures ranged from 15.9 ºC on March 8, 2013 (near Punta Rassa) to 29.0 ºC on August 31, 2012 (near Franklin Lock). The smallest variation in temperature recorded during a single survey was 2.7 ºC on November 3, 2011 (this survey was incomplete), and the largest variation in temperature during a survey was 13.2 ºC on March 8, 2013. Elevated water temperatures were recorded near the mouth of the Orange River on multiple dates (fig. 17).

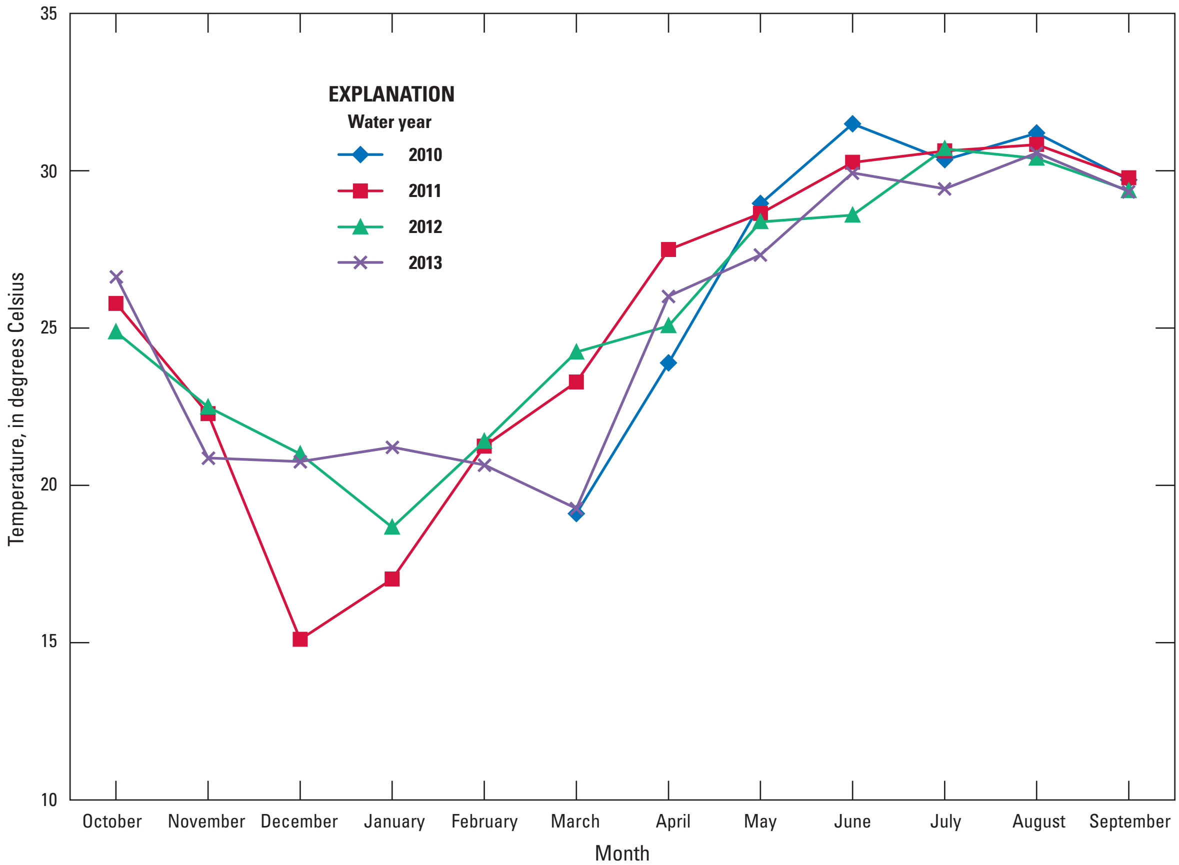


Figure 16. Monthly mean water temperature in McIntyre Creek during water years 2010–13.

Salinity

Monthly mean salinity in McIntyre Creek ranged from 35.9 ppt in June 2011 to 18.5 ppt in August 2013 (fig. 18). The maximum instantaneous salinity value (37.9 ppt) was recorded on June 27, 2011, and the minimum instantaneous salinity (12.9 ppt) was recorded on September 26, 2013.

Daily salinity at McIntyre Creek varied by less than 1 ppt during 55 percent of 2011, 49 percent of 2012, and 32 percent of 2013. Daily salinity varied by less than 3 ppt for 96 percent of 2011, 93 percent of 2012, and 81 percent of 2013. During 2011–12, salinities varied daily by more than 5 ppt less than 1 percent of the time. In 2013, daily salinities varied by more than 5 ppt about 4 percent of the time.

Maximum salinities during moving-boat surveys ranged from 29.2 ppt on September 27, 2013, in San Carlos Bay, to 35.6 ppt on November 3, 2011, offshore of Cayo Costa. Overall, maximum salinities were typically measured in San Carlos Bay or in the Gulf of Mexico. A minimum salinity of 0.1 ppt was measured on September 30, 2012; July 25, 2012; August 31, 2012; October 5, 2012; August 1, 2013; and September 27, 2013 (Booth and others 2014). Minimum salinities measured during individual surveys ranged from 0.1 to 6.5 ppt and typically occurred near Franklin Lock and in Caloosahatchee River tributaries. For example, salinity was 6.5 ppt near Franklin Lock on March 22, 2012 (fig. 19). The lowest salinity observed at the mouth of the Caloosahatchee River was less than 0.5 ppt on September 27, 2013.

Dissolved Oxygen Concentration

Monthly mean dissolved oxygen concentrations in McIntyre Creek ranged from 8.0 mg/L in December 2010 to 4.6 mg/L in August 2011 (fig. 20). Daily mean dissolved oxygen concentration was less than 4 mg/L on August 23–25, 2010, on 12 days during July and August 2011, and on September 26, 2013. Daily mean dissolved oxygen concentration exceeded 4 mg/L during all of water year 2012.

The maximum instantaneous value for dissolved oxygen concentration at McIntyre Creek was 17 mg/L recorded on April 22, 2010. The minimum instantaneous value was 1.1 mg/L, recorded on June 17, 2010, and August 10, 2011. Water year 2013 had the fewest days (2) with dissolved oxygen concentrations less than 2 mg/L and water year 2011 had the most days (11) (fig. 21).

The annual average daily range in dissolved oxygen concentrations at McIntyre Creek was 4.8 mg/L per day during water years 2011–13. Data for water year 2010 are incomplete; however, the average daily range for the available data was 5.6. The average daily dissolved oxygen concentration ranged from 2.2 to 13.5 mg/L in 2010, 2.0 to 8.8 mg/L in 2011, 1.8 to 9.9 mg/L in 2012, and 1.4 to 12.3 mg/L in 2013.

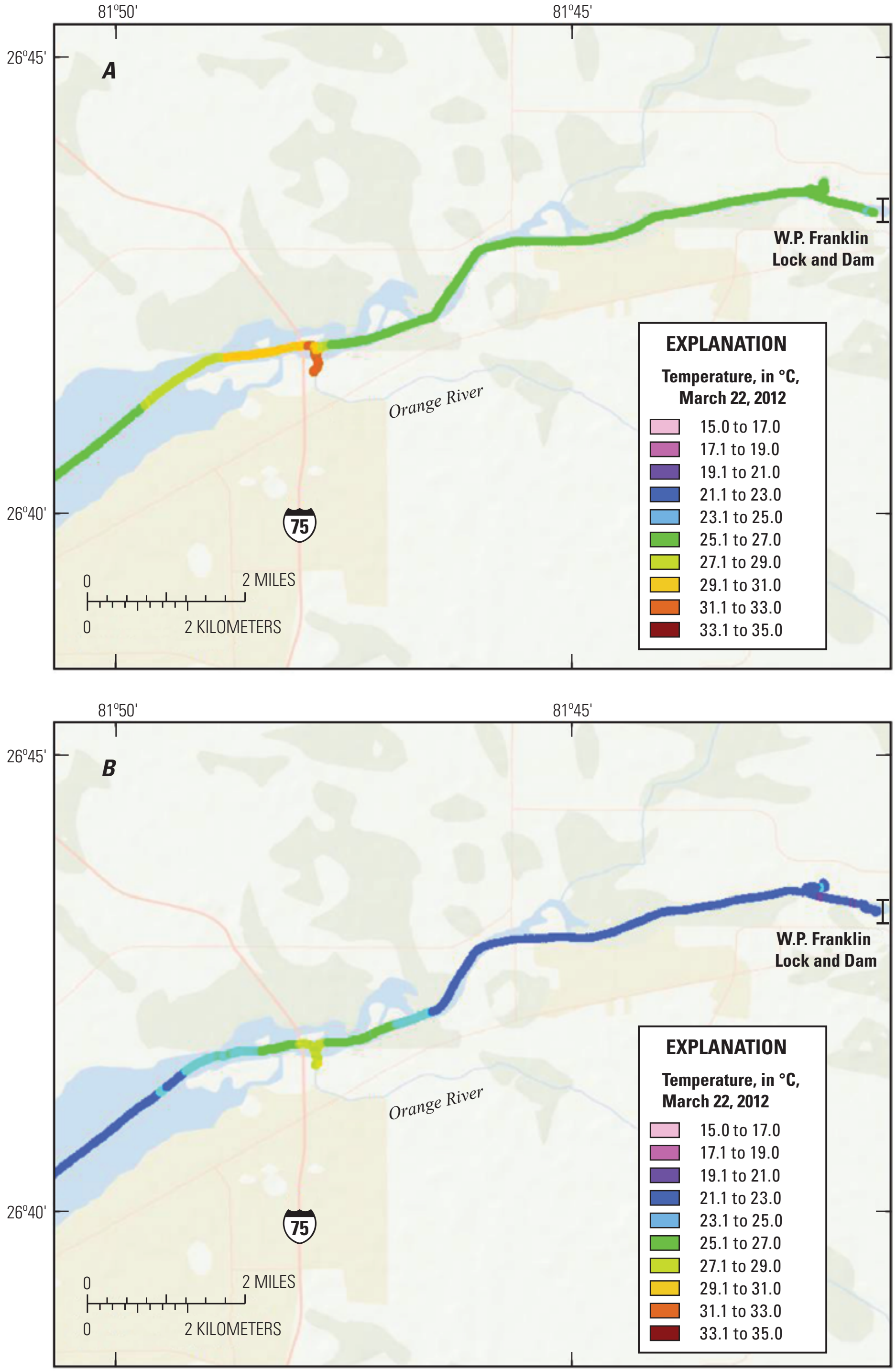


Figure 17. Water temperature on, *A*, March 22, 2012, and, *B*, March 8, 2013.

The highest and lowest dissolved oxygen concentrations recorded during a single water-quality survey were both observed on August 31, 2012; 16.0 mg/L was recorded in Charlotte Harbor and 2.2 mg/L was recorded near the mouth of Billy's Creek (fig. 22). Dissolved oxygen concentrations were particularly low during the September 30, 2011, water-quality survey, with the maximum value recorded during this survey (6.8 mg/L) in Charlotte Harbor and offshore of the cities of Sanibel and Fort Myers.

pH

Monthly median pH in McIntyre Creek ranged from 8.3 in December 2010, January 2012, April 2012, and May 2012 to 7.9 in October 2012 (fig. 23). The maximum instantaneous recorded value was 8.7 recorded on June 15 and 16, 2013. The minimum instantaneous recorded value was 7.4, recorded on numerous days in 2011 and 2013.

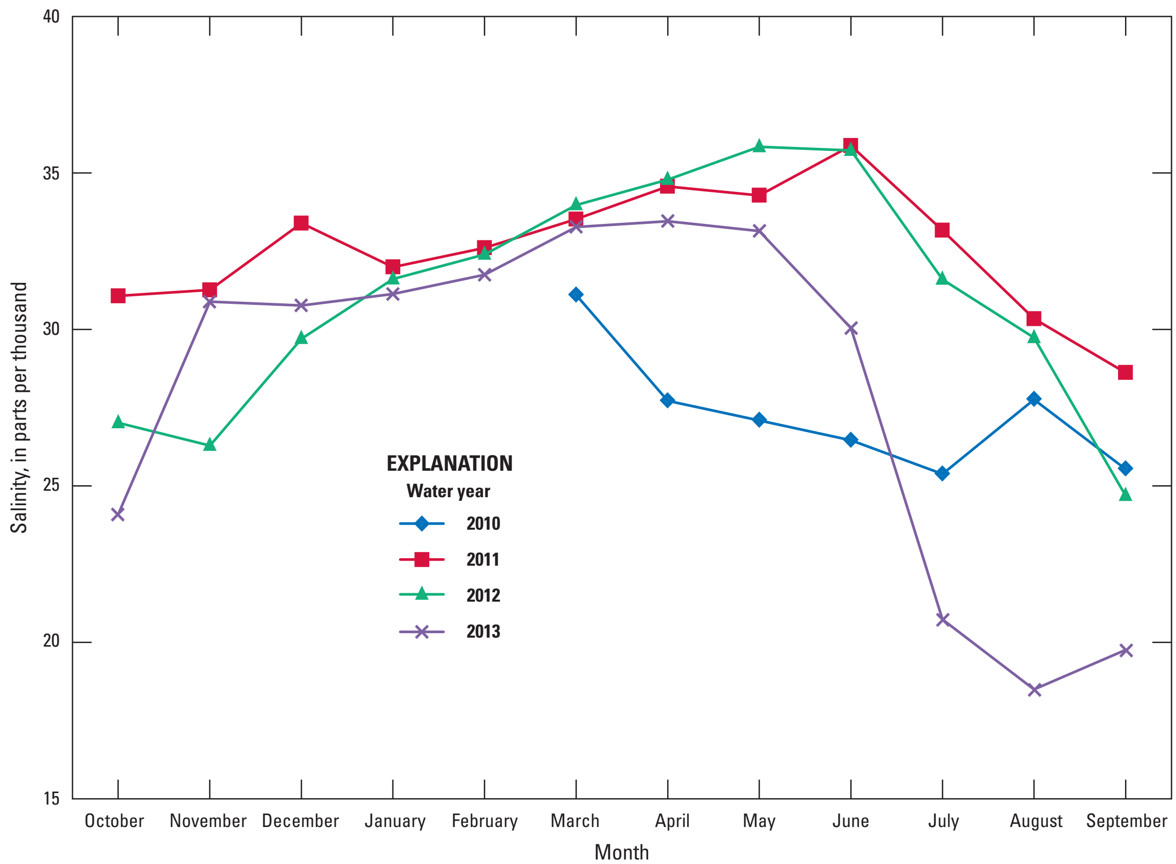


Figure 18. Monthly mean salinity in McIntyre Creek during water years 2010–13.

The highest pH recorded during a single moving-boat survey was 8.8, measured in Telegraph Creek on August 1, 2013 and in Charlotte Harbor on August 31, 2012 (fig. 24*A*). Maximum pH values ranged from 8.1 to 10.4. The lowest pH values recorded were 6.9 on July 25, 2012, and October 5, 2012 near the mouth of Telegraph Creek and on August 1, 2013 near the marina at the Fort Myers Yacht Basin (fig. 24*B*–*D*). Minimum pH values during individual surveys ranged from 6.9 to 8.0.

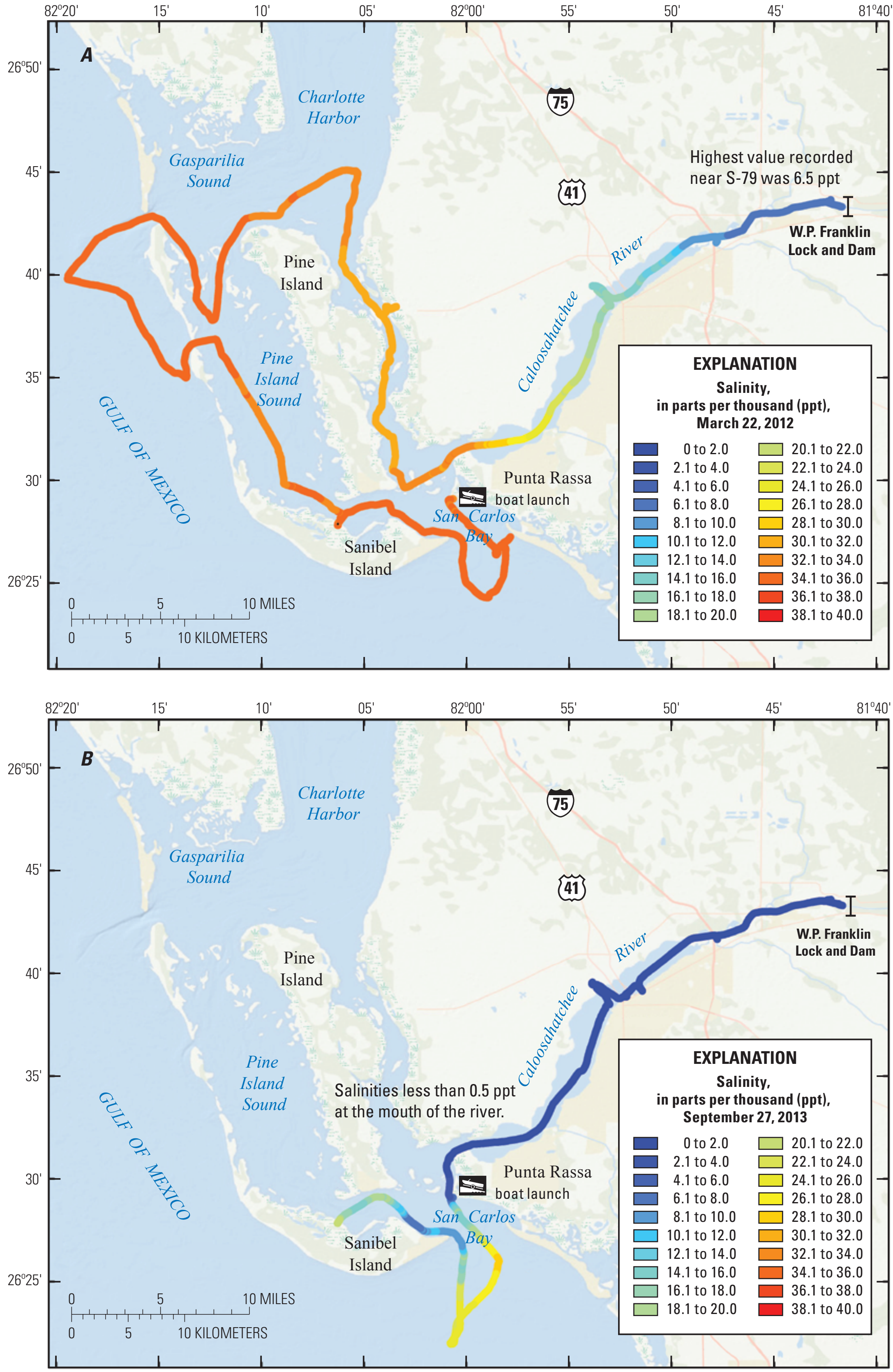
Turbidity

Monthly mean turbidity values in McIntyre Creek ranged from 5.7 FNU in October 2010 and 2011 to 1.5 FNU in December 2012 (fig. 25). The maximum instantaneous turbidity was 110 FNU recorded on August 26, 2012 during Tropical Storm Isaac. The minimum instantaneous value of 0.1 FNU was recorded on numerous days during several water years. The highest daily mean turbidity (33 FNU) was recorded on December 23, 2012 corresponding with the reported occurrence of a harmful algal bloom in the area (National Oceanic and Atmospheric Administration, 2011).

The highest turbidity value recorded during a single moving-boat survey was 26.4 FNU on March 22, 2012. This value was recorded in the breaker zone offshore of Fort Myers Beach when the survey boat deviated from the usual route due to the emergency rescue of a stranded jet skier. The values are probably due to the close proximity of the survey transect to the beach and the swash zone (fig. 26). Turbidity values greater than 20 FNU were recorded during 29 percent of the moving-boat surveys. More than half of the surveys (57 percent) documented turbidity values greater than 15 FNU. Turbidity values did not exceed 10 FNU during 21 percent of the surveys. The lowest maximum turbidity value recorded during a single water-quality survey (6.2 FNU) was recorded on December 10, 2013. The minimum turbidity value of 0.0 FNU was recorded on numerous dates, and this minimum value was documented during 64 percent of surveys.

Fluorescence of Chromophoric Dissolved Organic Matter (FDOM)

Monthly mean FDOM values in McIntyre Creek ranged from 117.2 ppb QSE in July 2013 to 17.5 ppb QSE in May 2012 (fig. 27). The maximum instantaneous value for FDOM (183.9 ppb QSE) was recorded on July 23, 2013; the minimum instantaneous value (3.1 ppb QSE) was recorded on June 26 and 27, 2012. Field conditions prevented discrete samples with FDOM values greater than 170 ppb QSE from being collected to determine the correction for absorbance, resulting in increased uncertainty in FDOM values greater than 170 QSE. The lowest daily mean value (10.4 ppb QSE) also was recorded on June 26, 2012. The highest daily mean value (174.9 ppb QSE) was recorded on July 25, 2013.



Base map sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 19. Salinity on, *A*, March 22, 2012, and *B*, September 27, 2013.

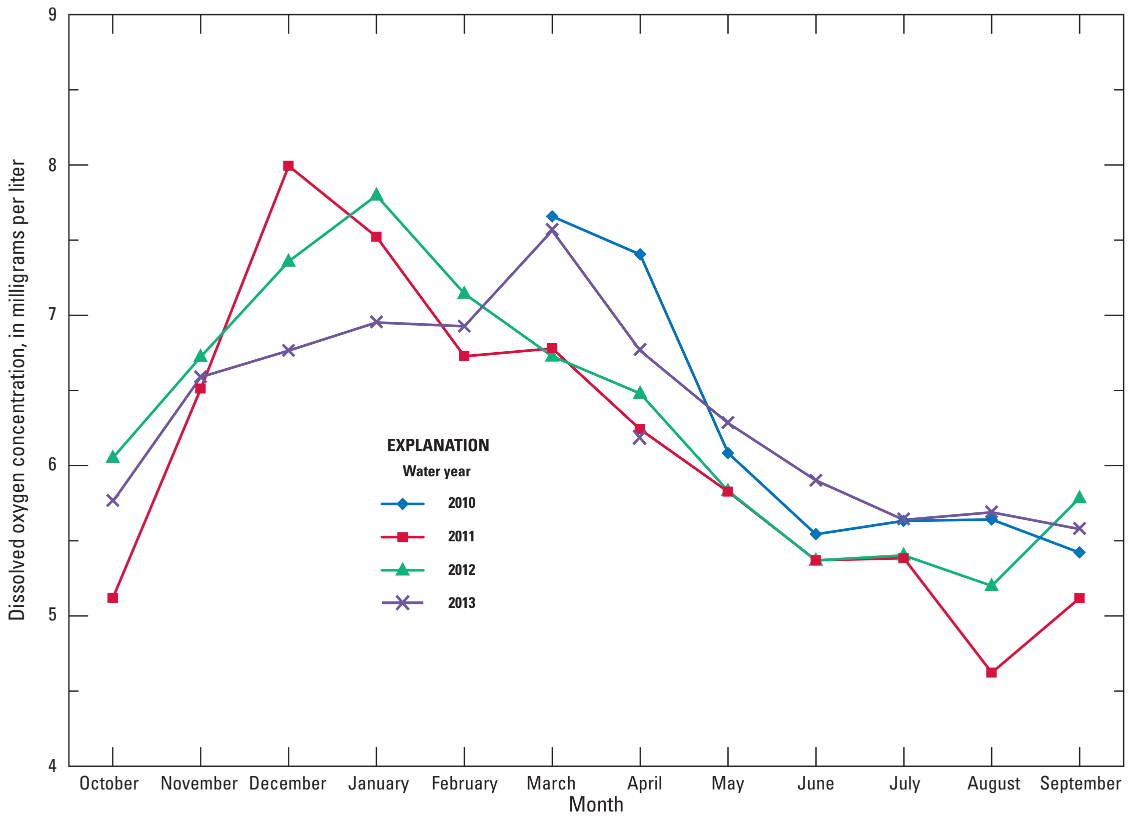


Figure 20. Monthly mean dissolved oxygen concentration in McIntyre Creek during water years 2010–13.

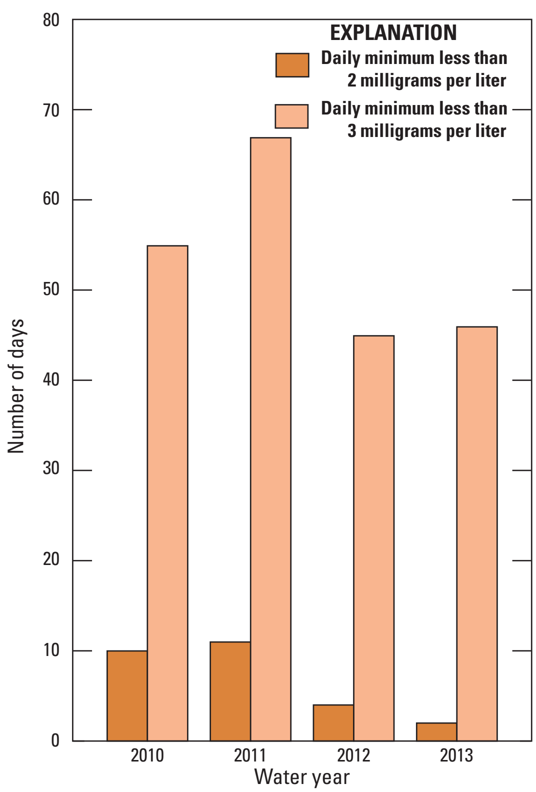
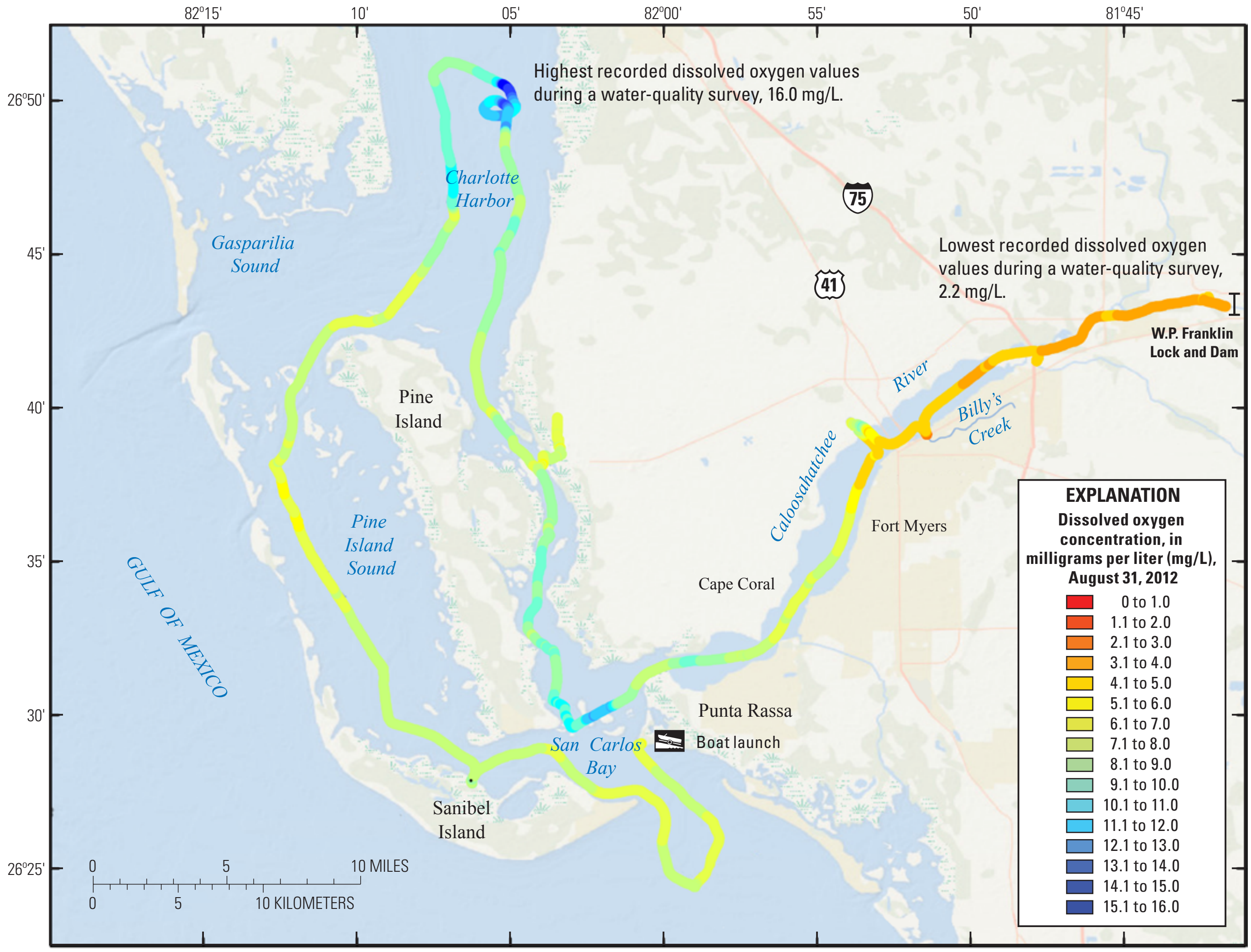


Figure 21. Number of days the instantaneous minimum concentration of dissolved oxygen was less than 2 and 3 milligrams per liter.

The highest FDOM value recorded during a single moving-boat survey (479.5 ppb QSE) was at the mouth of Billy's Creek on July 25, 2012. Instrument performance above 350 QSE was not verified against standards, and values greater than 350 QSE are subject to greater uncertainty. The highest FDOM values recorded occurred near the mouth of Billy's Creek during 37 percent of the surveys, immediately downstream of Franklin Lock during 26 percent of the surveys, upstream of the I–75 bridge near or at the mouth of Orange River during 26 percent of the surveys, and near the mouth of Telegraph Creek during 11 percent of the surveys. The lowest value (1.1 ppb QSE) was recorded approximately 3 mi south-southeast of the eastern tip of Sanibel Island on March 22, 2012. The lowest values recorded during moving-boat surveys typically were obtained in the Gulf of Mexico offshore of Sanibel Island and Fort Myers Beach. The highest minimum value for any single survey (40.7 ppb QSE) was recorded on September 27, 2013, 3 mi east-southeast of the eastern tip of Sanibel Island. FDOM values of 10 ppb QSE or less were recorded during 56 percent of the surveys.

Chlorophyll Fluorescence

Monthly mean chlorophyll fluorescence values at McIntyre Creek ranged from 213 ppb RWTE in September 2012 to 35.0 ppb RWTE in March 2013 (fig. 28). Monthly mean data are not available for July and August 2013



Base map sources: Esri, GEBCO, NOAA, National Geographic, DeLorme, HERE, Geonames.org, and other contributors

Figure 22. Dissolved oxygen concentration measured during a moving-boat survey in the study area on August 31, 2012.

because of heavy biofouling. The maximum instantaneous recorded value for chlorophyll was 2,860 ppb RWTE on December 26, 2011. In late December 2011 patchy, high concentrations (>1,000,000 cells/liter) of harmful algal blooms near Sanibel Island were reported (National Oceanic and Atmospheric Administration, 2011). The minimum instantaneous chlorophyll fluorescence value was 13.9 ppb RWTE, recorded on February 25, 2013. The lowest daily mean value, 21.7 ppb RWTE, was recorded on December 25, 2012. The highest daily mean, 342 ppb RWTE, was recorded on December 31, 2011. The average daily range in chlorophyll fluorescence was 99.4 ppb RWTE, and the median daily range was 69.3 ppb RWTE. A minimum daily range of 7.6 ppb RWTE occurred on December 25, 2012, and a maximum daily range of 2,748 ppb RWTE was recorded on December 26, 2011. The large daily ranges in December 2011 can be attributed to tidal movement of the patchy harmful algal bloom.

Effects of Flow Through Franklin Lock on Downstream Water Quality

Flow volume through Franklin Lock accounted for 72 to 85 percent of the monitored flow to the Caloosahatchee River Estuary between 2010 and 2012. Flow from Lake Okeechobee, as measured by flow volume through Moore Haven, accounted for 21 to 52 percent of the flow volume to Franklin Lock between 2010 and 2013. During wet years, a greater percentage of flow through the Franklin Lock was attributed to Lake Okeechobee than during dry years because lake levels are routinely lowered during wet years to protect the Herbert Hoover Dike.

Water temperature varied seasonally and was highest during the summer and lowest during the winter. The effects of releases through Franklin Lock on downstream water temperature were not studied. High water temperatures were recorded

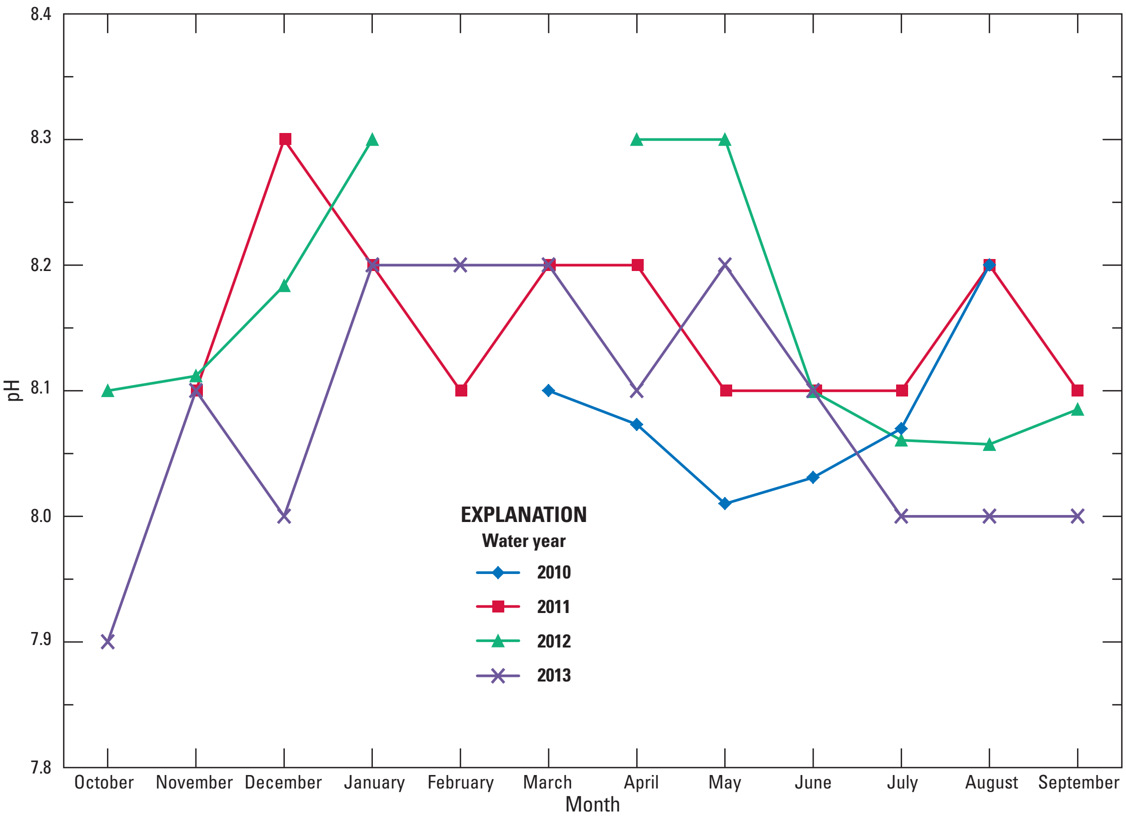


Figure 23. Median monthly pH in McIntyre Creek during water years 2010–13.

near the mouth of the Orange River (fig. 17). High temperatures are attributed to a Florida Power and Light power plant that releases warm water to the Orange River, providing a thermal refuge for manatees during winter months (Smith, 1993).

Salinity followed seasonal regimes and was highest at the end of the dry season and lowest during the wet season, corresponding with input from rainfall and releases from Franklin Lock. Average daily salinity in McIntyre Creek was highest in late June 2011, following many days of no flow at Franklin Lock (fig. 29). In addition, 2011 included the greatest number of days (151) with no measured flow at Franklin Lock. Monthly mean salinity at McIntyre Creek was highest (35.9 ppt) in June 2011. In contrast, the average monthly flow rate at Franklin Lock during the study period was lowest (29 ft^3/s) in May 2011, increasing to only 234 ft^3/s in June 2011. Monthly mean salinity recorded at McIntyre Creek was lowest (18.5 ppt) in August 2013, when monthly mean flow through Franklin Lock was highest (10,650 ft^3/s).

The average flow rate at Franklin Lock was 54.7 ft^3/s for the 30 days prior to June 27, 2011, when the period-of-record maximum instantaneous salinity (37.9 ppt) was also recorded at McIntyre Creek. In contrast, the average flow rate at Franklin Lock was 7,684 ft^3/s for the 30 days prior to September 26, 2013, when the period-of-record minimum instantaneous salinity (12.9 ppt) was recorded. Correlated component regressions between salinity in McIntyre Creek and flow rate at Franklin Lock, filtered flow rate, and water level at McIntyre Creek indicate that flow through Franklin Lock accounted for 61 percent of the variation in salinity in McIntyre Creek. An increase in flow rate is negatively correlated with salinity in McIntyre Creek (fig. 30). Although McIntyre Creek receives freshwater input from direct rainfall and runoff from the local watershed, the contribution of water through Franklin Lock to the estuary relative to other known freshwater sources indicates flow from Franklin Lock influences salinity in McIntyre Creek.

Water-quality surveys indicated a decrease in salinity in McIntyre Creek with increasing flow from Franklin Lock. Wet-season salinity surveys (October 21, 2011, November 4, 2011, August 31, 2012, October 5, 2012, August 1, 2013, and September 27, 2013; Booth and others, 2014), indicated that a freshwater plume from the Caloosahatchee River flows into San Carlos Bay and then enters McIntyre Creek. These surveys also indicate that the Sanibel Causeway restricts tidal flushing, thereby causing freshwater retention in the estuary. The highest salinities recorded at Franklin Lock during a water-quality survey were on March 22, 2012 (6.5 ppt), corresponding with an average daily flow rate of only 464 ft^3/s for the 30 days prior to the survey. The lowest salinities recorded at the mouth of the river (<0.5 ppt) occurred on September 27, 2013, corresponding with an average daily flow rate of 7,730 ft^3/s for the 30 days prior to the survey.

Dissolved oxygen concentrations exhibited seasonal trends: the lowest daily average concentrations at McIntyre Creek occurred during the warm months of June to October, and the highest daily averages occurred during the cold months of December to March (fig. 31). A correlated

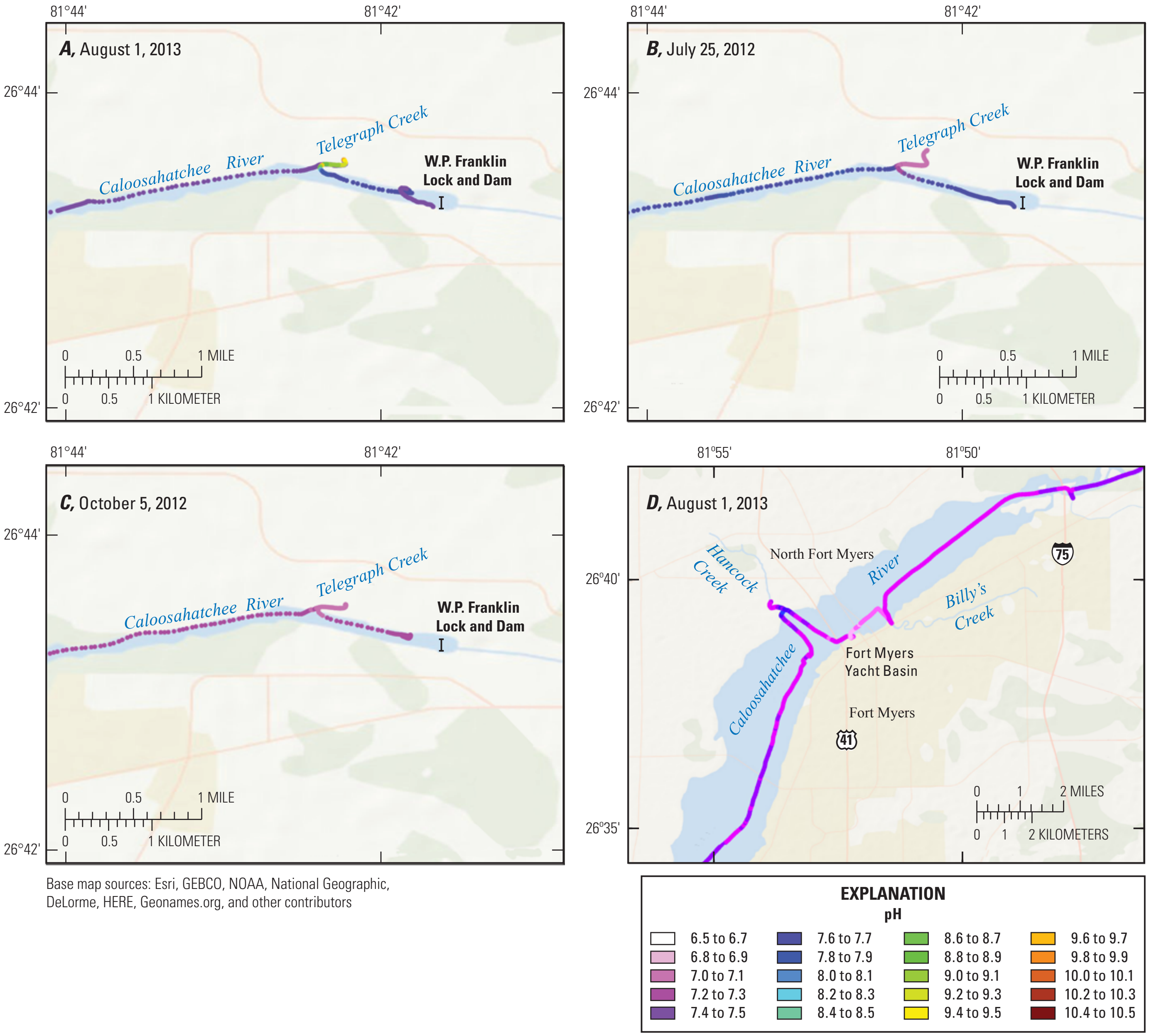


Figure 24. Maps showing pH near Telegraph Creek on, *A*, August 1, 2013; *B*, July 25, 2012; *C*, October 5, 2012; and *D*, near the Fort Myers Yacht Basin on August 1, 2013.

component regression using flow rate at Franklin Lock, filtered flow rate, water-surface elevation, salinity, and temperature at McIntyre Creek was used to predict dissolved oxygen concentrations. The only input retained in the model was temperature, which accounted for 56 percent of the variation in dissolved oxygen concentration. A regression for dissolved oxygen concentrations was calculated with flow rates at Franklin Lock as the predictor, and indicated a slight decrease in dissolved oxygen concentrations with an increase in flow rate through Franklin Lock; however, the results were not significant (fig. 32). These results indicate that temperature has the most substantial influence on dissolved oxygen, which can be explained by the greater oxygen-holding capacity of cold water relative to warm water.

Dissolved oxygen concentrations near the surface during moving-boat surveys (Booth and others, 2014) do not indicate any direct relations with flow through Franklin Lock. Dissolved oxygen concentrations less than 3 mg/L were observed in the Caloosahatchee River downstream of Franklin Lock on September 30, 2011, October 5, 2012, and August 1, 2013. Billy's Creek also had dissolved oxygen concentrations less than 3 mg/L on several survey dates.

Freshwater releases at Franklin Lock could indirectly affect dissolved oxygen concentrations in McIntyre Creek. If nutrients are released with the freshwater flow through Franklin Lock, these nutrients could increase phytoplankton growth and algal blooms, which would increase dissolved oxygen concentrations. Dissolved oxygen concentrations

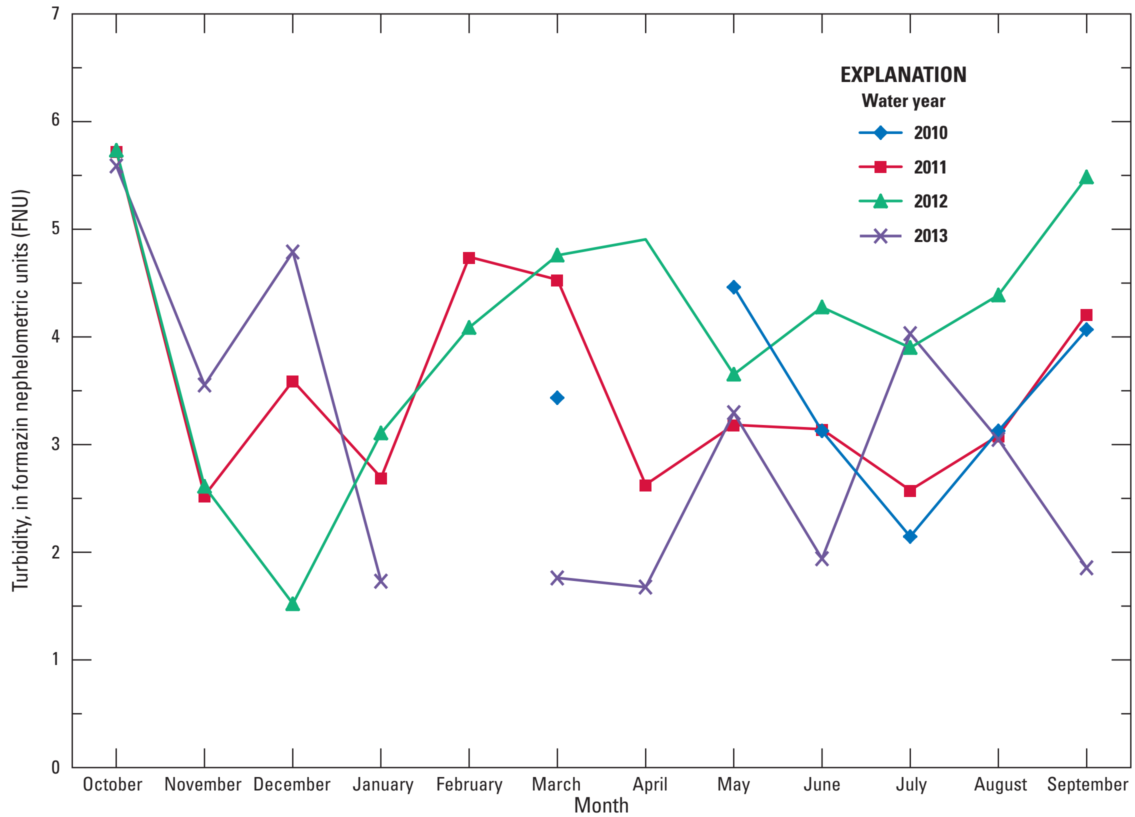


Figure 25. Monthly mean turbidity in McIntyre Creek during water years 2010–13.

could also decrease from dieoff of the increased phytoplankton growth and algal blooms. Additionally, a decrease in the photic zone in response to an increase in color (owing to high FDOM flow though Franklin Lock) could decrease dissolved oxygen concentrations by blocking light and decreasing photosynthesis rates, particularly in the nearshore parts of the estuary and tidal Caloosahatchee River where the FDOM values are greater. Additional research on nutrient fluxes and phytoplankton and algal community dynamics could help determine what affects, if any, freshwater releases through Franklin Lock have on dissolved oxygen concentrations. Additionally, this study only looked at dissolved oxygen concentrations near the surface; the relationship between dissolved oxygen near the substrate was not evaluated.

The highest daily median pH at McIntyre Creek (8.5) measured on January 4, 2012, corresponded with a period of no flow through Franklin Lock. When daily mean flow rate at Franklin Lock was greater than 4,000 ft^3/s, median pH recorded at McIntyre Creek never exceeded 8.2 (fig. 33). A correlated component regression using flow rate at Franklin Lock, filtered flow rate, water level, dissolved oxygen, salinity, and temperature in McIntyre Creek indicated that the only predictor of pH retained in the model was dissolved oxygen concentration. The positive correlation with dissolved oxygen concentration (which explained 31 percent of the variation in pH) may indicate that biological cycles, specifically algal dynamics, affect pH. Additional correlated component regression using flow rate at Franklin Lock, filtered flow rate, and water level at McIntyre Creek indicated that the flow rate at Franklin Lock was the only predictor retained (and explained 21 percent of the variation in pH) (fig. 34). Based on these results, flow through Franklin Lock decreased pH at McIntyre Creek by reducing the salinity. Generally, alkalinity increases with salinity in estuarine systems; the average pH is typically 7.0 to 7.5 in fresh estuarine areas and 8.0 to 8.5 in more saline areas (U.S. Environmental Protection Agency, 2006). Water-quality maps of pH indicated an increase in pH with distance from Franklin Lock. The lowest pH values observed, however, were recorded in Telegraph Creek on several dates, indicating that additional factors affect the pH in the Caloosahatchee River Estuary.

Daily mean turbidity at McIntyre Creek had a small range (fig. 35) and no apparent relations to daily mean flow rate at Franklin Lock were evident (fig. 36). Results from previous studies of the tidal Caloosahatchee River indicated that turbidity did not vary as a function of distance from Franklin Lock (Doering and Chamberlain, 1998). The elevated daily mean turbidity values in December 2012 corresponded to reports of a harmful algal bloom in the area (National Oceanic and Atmospheric Administration, 2011).

The FDOM values at McIntyre Creek were generally highest during July through October (fig. 37). The average flow rate at Franklin Lock was 8,766 ft^3/s during the 30 days prior to July 25, 2013 when the maximum average daily FDOM value (174.9 ppb QSE) was recorded. In contrast, the average flow rate at Franklin Lock was 528 ft^3/s the 30 days prior to June 26, 2012, when the average daily

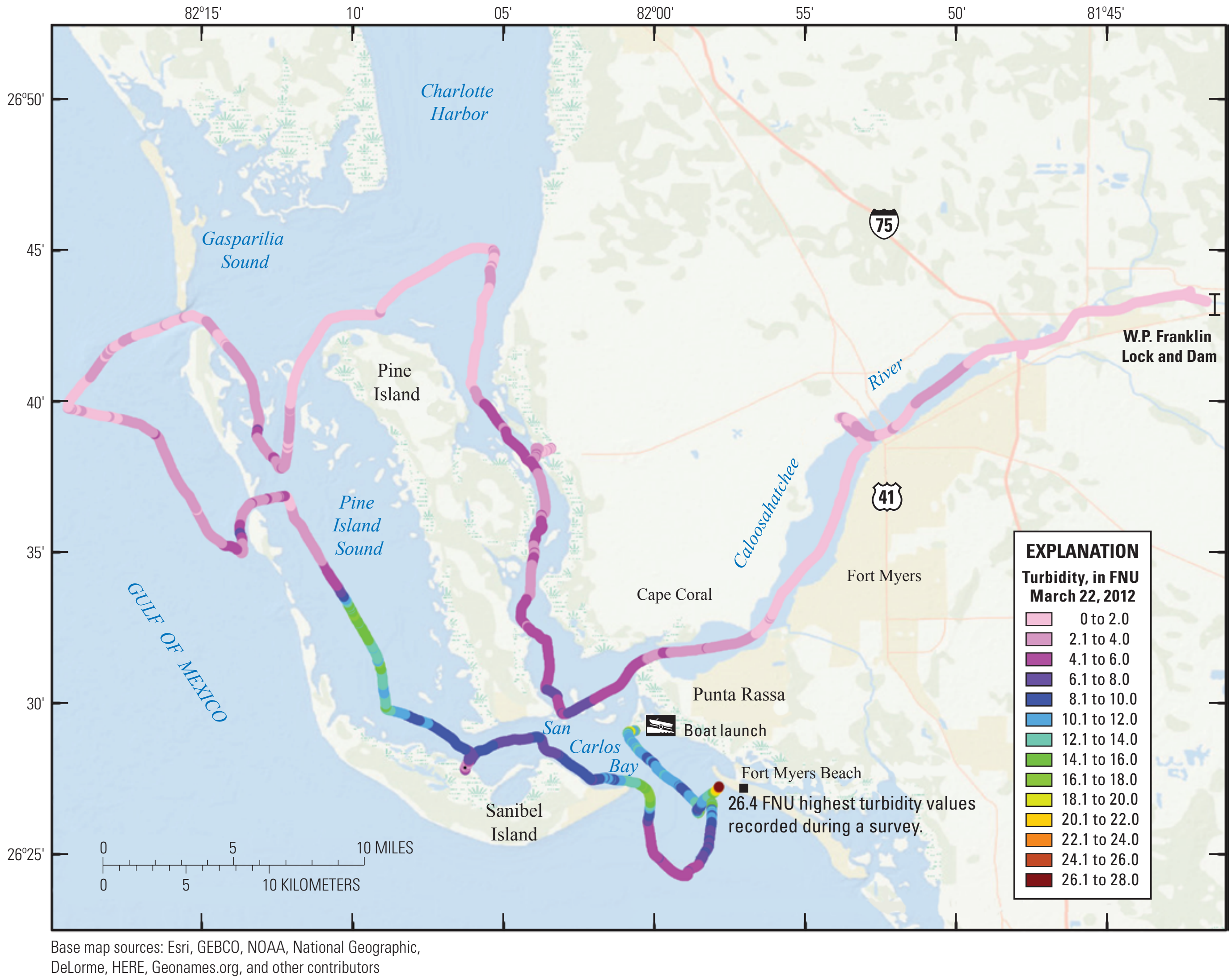


Figure 26. Turbidity measured during a moving-boat survey in the study area on March 22, 2012. [FNU, formazin nephelometric unit]

minimum (10.4 ppb QSE) for FDOM was recorded at McIntyre Creek. A correlated component regression using flow rate at Franklin Lock, filtered flow rate, water level, dissolved oxygen, salinity, and temperature at McIntyre Creek was used to model FDOM. The only predictor retained in the model was salinity, which accounted for 84 percent of the variation in FDOM. Correlated component regressions between FDOM at McIntyre Creek and flow rate at Franklin Lock, filtered flow rate, and water level at McIntyre Creek indicated that the flow rate through Franklin Lock was positively correlated with FDOM and accounted for 54 percent of the variation (fig. 38). The results indicate that in addition to salinity, freshwater releases through Franklin Lock affect FDOM at McIntyre Creek. The stronger correlation to salinity is probably attributable to the temporal lag, the time between the release of freshwater from Franklin Lock and its arrival at McIntyre Creek. The lag time is further complicated by variations caused by tides, wind, and flow magnitude at Franklin Lock. No attempt was made to account for the lag in the correlation analysis. As a result, the correlations between flow rate at Franklin Lock and FDOM, and flow rate at Franklin Lock and salinity, are inherently weaker than the correlation between FDOM and salinity, which experiences a similar lag.

Dissolved organic matter can originate from many different sources and processes, and it can be allocthonous or autochthonous in nature. The FDOM values in the Caloosahatchee River, McIntyre Creek and surrounding estuaries could differ based upon whether the source of the water is predominantly from runoff between Lake Okeechobee and the Franklin Lock, or if the water is predominantly from Lake Okeechobee by way of releases from Moore Haven, both of which can vary year to year. This variation probably explains why the correlation between flow though Franklin Lock and FDOM at McIntyre Creek is weaker than the correlation between flow through Franklin Lock and salinity at McIntyre Creek; even though the lag time and process of mixing of riverine and marine waters are the same for FDOM and salinity, FDOM is inherently more variable.

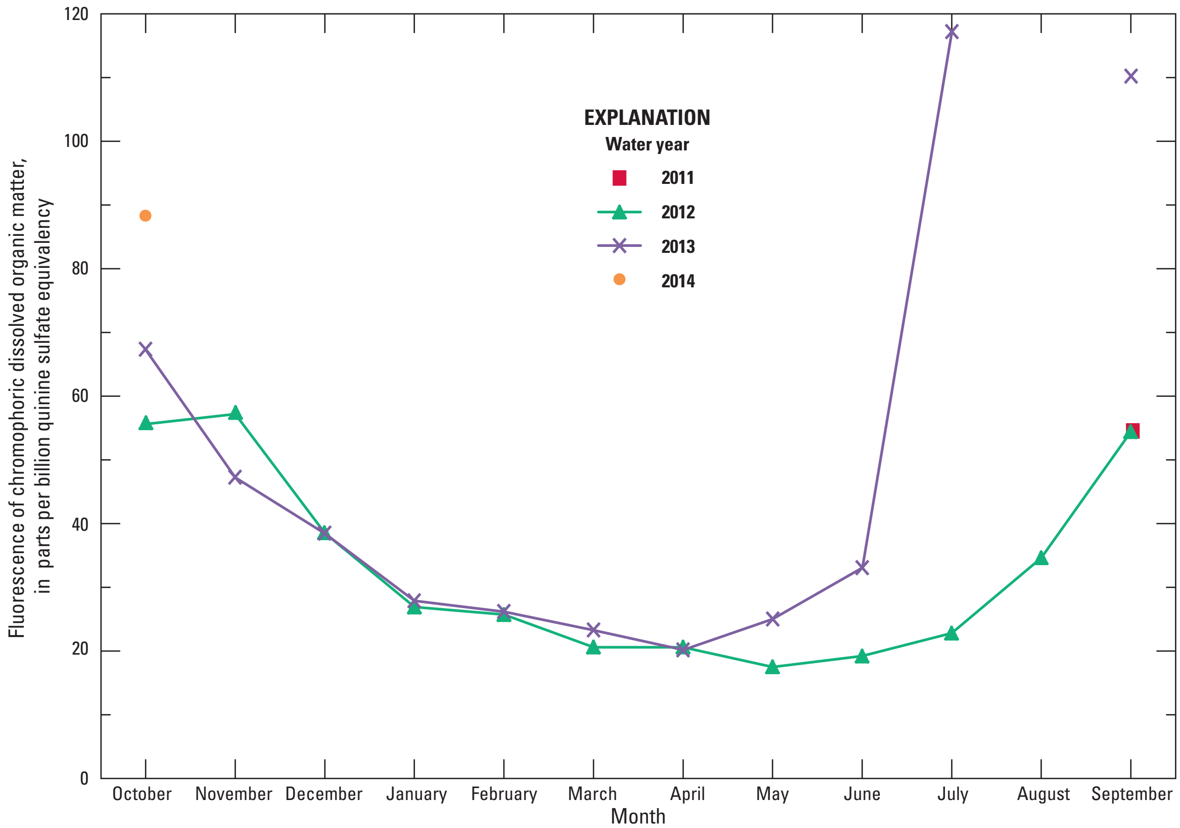


Figure 27. Monthly mean fluorescence of chromophoric dissolved organic matter in McIntyre Creek during water years 2011–14.

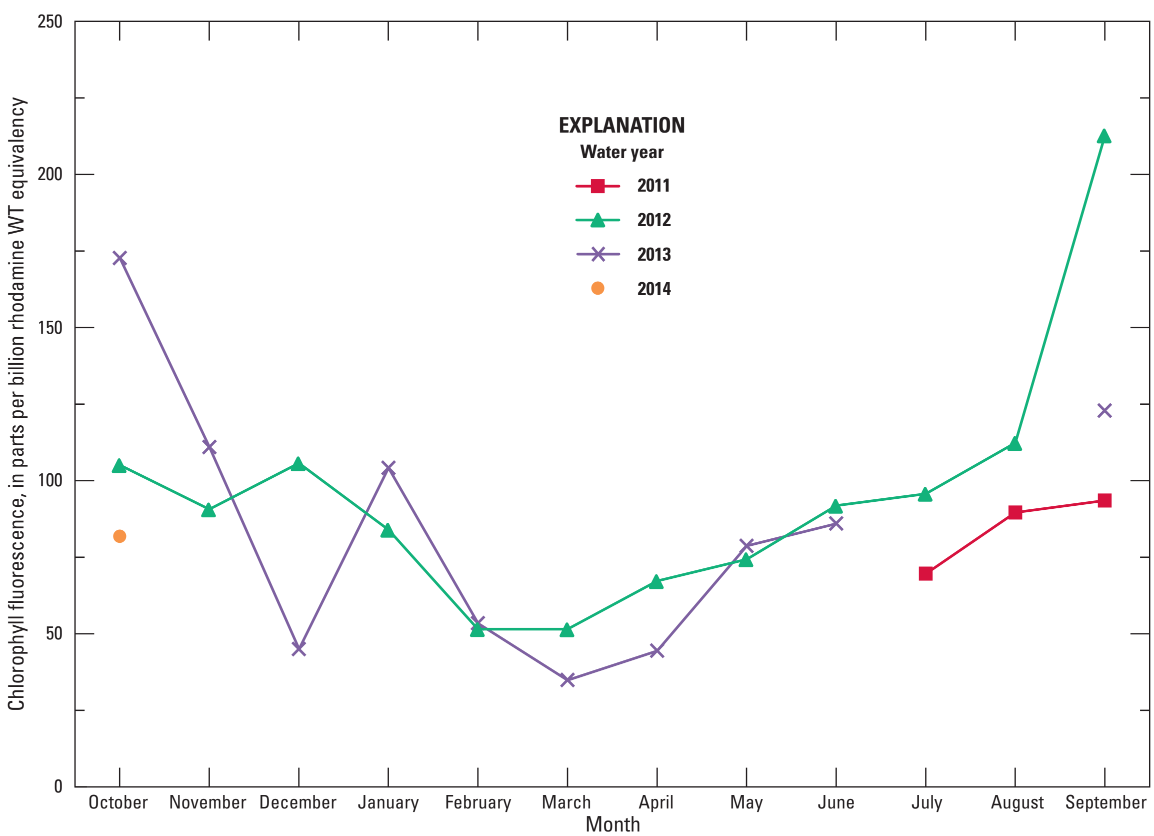


Figure 28. Monthly mean chlorophyll fluorescence in McIntyre Creek during water years 2011–14.

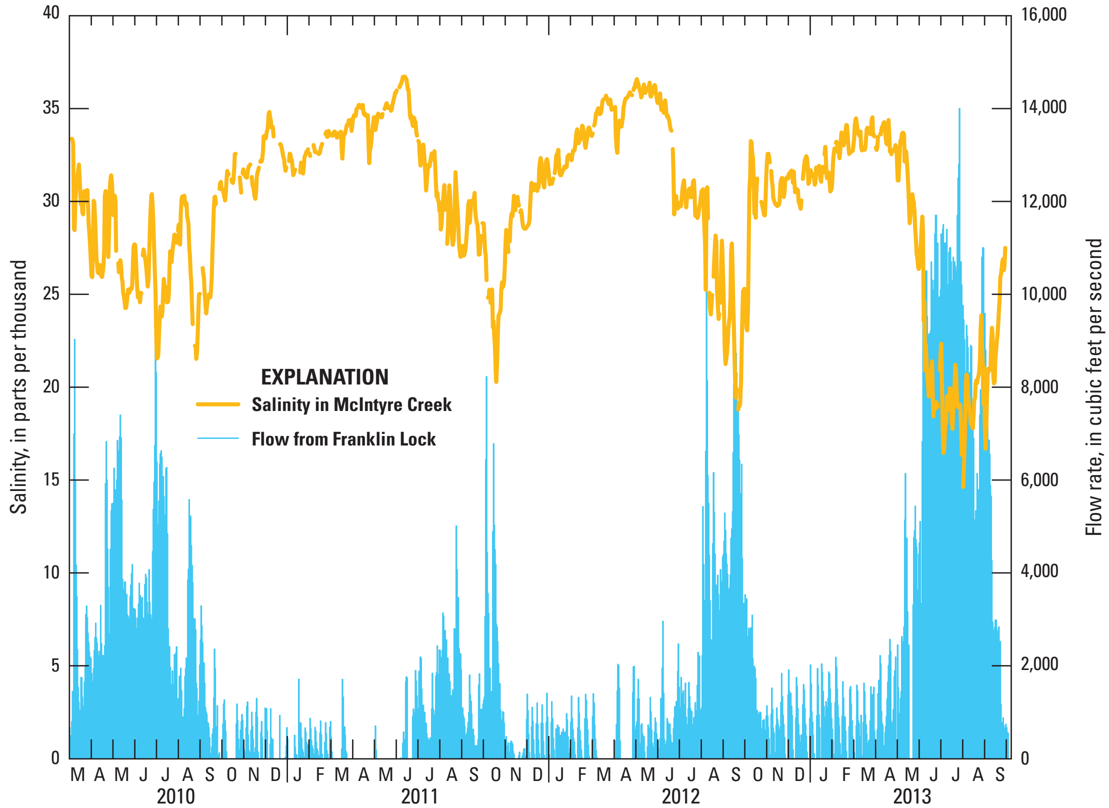


Figure 29. Average daily flow rate from Franklin Lock compared to average daily salinity in McIntyre Creek, March 2010 to October 2013.

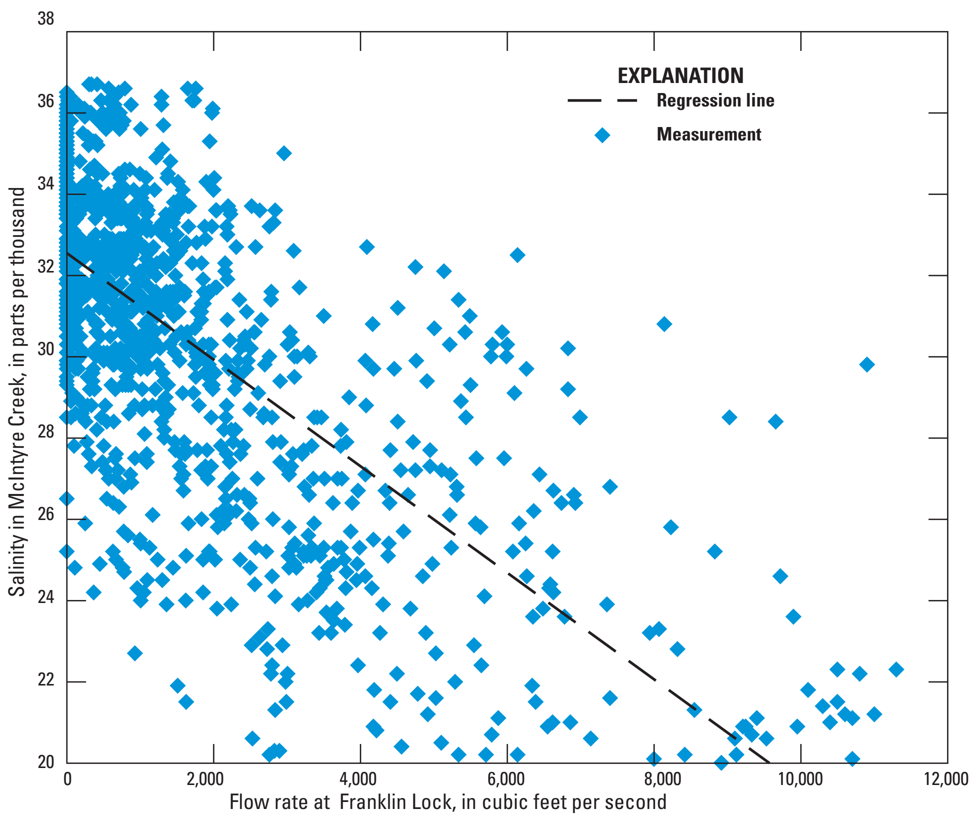


Figure 30. Relationship between flow rate at Franklin Lock and salinity in McIntyre Creek between March 2010 and October 2013.

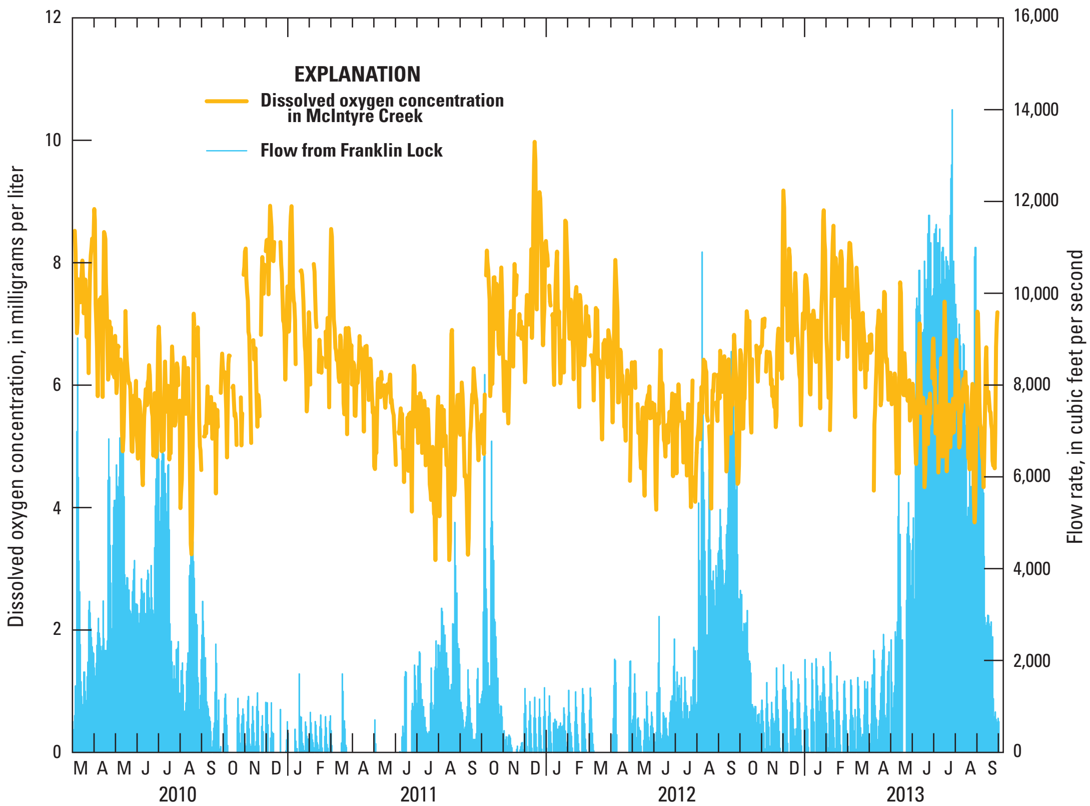


Figure 31. Showing average monthly flow rate from Franklin Lock compared to average monthly dissolved oxygen concentrations in McIntyre Creek, March 2010 to October 2013.

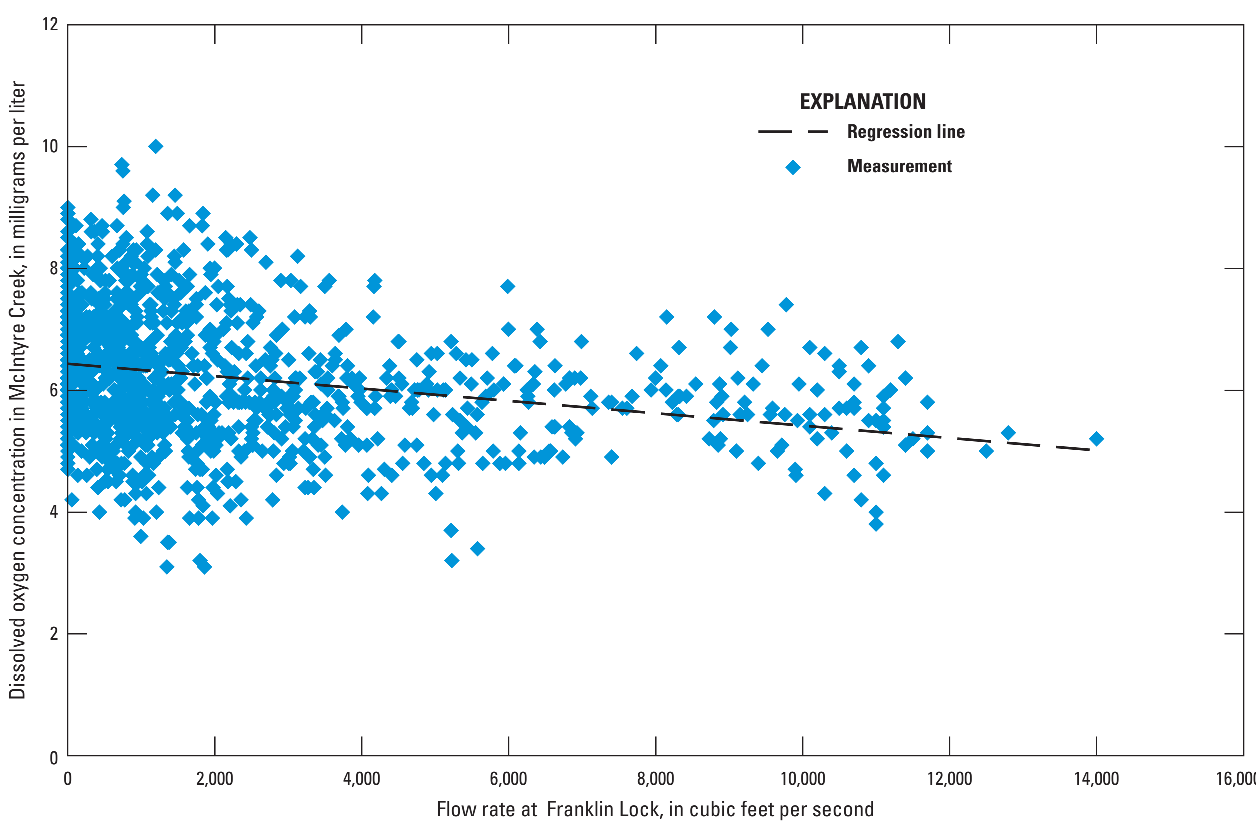


Figure 32. Relationships between flow rate at Franklin Lock and dissolved oxygen concentration in McIntyre Creek between March 2010 and October 2013.

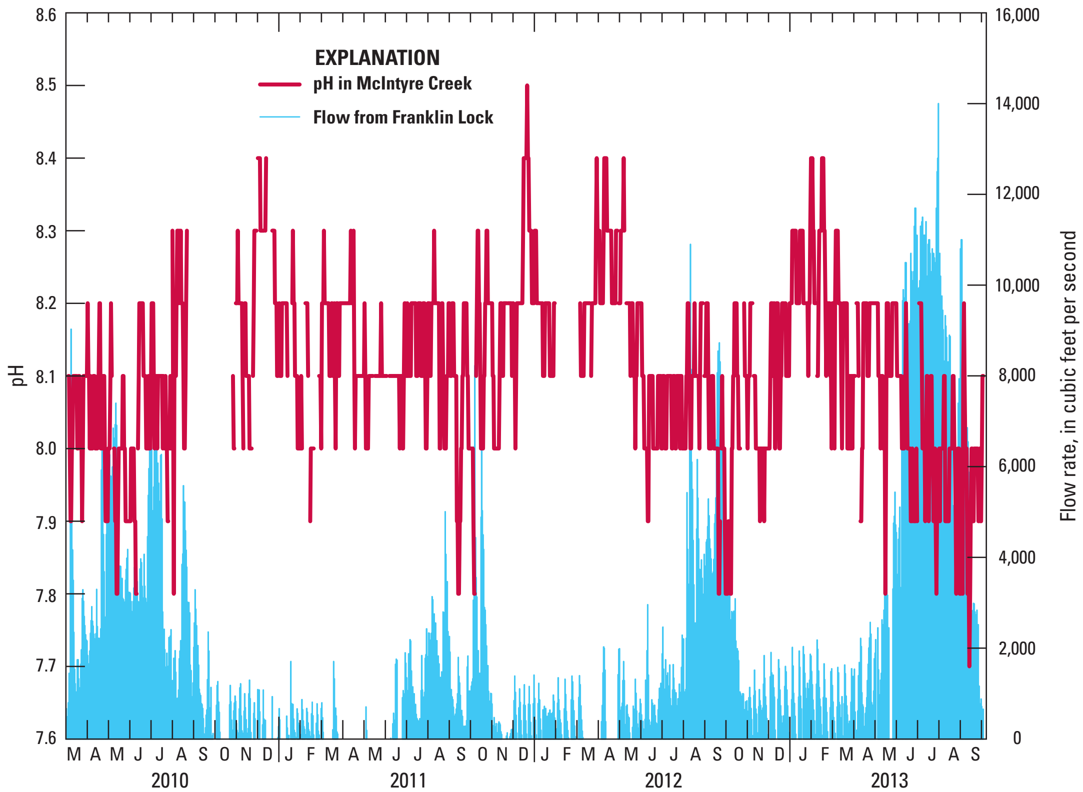


Figure 33. Average daily flow rate from Franklin Lock compared to median daily pH in McIntyre Creek, March 2010 to October 2013.

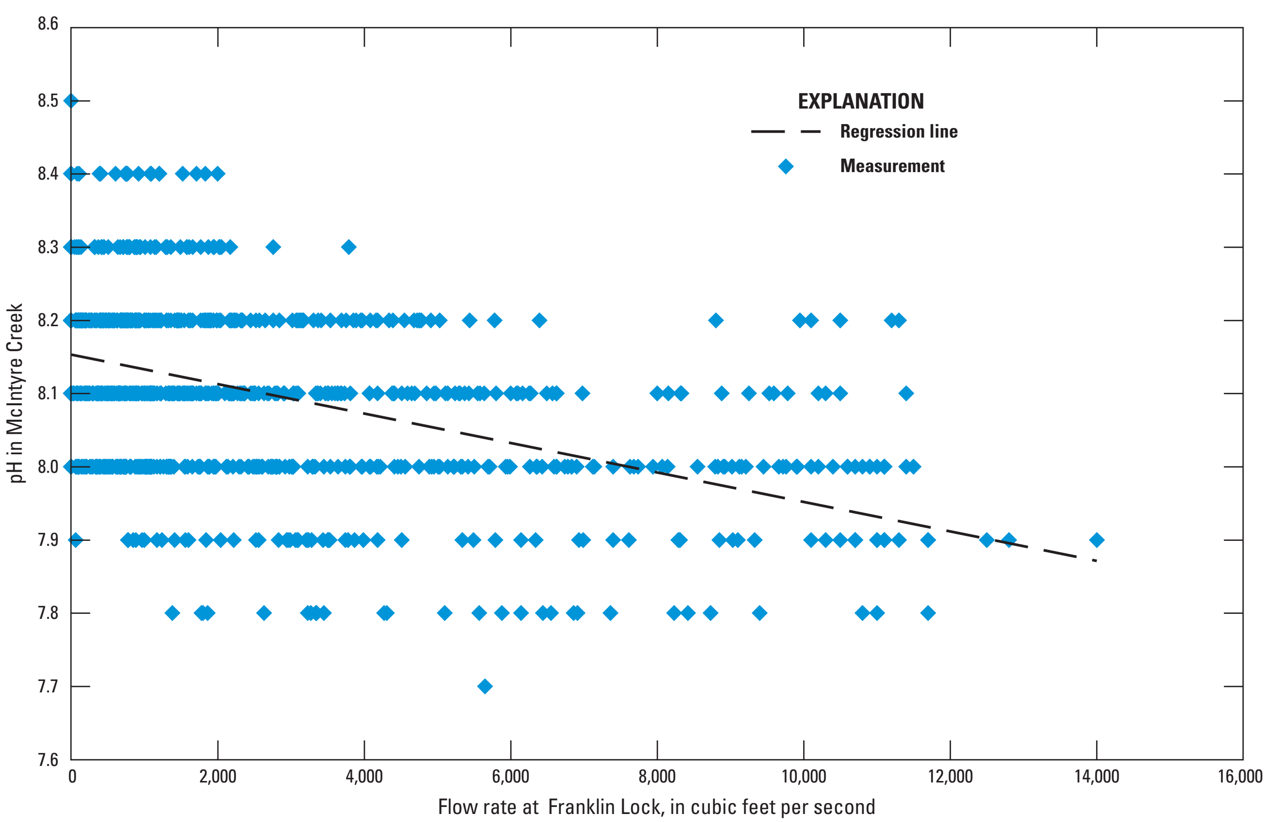


Figure 34. Relationship between flow rate at Franklin Lock and pH in McIntyre Creek between March 2010 and October 2013.

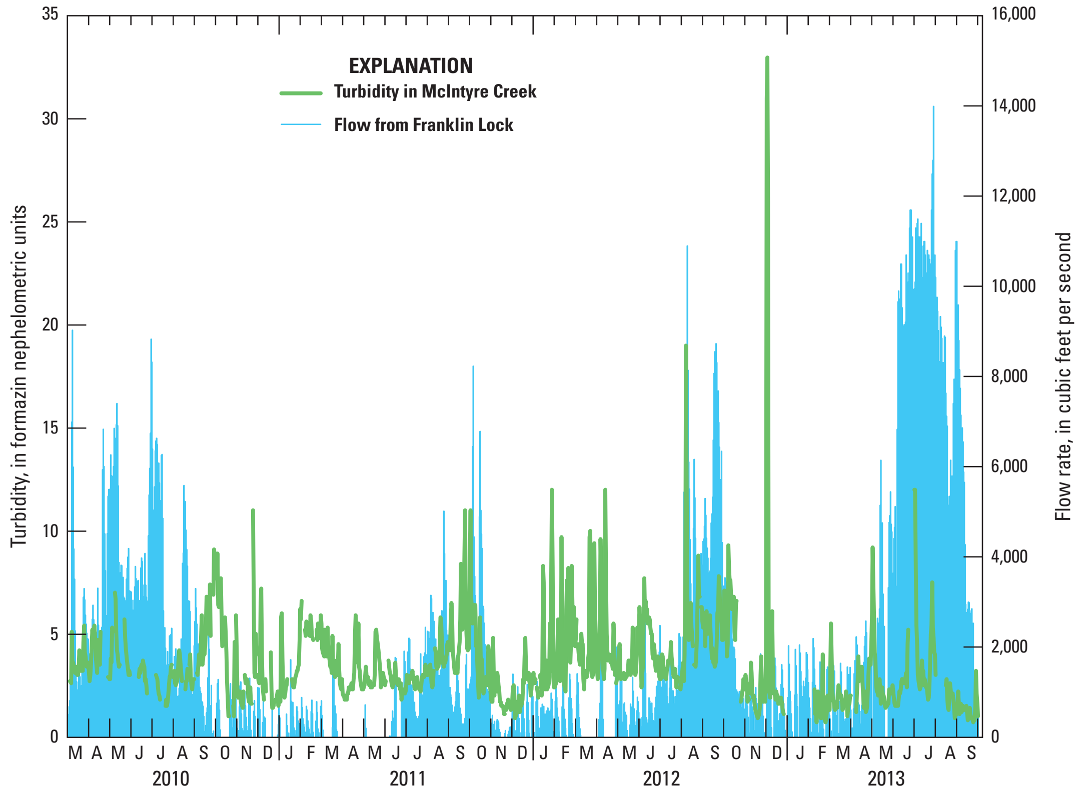


Figure 35. Average daily flow at Franklin Lock compared to average daily turbidity at McIntyre Creek, March 2010 to October 2013.

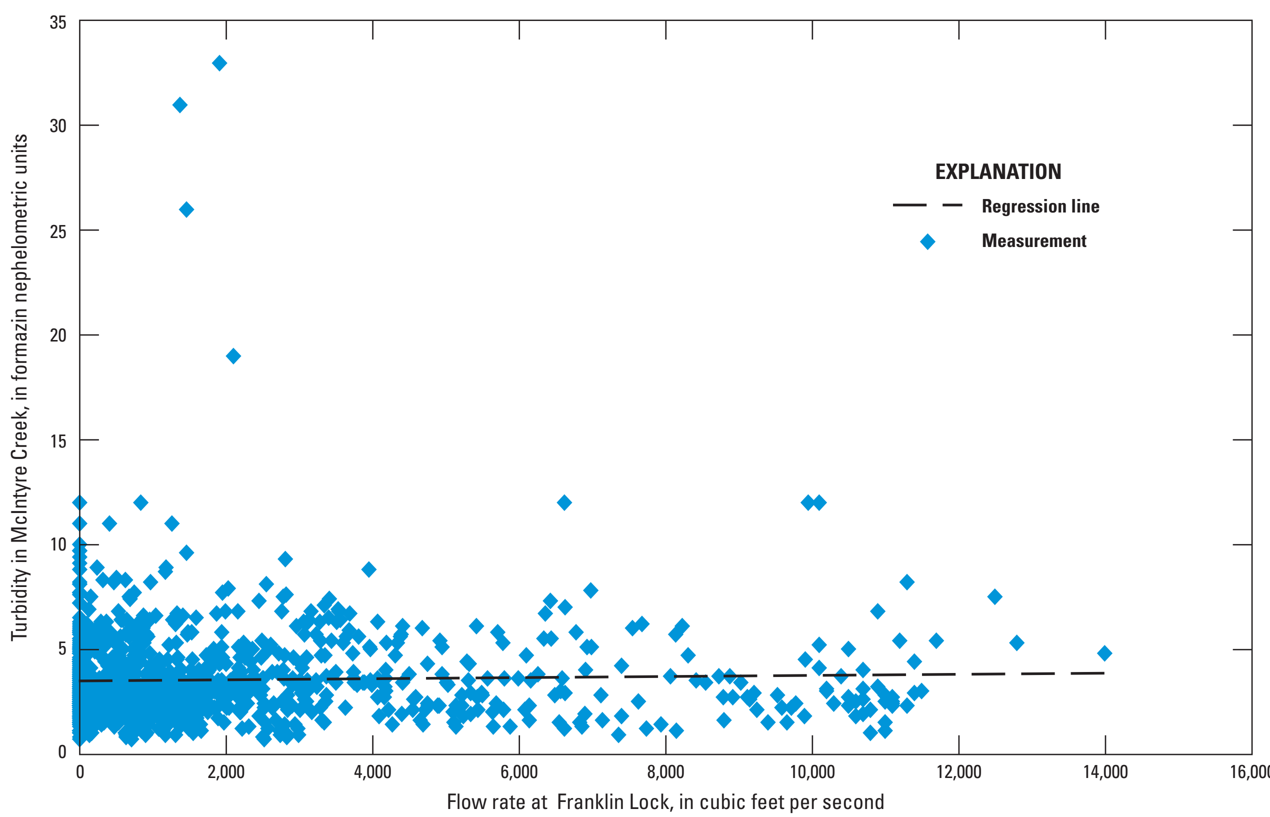


Figure 36. Relationship between flow rate at Franklin Lock and turbidity in McIntyre Creek between March 2010 and October 2013.

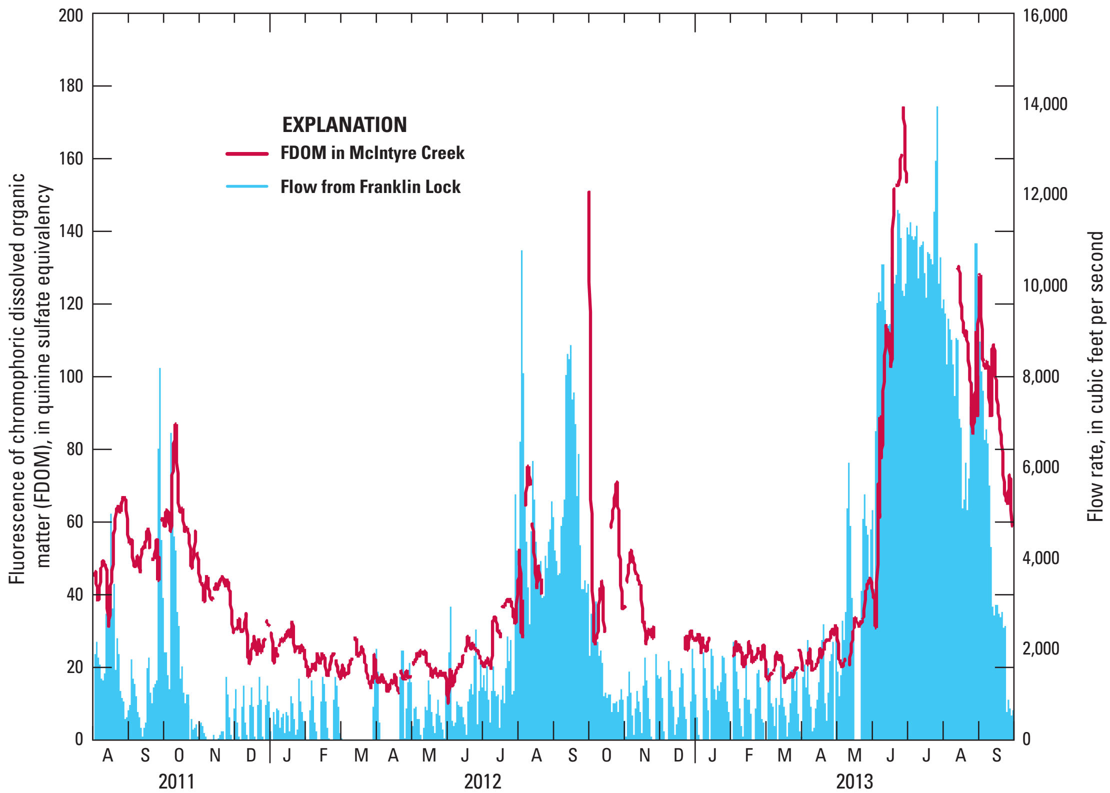


Figure 37. Average daily flow rate from Franklin Lock compared to average daily fluorescence of chromophoric dissolved organic matter in McIntyre Creek, March 2010 to October 2013.

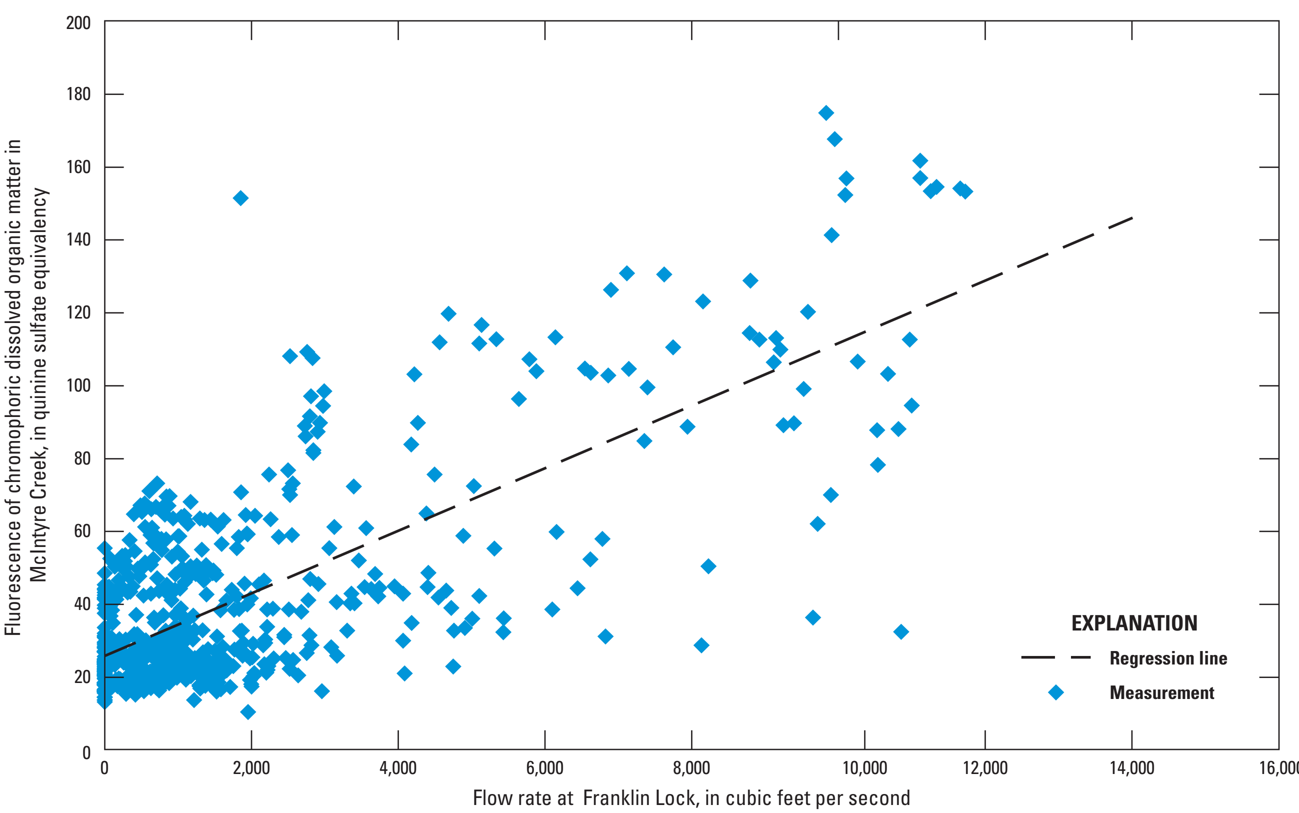


Figure 38. Relationship between flow rate at Franklin Lock and fluorescence of chromophoric dissolved organic matter in McIntyre Creek between March 2010 and October 2013.

Data from the moving-boat surveys confirm that in addition to freshwater, flow through Franklin Lock is also a source for high FDOM water to the Caloosahatchee River Estuary. Maps of FDOM values are inverse images of the salinity maps. The FDOM maps indicate a high FDOM plume of water extends from the Caloosahatchee River and flows into San Carlos Bay, then enters McIntyre Creek (Booth and others, 2014). Water-quality mapping confirmed that the Sanibel Causeway restricts tidal flushing, resulting in the retention of this water in the estuary. The highest salinities and lowest FDOM values were both recorded at Franklin Lock during a survey on March 22, 2012, corresponding with an average daily flow rate of 464 ft^3/s for the 30-day period prior to the survey. Although the highest FDOM values were recorded on July 25, 2012, near Billy's Creek, the highest FDOM values in the lower tidal Caloosahatchee and downstream estuary were associated with large discharges of freshwater through Franklin Lock. The highest FDOM values measured in San Carlos Bay were recorded on September 27, 2013, corresponding with an average daily flow rate of 7,731 ft^3/s for the 30 days prior to the survey.

Elevated chlorophyll fluorescence values corresponded with periods of increased flow from Franklin Lock in September and October 2012, and July through September 2013 (fig. 39). Elevated chlorophyll fluorescence levels were also measured during late December 2011, early January 2012, January 2013, and February 2013, but these periods did not correspond with periods of elevated flow through Franklin Lock. The maximum daily values for chlorophyll fluorescence were recorded in late December 2011 when patchy, high concentrations of algae (>1,000,000 cells/liter) associated with harmful algal blooms were reported near Sanibel Island (National Oceanic and Atmospheric Administration, 2011). The flow rate through Franklin Lock was positively correlated with chlorophyll fluorescence and accounted for 23 percent of the variation (fig. 40). A possible explanation is that the water released from the Franklin Lock provides nutrients that allow the phytoplankton populations to increase. Another explanation is that seasonal variation in temperature causes seasonal variation in phytoplankton dynamics. In this case, releases from Franklin Lock correlate with changes in phytoplankton dynamics but do not cause them. Additional studies are needed to determine which explanation is correct.

Limitations

Moving-boat water-quality surveys conducted were single-track measurements, generally within the navigation channel; the surveys did not sample the entire width of the river or bays and therefore lacked horizontal stratification. In addition, water-quality characteristics were measured within 1.5 ft of the water surface and therefore lacked vertical stratification as well. Diurnal fluctuations in water-quality characteristics, specifically temperature, were not measured. The lowest temperatures observed during surveys were often observed near Punta Rassa and San Carlos Bay, where the surveys began early in the day, probably indicating the influence of diurnal variation. Dissolved oxygen concentration and pH are also subject to diurnal variation. Lastly, surveys are performed in a dynamic tidal environment. To improve consistency between water-quality maps, surveys were scheduled to coincide with ebb tide at the tributaries; however, tidal ranges vary between survey dates.

Chlorophyll fluorescence can vary based on algal species composition, cell morphology, cell health, light adaptation by the cell, and turbidity in the water column (Turner Designs, 2011). Chlorophyll fluorescence was not corrected to account for turbidity or inner filter effects. Turbidity and inner filter effects are probably minimal in consequence relative to the effect of species composition. Although beyond the scope of this study, the collection and laboratory analysis of discrete chlorophyll samples could aid in quantifying continuous chlorophyll fluorescence.

This study investigated the correlation between water-quality characteristics in McIntyre Creek and flow at Franklin Lock. Although flow through Franklin Lock is often the largest single contributor of water to the Caloosahatchee River Estuary, it is not the only source. Thus, this report does not investigate all potential influences on water quality in the Ding Darling Refuge.

Summary and Conclusions

This report documents the basic water-quality dynamics at the mouth of McIntyre Creek and characterizes the correlations between water quality in McIntyre Creek and the Caloosahatchee River Estuary with surface-water flows through Franklin Lock. Additionally, this report summarizes Lake Okeechobee outflow data and tributary flow to the Caloosahatchee River and Estuary between 2010 and 2013.

During water years 2010, 2012, and 2013, Moore Haven Lock and Dam released more water from Lake Okeechobee than any other structure monitored by the U.S. Geological Survey. As measured by flow though Moore Haven, Lake Okeechobee accounted for 21 to 52 percent of the flow through Franklin Lock during this period; a greater percentage of flow was attributed to Lake Okeechobee during wet years than dry years. During water years 2010–12, Franklin Lock was the largest contributor of freshwater flow to the tidal Caloosahatchee River. Data were incomplete for water year 2013. Flow volume from the tributaries relative to flow volume through Franklin Lock ranged from 13 percent in 2010 to 30 percent in 2011, indicating that the tributaries contribute a larger percentage of water during the dry years compared to wet years.

Monthly mean temperature values at McIntyre Creek ranged from 31.5 ºC in June 2010 to 15.1 ºC in December 2011. Elevated temperatures occurred near Orange River during multiple surveys, and are attributed to a Florida Power and Light power plant that releases warm water.

The highest monthly mean salinities at McIntyre Creek (35.9 parts per thousand) were recorded in June 2011, coinciding with the lowest average monthly flow rate at

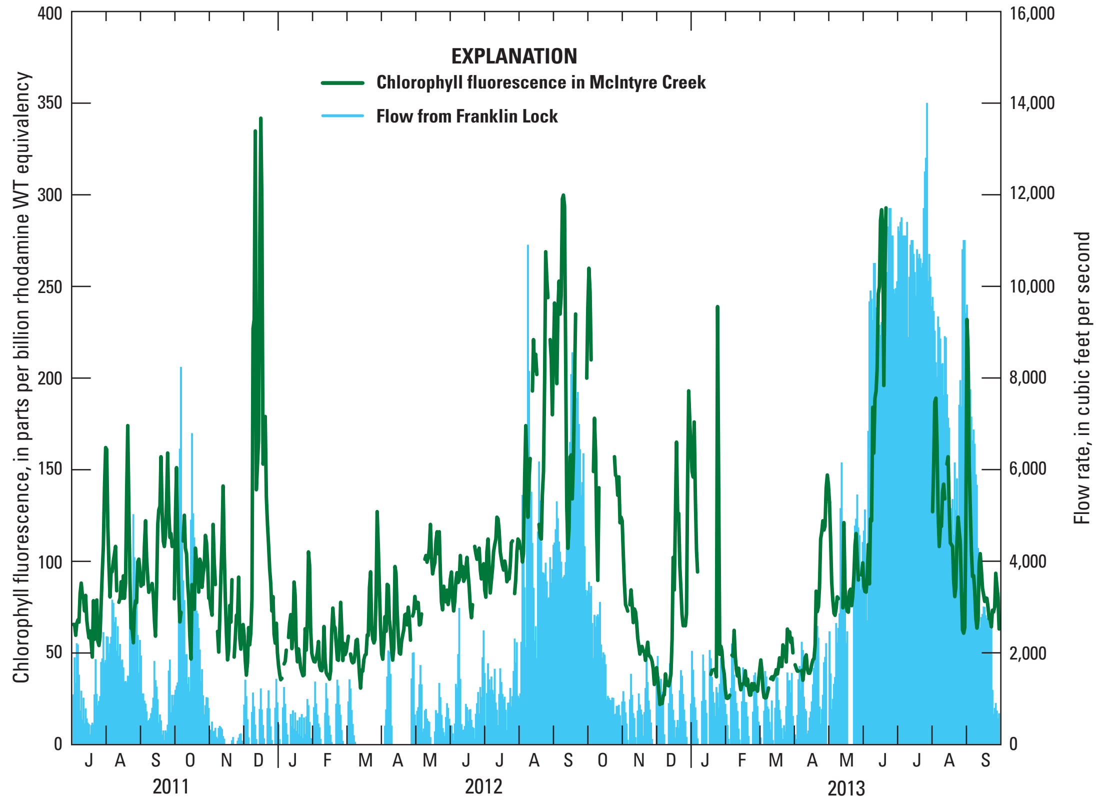


Figure 39. Average daily flow from Franklin Lock compared to average daily chlorophyll fluorescence in McIntyre Creek, March 2010 to October 2013.

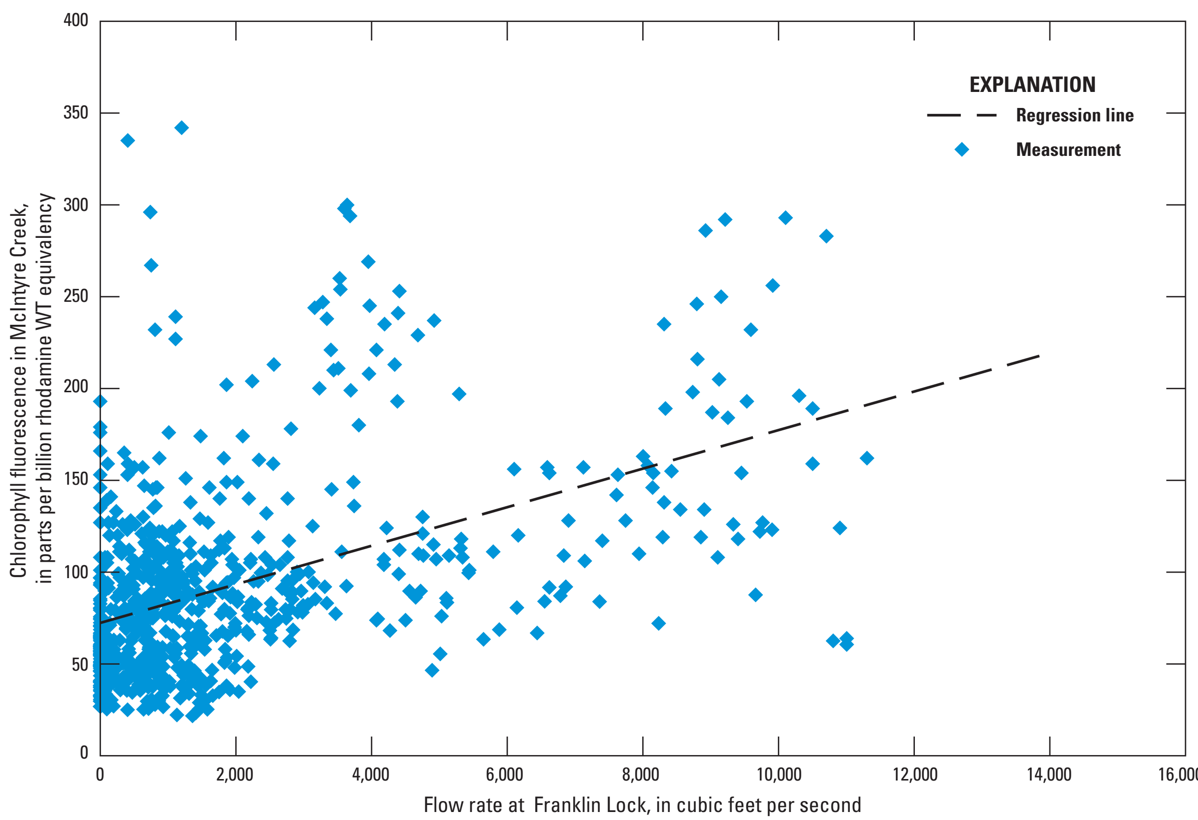


Figure 40. Relationship between flow rate at Franklin Lock and chlorophyll fluorescence in McIntyre Creek between March 2010 and October 2013.

Franklin Lock during May 2011 (29 cubic feet per second). The lowest monthly mean salinities at McIntyre Creek (18.5 parts per thousand) were recorded in August 2013, coinciding with the highest monthly mean flow rate through Franklin Lock (10,650 cubic feet per second). The flow rate through Franklin Lock was negatively correlated with salinity at McIntyre Creek and accounted for 61 percent of the variation. Salinity data from moving-boat surveys indicated that as the flow volume released through Franklin Lock increased, the mixing of fresh riverine waters from the Caloosahatchee River with marine waters from the Gulf of Mexico decreased salinity throughout the Caloosahatchee River Estuary, including McIntyre Creek. Conversely, when flow from the Franklin Lock was reduced or eliminated, the mixing of riverine and marine waters decreased and salinity rose.

Monthly mean fluorescence of chromophoric dissolved organic matter (FDOM) at McIntyre Creek ranged from 117.2 parts per billion quinine sulfate equivalents in July 2013 to 17.5 parts per billion in May 2012. FDOM was positively correlated with an increase in flow, and flow rates through Franklin Lock accounted for 54 percent of the variation in FDOM in McIntyre Creek. The variation can be attributed to the mixing of highly colored, high FDOM riverine waters with the clearer marine waters from the Gulf of Mexico. FDOM is probably affected by the source of the water released from Franklin Lock, which can vary from being predominantly Lake Okeechobee water released from Moore Haven, to runoff into the Caloosahatchee River between Moore Haven and Franklin Lock. FDOM data from moving-boat surveys indicated a similar pattern and revealed that the plume of higher FDOM waters from the mouth of the Caloosahatchee River extends out into the estuary, including McIntyre Creek.

Monthly median pH values were highest (8.3) in December 2010, and January, April, and May 2012. The lowest monthly median pH value was 7.9, recorded in October 2012. In McIntyre Creek, dissolved oxygen concentrations explained 31 percent of the variation in pH. A negative correlation was found between pH and increasing flow rate at Franklin Lock, and explained 21 percent of the variation in pH at McIntyre Creek. Discharges through Franklin Lock decrease pH in McIntyre Creek by reducing the salinity and alkalinity.

Dissolved oxygen concentrations were highest during the colder months of December, January, and March, and lowest during the warmer months of June to October, because the concentration of dissolved oxygen is inherently higher in colder water than it is in warmer water. Monthly mean dissolved oxygen concentrations at McIntyre Creek ranged from 8.0 milligrams per liter in December 2010 to 4.6 milligrams per liter in August 2011. Dissolved oxygen fluctuations did not demonstrate a correlation with flow through Franklin Lock.

Monthly mean turbidity at McIntyre Creek ranged from 5.7 formazin nephelometric units in October 2010 and 2011 to 1.5 formazin nephelometric units in December 2012. Turbidity fluctuations at McIntyre Creek did not demonstrate a correlation with flow through Franklin Lock.

Monthly mean chlorophyll fluorescence values at McIntyre Creek ranged from 213 parts per billion rhodamine WT equivalency in September 2012 to 35.0 parts per billion Rhodamine WT equivalency in March 2013. Chlorophyll fluorescence was positively correlated to flow rate through Franklin Lock and explained 23 percent of the variation. One possible explanation for this is that the water released from the Franklin Lock provides nutrients that allow phytoplankton populations to increase. Another possibility is that seasonal changes in phytoplankton dynamics are caused by changes in temperature, independent of flow at Franklin Lock. Using chlorophyll fluorescence as a surrogate for chlorophyll concentrations has limitations in the methodology and additional research is needed to determine whether flow through Franklin Lock affects chlorophyll concentrations at McIntyre Creek.

Although not all water-quality constituents analyzed in this study exhibited variations directly related to discharge management at Franklin Lock, it is evident that management practices influenced water quality in the Caloosahatchee River Estuary and Ding Darling Refuge. An increase in flow rate at Franklin Lock was correlated with a decrease in salinity and pH, and an increase in FDOM and chlorophyll fluorescence, in McIntyre Creek. Turbidity and dissolved oxygen concentration in McIntyre Creek were not affected by flows from Franklin Lock. Additional studies are needed to understand the effects of freshwater releases from Franklin Lock on chlorophyll fluorescence in Ding Darling Refuge.

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